한국도로학회 논문집
第7券4號 2005年 12月
pp. 49 ~ 56

공용성에 근거한 파괴기준을 이용한 개질 아스팔트 포장의 비용 효과 분석

Cost Analysis of Modified Asphalts using a Performance Based Fracture Criterion

김 부 일*
Kim, Booil

요 지

일반적으로 아스팔트 포장에서 개질재의 효과는 개질 아스팔트 혼합물과 일반 아스팔트 혼합물 사이의 재료 특성(인장강도, 스티프니스 등)을 단순히 비교함으로써 평가된다. 그러나 개질 아스팔트의 효과를 평가하는데 있어서 이러한 단순 비교는 아스팔트 혼합물의 특성을 제대로 반영하지 못하는 결과를 초래할 수 있다. 따라서 개질 아스팔트 혼합물의 특성을 효과적으로 평가하기 위해서는 아스팔트 혼합물의 주요한 특성들을 종합적으로 반영할 수 있는 합리적인 매개변수가 요구된다. 본 연구에서는 이러한 매개변수로서 최근에 새롭게 개발된 공용성에 근거한 파괴 기준 (Energy Ratio)을 이용하여 SBS 개질 아스팔트와 Crumb Rubber 개질 아스팔트의 파괴 저항성의 효과를 정량화하고 그에 따른 비용 효과를 비교 분석하였다. 분석 결과, SBS 개질 아스팔트 혼합물의 Energy Ratio가 Crumb Rubber 개질 아스팔트나 일반 아스팔트 혼합물의 Energy Ratio에 비해 두 배 이상 높음을 알 수 있었으며, 그에 따른 SBS 개질재의 비용 절감효과는 최대 24% 정도로 나타났다. 본 연구 결과, Energy Ratio는 개질 아스팔트의 효과를 평가하는데 유용할 뿐만 아니라, 공용성에 근거한 아스팔트 포장의 두께 설계의 파괴 기준으로도 이용 가능함을 확인할 수 있었다.

핵심용어 : 아스팔트 혼합물, 개질 아스팔트, 공용성 근거 파괴 기준, Energy Ratio, 비용 효과 분석

Abstract

The effect of modified asphalts is evaluated by simple comparison of a single parameter (i.e., tensile strength, stiffness, etc.) between modified asphalt mixture and unmodified mixture. The use of a single parameter to evaluate the effect of modified asphalt must be questioned. Rather, a single unified framework that accounts for changes in key mixture properties is needed to effectively evaluate the modified asphalt mixtures. This study used a new performance-based fracture parameter as a single unified framework, the Energy Ratio (ER), for quantifying the effect of modified asphalts on the fracture resistance of mixtures. The Energy Ratio was then used as a performance criterion for calculating the construction cost of two modified asphalt pavements (SBS and Crumb Rubber) and unmodified asphalt pavement. The results showed that the Energy Ratio of SBS modified asphalt was higher than those of crumb rubber and unmodified asphalt. Cost analyses indicated that the construction cost of the AC layer would be reduced by up to 24% by SBS modification. Based on the results, the Energy Ratio is capable of evaluating the effect of modified mixtures, and may form the basis of a promising fracture criterion for performance-based thickness design in asphalt pavements.

Keywords : asphalt mixture, modified asphalt, performance based fracture criterion, energy ratio, cost analysis

* Member · Highway Division, Korea Institute of construction Technology, Senior Researcher

1. INTRODUCTION

1.1 Background

Asphalt modifiers have become popular because of their apparent success in increasing the performance life of asphalt pavements in the field. In recent years, several studies have investigated the cracking performance of modified asphalt mixtures including Styrene Butadiene Styrene (SBS) and Crumb Rubber Modifier (CRM). Results of these studies have indicated that these kinds of modified asphalt can improve mixture properties such as tensile strength, fatigue cracking resistance, and permanent deformation (1 to 7). However, a simple comparison of these properties between modified asphalt mixture and unmodified mixture has been performed in the laboratory. Otherwise, a simple comparison of performance in the field was usually conducted so far. The simple comparison in the laboratory to evaluate the effect of modified asphalt must be questioned. Rather, a single unified framework that accounts for changes in key mixture properties is needed to effectively evaluate the modified asphalt mixtures. In addition, little work has been done to evaluate the cost effectiveness for use of modifier in asphalt pavement.

