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아스팔트 혼합물의 균열 저항성 평가 연구

Laboratory Test and Evaluation to Characterize the Cracking Resistance of Asphalt Mixtures

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요 지

아스팔트 혼합물의 균열 저항성은 일반적으로 인장 강도, 스티프니스와 같은 단일 물성치를 측정함으로써 평가된다. 그러나, 아스팔트 혼합물의 균열 성능을 평가함에 있어서 단일 물성치의 이용은 의문시 되어 왔다. 따라서 본 연구에서는 아스팔트 혼합물의 균열 저항성과 관련이 있는 주요 특성치를 좀 더 심도 있게 규명하고자 하였다. 이를 위해 다양한 하중 조건 하에서 파괴 시험, 크리프 시험, 강도 시험이 일반 아스팔트 혼합물과 개질 아스팔트 혼합물에 대해서 수행되었다. 시험 결과, 혼합물의 균열 저항성은 주로 미세 손상 축적 속도에 영향을 받음을 알 수 있었으며, 이 값은 파괴 에너지 한계에 영향을 주지 않으면서 m값에 반영됨을 알 수 있었다. 또한, 짧은 하중 재하 시간 (탄성 거동) 동안 얻어지는 스티프니스는 혼합물의 균열 저항성의 차이를 규명하는데 한계가 있음을 알 수 있었다. 따라서 아스팔트 혼합물의 균열 저항성을 보다 명확히 평가하기 위해서는 혼합물의 크리프 거동과 파괴 한계점을 동시에 고려하는 것이 필수적임을 알 수 있었다. 또한 수퍼페이브 간접 인장 강도 시험으로부터 구한 잔여 소멸 에너지는 비교적 손쉬운 실험을 통해 아스팔트 혼합물의 균열 저항성의 상대적인 차이를 보여줄 수 있는 유용한 물성치임을 알 수 있었으며, 장기 크리프 시험에서 얻어지는 파괴 변형률은 아스팔트 혼합물의 크리프 거동과 파괴 한계점을 동시에 고려함으로써 균열 저항성을 평가할 수 있는 유용한 물성치 임을 알 수 있었다.

핵심용어 : 아스팔트 혼합물, 균열 저항성, 크리프, 파괴 한계점, 잔여 소멸 에너지

Abstract

The cracking resistance of asphalt mixtures is generally evaluated by measuring a single parameter (i.e., Tensile strength, Stiffness). However, the use of a single parameter has been questioned in the evaluation of asphalt mixture cracking performance. The focus of this study was to clearly identify the key properties and characteristics associated with the cracking resistance of asphalt mixtures. Results of fracture, creep, and strength tests at multiple loading rates performed on the modified and unmodified mixtures showed that the mixture cracking resistance was primarily affected by the rate of micro-damage accumulation. This was reflected in the m-value, without affecting the fracture energy limit.

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It was also observed that the short loading time (elastic) stiffness alone could not differentiate the mixture cracking resistance of the mixtures. It was concluded that the key to characterize the cracking resistance of asphalt mixture is in the evaluation of the combined effects of creep and failure limits. It was also found that a residual dissipated energy parameter measured from Superpave IDT strength test gave the quick and useful way to distinguish the difference of cracking resistance of asphalt mixtures. Failure strain in the longer-term creep test appeared to be a useful parameter for evaluating the combined effects of creep and failure limits of asphalt mixtures.

Keywords : asphalt mixture, cracking resistance, creep, failure limits, residual dissipated energy

1. Introduction

It is important to evaluate the cracking performance of asphalt mixtures in material selection, pavement design, and pavement management. Parameters such as resilient modulus, dynamic modulus, and tensile strength have been measured and simply compared for the evaluation of asphalt mixture cracking performance. However, these parameters have limitations in identifying behavioral characteristics of asphalt mixtures like visco-elasticity, and thus the simple comparison of these parameters is not considered adequate for proper characterization of asphalt mixture cracking performance.

The objective of this study was to measure the cracking parameters of asphalt mixtures from various laboratory tests. The test results were then evaluated for better understanding of parameters related to cracking performance of asphalt mixtures.