1.2 Objectives

The overall objective of this study was to use a new performance-based fracture criterion as a single unified framework, the Energy Ratio (ER), for quantifying the effect of modified asphalts on the fracture resistance of mixtures. The Energy Ratio was then used as a performance criterion for calculating the construction cost of two modified asphalt pavements (SBS and CRM) and unmodified asphalt pavement. A clearer understanding of this cost effectiveness will lead to better guidelines for the use, as well as the potential benefits of these modifiers in specific mixtures and loading environments. More specific objectives of the study may be summarized as follows:

- Understand specific mixture properties and/or behavioral characteristics that uniquely characterize the SBS and CRM modified asphalt mixtures.
- Identify an appropriate parameter that can be used to evaluate fracture resistance of modified mixtures.
- Analyze the cost effectiveness of modified binders on the cracking performance of asphalt pavements.

2. PERFORMANCE BASED FRACTURE CRITERION

Kim, Roque, and Birgisson (7) showed that the key to characterize the cracking resistance of asphalt mixture is in the evaluation of the combined effects of creep and failure limits, and the hot mix asphalt (HMA) fracture mechanics model that unify the creep and failure limits for evaluating the cracking resistance can properly characterize the effect of modified asphalt. The main feature of HMA fracture mechanics developed by the University of Florida is in the threshold concept. Figure 1 shows a conceptual illustration of the HMA fracture mechanics framework. The figure shows two ways for mixture to be failed; (1) when the accumulated creep energy exceeds the dissipated creep strain energy (DCSE) threshold, (2) when the accumulated creep energy plus elastic energy exceeds the fracture energy (FE) threshold. Zhang et al. (8) discovered that the DCSE and the FE threshold of asphalt mixtures can be easily determined from the tensile strength and resilient

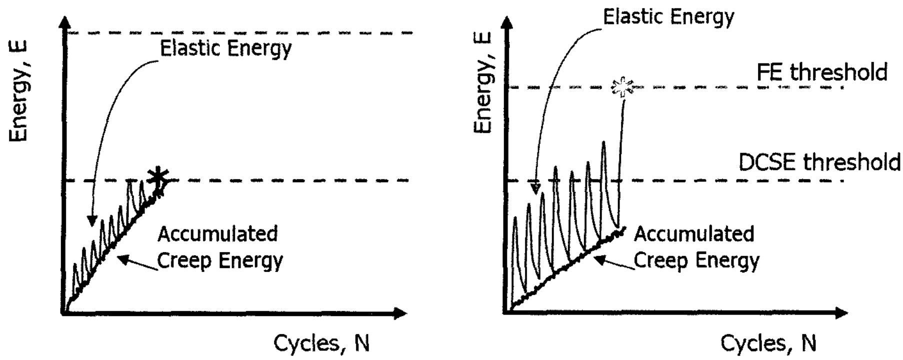

Figure 1. Conceptual illustration of HMA fracture mechanics model

modulus test using the Superpave IDT.

The rate of damage growth under the threshold is governed by the creep properties of the mixture. The creep compliance of the mixtures can be represented using the following power function:

$$D(t) = D_0 + D_1 t^m \quad (1)$$

where $D(t)$ is creep compliance, D_0, D_1, and m are parameters obtained from creep tests. Hence, the rate of micro-damage is assumed to be controlled by the m-value and D_1. Figure 2 shows a conceptual illustration of the effect of rate of creep and m-value on rate of damage. The higher the m-value, the faster is the rate of accumulation of *DCSE*, and thus the faster the *DCSE* limit is reached.

Based on the forensic investigation of 36 field

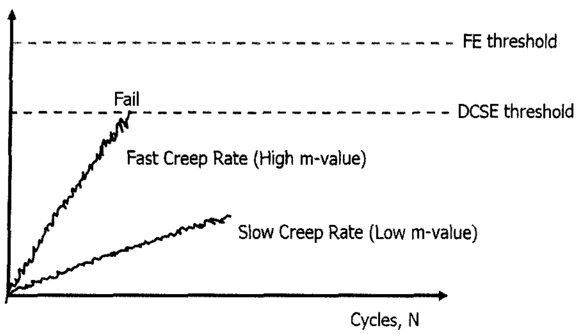

Figure 2. Effect of rate of creep and m-value

pavement sections of known cracking performance, a HMA fracture mechanics-based performance specification criterion, termed the "Energy Ratio" (ER), was developed at University of Florida (9). This parameter is a measure of the fracture resistance of mixtures, and is expressed by:

$$ER = DCSE_f / DCSE_{min} = (a \times DCSE_f) / (m^{2.98} \times D_1) \quad (2)$$

Where:

$DCSE_f$ = Dissipated Creep Strain Energy (in KJ/m^3)

$DCSE_{min}$ = Minimum Dissipated Creep Strain Energy for adequate cracking performance (in KJ/m^3)

$a = 0.0299\,\sigma^{-3.1}\,(6.36 - S_t) + 2.46 \times 10^{-8}$

in which σ = Tensile stress of asphalt layer (in psi)

S_t = Tensile strength (in MPa)), and

m and D_1 = Creep parameters in (1/psi)

3. RESEARCH APPROACH

3.1 Materials

This study focused primarily on the evaluation of mixture properties and cost effectiveness for modified mixtures in asphalt pavement. Three binders were involved in this study. One is control binder, which is unmodified and categorized into viscosity grade AC-30, another is SBS(3%) modified asphalt, and the other is CRM asphalt. The unmodified asphalt (AC-30) was used for the base asphalt of modified asphalts. The properties of these binders are presented in Table 1. Penetration and DSR tests at mediate temperature indicated that SBS modified asphalt appeared to be less stiff than those of the others, resulting the lower G*sin(δ). However, DSR tests at high temperature showed that SBS modified and CRM asphalts were much more rigid than that of unmodified asphalt.

Total Six types of asphalt mixtures with coarse graded (gradation below the restricted zone of Superpave mix design) limestone aggregate and three binders (SBS, CRM, and unmodified) were produced at two design asphalt contents (6.1% for high traffic level and 7.2% for low traffic level) in accordance with Superpave mix design. Asphalt mixture properties were obtained using the Superpave IDT (Indirect Tensile Test), which is described in AASHTO TP-9. Mixtures were Short Term Oven Aged (STOA), and then compacted to 7% (± 0.5%) air voids.

3.2 Mixture Tests

The mixture properties from the standard Superpave Indirect Tensile Tests (IDT) are presented in Table 2. As shown in the table, the SBS modifier had little effect on resilient modulus. This seems to indicate that the polymer has little effect on response at small strain or short loading times. Conversely, the SBS modifier dramatically reduced the creep compliance of mixtures at both low and high asphalt contents. Thus, the test results show that the SBS polymer has a much greater influence on the time-dependent response, and perhaps specifically the creep response, than on the elastic response of the mixture. As shown in Figure 1, the lower rate of creep response is clearly reflected in the lower m-value of the modified mixtures at both asphalt contents. The results presented in Table 2 also indicate the SBS polymer had almost no effect on the tensile strength, the fracture energy (FE), or the dissipated creep strain energy to failure (DCSEf). On the other hand, prior research (8) clearly showed that there is a direct relationship between the rate of creep and the rate of micro-damage accumulation in asphalt mixtures. Therefore, it appears that the benefit of the

Table 1. Asphalt binder properties

Binder Type	Replicate	Penetration @25℃	DSR at 25℃			DSR at 64℃		
			G*(kPa)	δ	G*Sin(δ)	G*(kPa)	δ	G*Sin(δ)
Unmodified Asphalt (AC-30)	1	61	1110	66.7	1020	1.93	86.2	1.93
	2	60	1070	67.4	985	2.01	86.1	2.02
	3	60	902	67.4	833	2.01	86.2	2.02
	Average	60	1027	67.2	946	1.98	86.2	1.99
CRM Asphalt	1	36	1140	58.1	968	5.94	78.3	6.06
	2	36	1100	57.8	930	5.79	78.5	5.91
	3	35	1062	57.9	900	5.46	78.3	5.57
	Average	36	1101	57.9	933	5.73	78.4	5.85
SBS Modified Asphalt	1	50	748	58.7	639	6.16	63.9	6.86
	2	51	737	61.0	644	6.24	64.5	6.91
	3	50	733	60.5	638	6.12	64.5	6.80
	Average	50	739	60.1	640	6.17	64.3	6.86