2. Research Approach

2.1 Materials

Two binders were involved in this study; one control and one polymer (SBS 3%) modified asphalt. The properties of those binders are presented in Table 1. Four types of asphalt mixtures were produced: coarse-graded (gradation below the restricted zone of Superpave mix design) mixtures produced with 6.1% and 7.2% asphalt contents. 6.1% and 7.2% asphalt contents were designed with the Superpave mix design procedures for traffic level 6 and level 2, respectively. Limestone, which is one of the major aggregates currently used in the state of Florida was used to produce asphalt mixtures. Even though number of samples is small (four samples), five test methods, which is described in the following chapter, were performed to give a full explanation about cracking properties of asphalt mixtures. The modified mixtures were produced with the same asphalt content as the unmodified asphalt mixtures. This approach assured that only the effect of the modifier would affect the test results. Mixtures were short-term oven aged (Florida Department of Transportation, 2001), and then compacted to 7% ± 0.5% air voids.

2.2 Test Methods

All tests were performed using the Superpave Indirect Tensile Test (IDT), which is described in AASHTO TP- 9, and associated hot-mix-asphalt (HMA) fracture mechanics model (Zhang et al., 2001). Crack growth as predicted by the model using the dissipated creep strain energy limit obtained from Superpave IDT was used to evaluate the cracking resistance of mixtures in this study. Standard Superpave IDT tests were performed on all mixtures to determine resilient modulus, creep compliance, m-value,

Table 1. Asphalt binder properties

Aging	Properties	Test Methods	Asphalt Binder	
			PG 67-22 (Control)	PG 76-22 (Modified)
Original	Viscosity(20rpm) @135℃, Pa-s	ASTM D4402	0.51	1.315
	Viscosity(20rpm) @165℃, Pa-s	ASTM D4402	0.155	0.368
	Dynamic Shear(10rad/sec) G*/sinδ andδ, kPa	AASHTO TP5	1.27 and 85.8 @67℃	1.386 and 71.6 @76℃
RTFO (AASHTO TP240)	Dynamic Shear(10rad/sec) G*/sinδ, kPa	AASHTO TP5	2.864@67℃	3.025@76℃
PAV (AASHTO PP1)	Dynamic Shear(10rad/sec) G*/sinδ, kPa	AASHTO TP5	2754@25℃	2879@25℃ 1432@31℃
	Creep Stiffness and m-value, 60sec	AASHTO TP1	155 and 0.362 @-12℃	131 and 0.355@-12℃ 263 and 0.298@-18℃

tensile strength, failure strain, fracture energy and dissipated creep strain energy to failure (Roque et al., 1997). Many addditional tests were also performed including repeated load fracture tests (Roque et al., 1999) to evaluate measured crack growth behavior and strength test at slower loading rates to evaluate differences in the post-fracture behavior of modified mixture. Triplicate specimens were tested for each test.

3. Results and Evaluation

3.1 Standard Superpave IDT

Results of Superpave IDT tests are presented in Table 2. As expected, the mixtures had higher resilient modulus at lower binder contents, but the polymer modification had relatively little effect on resilient modulus at either binder content. Modification had no effect on resilient modulus at 7.2% binder content and reduced the resilient modulus by about 20% at 6.1% binder content. This seems to indicate that the polymer has little effect on response at small strain or short loading times. Conversely, the polymer modifier dramatically reduced the creep compliance of mixtures at both low and high asphalt contents. Thus, the modification appears to have a much greater influence on the time-dependent response, and perhaps specifically the creep response, than on the elastic response of the mixture. The lower rate of creep response is more clearly reflected in the much lower m-value of the modified mixtures at both asphalt contents, as shown in Table 2. Prior research (Zhang et al., 2001), which resulted in the development of an HMA fracture mechanics model, clearly showed that there is a direct relationship between the rate of creep and the rate of micro-damage accumulation in asphalt mixtures.