Table 2. Asphalt Mixure properties measured from Superpave IDT

Sample	Properties						
	Resilient Modulus (Gpa)	Creep Compliance at 1000sec. ((1/Gpa)	Tensile Strength (Mpa)	Fracture Energy (kJ/m^3)	D1 (×10^{-7}, 1/psi)	m-value	DCSE (kJ/m^3)
Unmodified mixtures							
6.1	11.56	5.90	1.87	4.00	6.04	0.61	3.85
7.2	7.18	13.42	1.69	4.90	12.1	0.62	4.70
Crumb Rubber Modified Mixtures							
6.1R	11.09	3.49	1.87	2.20	6.20	0.59	2.04
7.2R	7.16	8.50	1.29	3.30	10.4	0.58	3.18
SBS Modified Mixtures							
6.1S	9.26	3.04	1.95	3.80	7.69	0.45	3.59
7.2S	7.37	5.21	1.93	5.10	13.3	0.47	4.85

polymer is primarily and almost exclusively reflected in the reduced m-value, which indicates a reduced rate of micro-damage accumulation.

On the other hand, the cracking related properties of CRM asphalt mixture were almost identical with those of unmodified asphalt mixture. There was no difference in resilient modulus, tensile strength, fracture energy, and m-value between CRM asphalt and unmodified asphalt mixtures. However, the creep compliance of CRM asphalt was much less than that of unmodified asphalt. Thus, the test results appear to show that the crumb rubber has little influence on fracture resistance, while high influence on permanent deformation.

4. COST ANALYSIS USING THE ENERGY RATIO

In order to perform the cost analysis for various types of asphalt pavements, three typical asphalt pavements were designed. As shown in the Figure 3, (1) conventional asphalt pavement with crushed stone base, (2) full depth asphalt pavement, and (3) HMA overlay on the conventional asphalt pavement. Based on the Superpave traffic level criteria, three traffic levels were selected for pavement design in this study; 3 million ESALs for low traffic level, 10 million ESALs for medium traffic level, and 30 million ESALs for high traffic level. For the selected pavement types and traffic levels, design AC layer thickness was determined according to the AASHTO procedure (10). As input values for to the AASHTO design procedure, an asphalt concrete (AC) modulus was determined from the results of Superpave IDT, and typical moduli of base (40,000 psi) and subgrade (10,000 psi) were selected. Structural coefficient (a_i) and drainage coefficient (m_i) were assumed, as shown in Table 3. The following design inputs were assumed in all cases: 95% reliability (R), 0.4 standard deviation (S_o), and 2.0 design serviceability loss (ΔPSI).

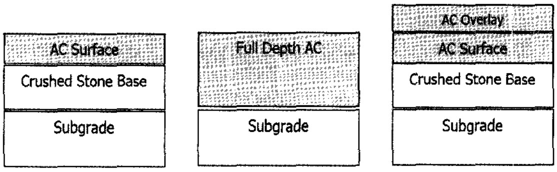

Figure 3. Pavement designs for cost analysis

Table 3 shows the resulting design layer thickness and the resulting tensile stresses at the bottom of the

Table 3. Design layer thickness and calculated tensile stresses

			Low Traffic	Medium Traffic	High Traffic
Conventional	Modulus(psi)	a_i & m_i	LAYER THICKEN(inches)		
AC	1,200,000	0.40	6.0	7.0	8.5
Crushed stone base	40,000	0.14 & 1.2	8.5	10.5	10.0
Subgrade	10,000				
σ_t(psi) at the bottom of AC layer			204.0	165.0	129.0
HMA Full Depth	Modulus(psi)	a_i & m_i	LAYER THICKEN(inches)		
AC	1,200,000	0.40	10.0	12.0	14.0
Subgrade	10,000				
σ_t(psi) at the bottom of AC layer			119.0	87.6	67.1
HMA Overlay	Modulus(psi)	a_i & m_i	LAYER THICKEN(inches)		
AC Overlay	1,200,000	0.40	3.0	3.5	4.5
AC	1,200,000	0.40	6.0	7.0	8.5
Crushed stone base	40,000	0.14 & 1.2	8.5	10.5	10.0
Subgrade	10,000				
σ_t(psi) at the bottom of AC layer			121.0	94.7	68.0

AC layer. The tensile stresses were calculated for each design pavement structure using multi-layer elastic analysis program, BISAR, using a 9000 (lb) single axle load with 6-inch radius. Table 4 shows the calculated ER for the design pavement structures with material properties shown in Table 2 and the calculated tensile stress shown in Table 3. The ER of SBS modified mixture was much higher than those of CRM and unmodified mixtures. However, the ER of CRM mixture was almost identical with unmodified mixtures in this study.

As shown in Table 4, the ER of SBS modified mixture was higher than those of CRM and unmodified mixtures for all the cases. Thus, for the relative cost analysis of SBS, CRM and unmodified mixtures, the ER of unmodified mixture (ERHMA) and CRM mixture (ERCRM) was increased to meet the ER of SBS modified mixture (ERSBS) by increasing the thickness of AC layer resulting in the decreased tensile stress at the bottom of AC layer, which results in equivalent fatigue cracking of SBS modified AC layer.

Table 5 shows the cost of unmodified AC layer and modified AC layer having equivalent ER. The unit cost of unmodified HMA, SBS modified HMA and CRM HMA are assumed at 50 dollars per ton, 70 dollars per ton and 55 dollars per ton, respectively considering the market price. When it is assumed that the specific gravities of all HMA are identical, these prices can be converted to 2.82 dollars per inch for unmodified HMA. 3.95 dollars per inch for SBS modified HMA and 3.10 dollars per inch for CRM HMA. As shown in Table 5, while the cost of CRM HMA is 8% higher for all the cases than that of unmodified HMA, the cost of SBS modified AC layer is largely varied from 24% lower to 19% higher. For example, the cost of SBS modified AC layer is 12% lower for low traffic level and 8% higher for high traffic level than those of unmodified AC layer in conventional pavement structures. However, in HMA full depth pavement structures, the cost of SBS modified AC layer is 14% to 19% higher for all traffic levels than those of unmodified AC layer. For HMA overlay structures, SBS modified mixture resulted in lower cost (3% to 24% lower cost of modified AC layer than those of

Table 4. Calculated Energy Ratio

Pavement type / Traffic level \ Sample Type	Unmodified (6.1%AC)	Unmodified (7.2%AC)	CRM (6.1%AC)	CRM (7.2%AC)	SBS (6.1%AC)	SBS (7.2%AC)
Conventional Low traffic	0.94	0.55	0.97	0.76	1.71	1.17
Conventional Medium traffic	1.18	0.68	1.22	0.95	2.14	1.47
Conventional High traffic	1.75	1.01	1.81	1.41	3.17	2.17
Full depth Low traffic	2.05	1.19	2.12	1.65	3.71	2.55
Full depth Medium traffic	4.21	2.44	4.35	3.40	7.64	5.24
Full depth High traffic	8.74	5.08	9.04	7.05	15.85	10.88
HMA Overlay Low traffic	1.98	1.15	2.05	1.60	3.59	2.46
HMA Overlay Medium traffic	3.45	2.01	3.57	2.79	6.26	4.30
HMA Overlay High traffic	8.42	4.89	8.70	6.79	15.26	10.47

unmodified AC layer). These results are due to the thickness of AC layer. That is, the thinner the AC layer, the higher the cost reduction by applying SBS modifier in this analysis. However, the CRM was not able to reduce the cost of AC layer by applying this type of modifier due to the higher unit price as compared with the lower increase of fracture resistance.