As shown in Figure 1, fracture energy (FE) and dissipated creep strain energy (DCSE) can be determined from the strength test and the resilient modulus test. Fracture energy is the total energy applied to the specimen until the specimen fractures. Dissipated creep strain energy is the absorbed energy that damages the specimen, and dissipated creep strain energy to failure ($DCSE_f$) is the

Table 2. Superpave IDT results

Temperature : 10℃

Samples	Properties						
	Resilient Modulus (Gpa)	Creep Compliance at 1000sec. (1/Gpa)	Tensile Strength (Mpa)	Fracture Energy (kJ/m³)	Failure Strain (10^{-6})	m-value	DCSEf (kJ/m³)
6.1 (6.1% binder content, unmodified)	11.56	5.90	1.87	4.00	2468	0.61	3.85
7.2 (7.2% binder content, unmodified)	7.18	13.42	1.69	4.90	3756	0.62	4.70
6.1M (6.1% binder content, polymer modified)	9.26	3.04	1.95	3.80	2291	0.45	3.59
7.2M (7.2% binder content, polymer modified)	7.37	5.21	1.93	5.10	3726	0.47	4.85

absorbed energy to fracture. Including these properties, the results presented in Table 2 indicate the polymer had almost no effect on other properties such as tensile strength and failure strain. Therefore, it appears that the benefit of the polymer is primarily and almost exclusively reflected in the reduced m-value, which indicates a reduced rate of micro-damage accumulation. Fracture and longer-term creep test results presented later in the paper will further confirm this point.

Unfortunately, lower m-values are not uniquely related to the addition of polymers. For example, age-hardening a mixture will reduce its m-value, but it will also reduce its FE and DCSE, which would counteract and likely overwhelm any benefit gained by reducing the m-value in this way. The benefit of the polymer comes from the fact that the m-value is reduced without affecting FE or DCSEf. It is thought that the network, or secondary structure of the polymer phase, reduced the m-value, which is related to the viscous response of the mixture. However, the polymer does not have sufficient time to affect FE during the strength test (around 4 to 5 seconds). Therefore, further research was conducted to evaluate other tests and/or interpretation procedures that may be used to properly characterize the cracking resistance of asphalt mixtures.

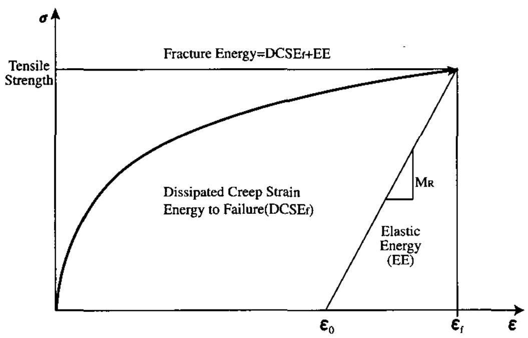

Figure 1. Determination of Fracture Energy and Dissipated Creep Strain Energy to failure

3.2 Fracture (Crack Growth) Test

Fracture tests were performed to evaluate the rate of micro-damage development and rate of macro-crack growth. Tests were performed and analyzed according to the procedures described by Roque et al. (1999). Figure 2 shows normalized resilient deformation (δ_H/δ_o) as a function of load repetitions. As explained by Roque et al.

(1999), an increase in normalized resilient deformation is directly related to the development of damage in the mixture. When the rate of change of δ_H/δ_o is linear (early in the test), the mixture is undergoing micro-damage development. The initiation of macro-damage (macro-crack) occurs when the rate of change of δ_H/δ_o no longer linear.

The results presented in Figure 2 clearly show that the polymer reduced the rate of micro-damage development and consequently increased the number of load repetitions required for crack initiation. This is consistent with the lower m-value determined for the modified mixtures. The Figure also shows that δ_H/δ_o prior to crack initiation was about the same for all mixtures, modified or unmodified. This is consistent with the fact that the failure limits (FE and $DCSE_f$) were relatively same for all mixtures. It should be noted that for this particular coarse-graded mixture, the mixture with lower binder content exhibited greater resistance to fatigue-type crack growth (modified and unmodified). Apparently, 6.1% is a sufficient amount of asphalt for this particular mixture, where additional binder provided no further benefit. However, this is obviously not a general trend, as many mixtures, particularly fine-graded mixtures will exhibit improved resistance to fatigue-type cracking with higher binder contents. The key is that one cannot generalize trends in cracking performance across all mixture types.

3.3 Slow Rate Strength Test

It was hypothesized that the effects of the SBS modification may become evident if the strength test were performed at a slower rate of loading. A rate of 50 mm/min is used in the standard Superpave IDT strength test, which allows little or no time for stress relaxation or creep to develop prior to failure. Therefore, even if there is a polymer network present in the mixture, the high stresses developed in this test will simply break through this network immediately when the strength of the mixture is exceeded. This is why there is little or no difference in failure limits between modified and unmodified mixtures tested at this loading rate. A slower rate of loading will result in lower stresses such that the SBS polymer network may be able to carry these stresses even after the mixture has failed.