Table 5. Cost of AC layer with the equivalent ER

(Unit:$)

Pavement Type	Binder Type	Low Traffic	Medium Traffic	High Traffic
Conventional	Unmodified	26.8	28.2	31.0
	CRM	28.8	30.4	33.5
	SBS	23.7	27.7	33.6
Full Depth	Unmodified	34.7	40.6	46.5
	CRM	37.2	43.4	50.5
	SBS	39.5	47.4	55.3
HMA Overlay	Unmodified	15.5	16.9	18.3
	CRM	16.7	18.3	19.8
	SBS	11.9	13.8	17.8

5. SUMMARY AND CONCLUSIONS

Prior research to evaluate the effect of SBS modifiers on cracking resistance of asphalt mixtures, has shown that the benefit of SBS modifiers to mixture cracking resistance appeared to be primarily derived from a reduced rate of micro-damage accumulation, which was reflected in a lower m-value without a reduction in fracture limit or healing rates. The results of this study showed that the Energy Ratio of SBS modified asphalt was higher than those of crumb rubber and unmodified asphalt. Based on the results, the Energy Ratio is capable of evaluating the effect of modified mixtures, and may form the basis of a promising fracture criterion for performance-based thickness design in asphalt pavements

A cost analysis was conducted using the energy ratio as the performance criterion to compare the construction costs of AC layers with Crumb Rubber Modifier and SBS polymer modifier. The result of cost analysis for the cases where both unmodified and modified mixtures had an equivalent energy ratio, indicated that the construction cost of the AC layer would be reduced by up to 24% by SBS modification. However, the CRM was not able to reduce the cost of AC layer by applying this type of modifier due to the higher unit price as compared with the lower increase of energy ratio.

REFERENCES

1. Heshmet A. Aglan, "Polymer modifiers for improved performance of asphalt." *In Asphalt Science and Technology,* Usmani, Marcel Dekker, 1997. pp. 197-216.
2. Stephen D. Jones, Kamyar C. Mahboub, R, Michael Anderson, and Hussain U. Bahia, "Applicability of Superpave to modified asphalts ? A mixture study." *Transportation Research Record 1630,* TRB, National Research Council, Washington, D.C., 1998, pp.42-50.
3. Mohammad Jamal Khattak and Gilbert Y. Baladi, "Engineering Properties of Polymer Modified Asphalt Mixture." *Transportation Research Record 1638,* TRB, National Research Council, Washington, D.C., 1998, pp.12-22.
4. Wegon, Vibeke & Bernard Brûlé, "The Structure of Polymer Modified Binders and Corresponding Asphalt Mixtures." *Journal of the Association of Asphalt Paving Technologists, Vol. 68,* pp. 64-88, 1999.
5. Mohammad Jamal Khattak and Gilbert Y. Baladi, "Fatigue and Permanent Deformation Models for Polymer-Modified Asphalt Mixtures." *Proceedings of the 80th TRB Annual Meeting,* TRB ID No. 01-2813, Washington D.C., January 2001.
6. H. Bahia, D. I. Hanson, et al., "Characterization of Modified Asphalt Binders in Superpave Mix Design.' *NCHRP Report 459,* Transportation Research Board National Research Council, National Academy Press, Washington D.C., 2001.
7. Booil Kim, R. Roque, B. Birgisson, "Laboratory Evaluation of the Effect of SBS Modifier on Cracking Resistance of Asphalt Mixture." *Proceedings of the 82nd TRB Annual Meeting,* TRB ID No. 03-3399, Washington D.C., January 2003.
8. Zhang, Z., Roque, R., and Birgisson, B., "Identification and Verification of a Suitable Crack Growth Law." *Journal of the Association of Asphalt Paving Technologists, Vol. 70,* pp. 206-241, 2001.
9. Jajliardo, P. Adam, *"Development of Specification criteria to mitigate top-down cracking"*, Thesis (M.E.), University of Florida, 2003.
10. American Association of State Highway and Transportation Officials, *"AASHTO Guide for Design of Pavement Structures."* AASHTO, Washington D.C., 1993.

〈접수 : 2005. 5. 20〉