Figure 3 illustrates schematically how the residual dissipated energy is obtained as the energy between crack initiation and the point when the maximum load is reached during testing. According to the standard IDT strength test method (AASHTO TP- 9), the tensile strength is not the peak stress during the strength test but the stress at the first peak of the curve in which vertical strain (V) minus horizontal strain (H). However, as shown in Figure 3, the

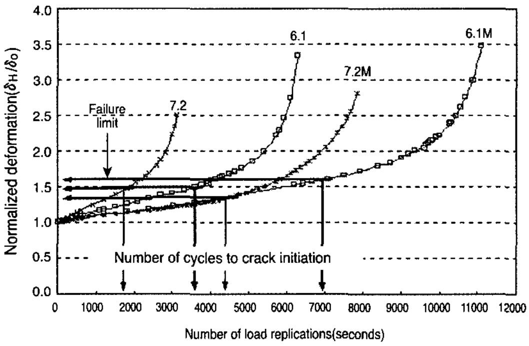

Figure 2. Fracture test results (Normalized resilient deformation vs. Number of load replications)

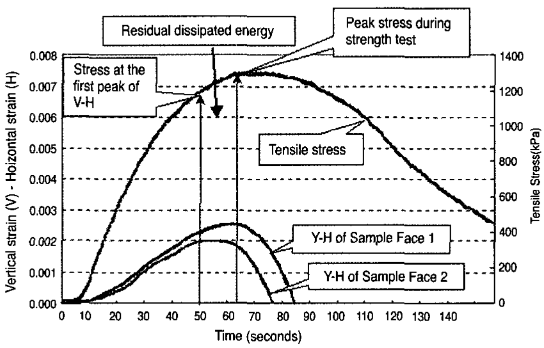

Figure 3. Determination of the residual dissipated energy

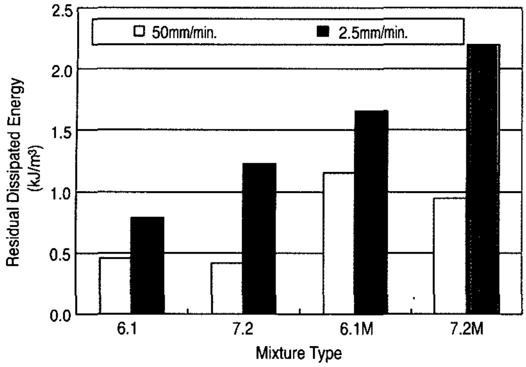

Figure 4. Comparison of residual dissipated energy

residual dissipated energy may be able to carry the stress even after the mixture reaches the first peak of the V-H curve. Residual dissipated energy was calculated by multiplying tensile stress with strain that was converted from time. From the tests, it was found that the residual dissipated energy of modified mixtures was significantly enhanced. Figure 4 shows that the residual dissipated energy was significantly higher for the modified mixture for both asphalt contents and for both 50mm/min. (standard loading rate of Superpave IDT strength test) and 25mm/min. (slower loading rate selected in this study) loading rates. It appears that this may be a useful parameter for properly characterizing the cracking resistance of asphalt mixtures.

3.4 HMA fracture model

Zhang et al. (2001) developed the HMA fracture model to predict the crack growth using the combined effects of m-value, fracture energy, and loading conditions. In the HMA fracture model, number of cycles to failure (Nf) is calculated as follows.

- Number of cycles to failure = $DCSE_f$ / (DCSE/cycle)
- DCSE/cycle = $1/20 \times \sigma_{AVG}^2 \times D_1 \times m \times 100^{(m-1)}$

where σ_{AVG} is the average stress near crack tip, D_1 and m are material parameters obtained from creep compliance tests.

Figure 5 shows that the number of cycles to initiate cracking (N_f) predicted from the HMA fracture model, is in good agreement with that measured from the fracture tests in the laboratory ($R^2 = 0.98$). DCSE/cycle and number of cycles to failure can be calculated as follows. From the comparison shown in Figure 5, the validity of the concepts associated with the HMA fracture model were confirmed. This result shows that the HMA fracture model is also suitable to uniquely identify the presence and benefits of polymer modifier.

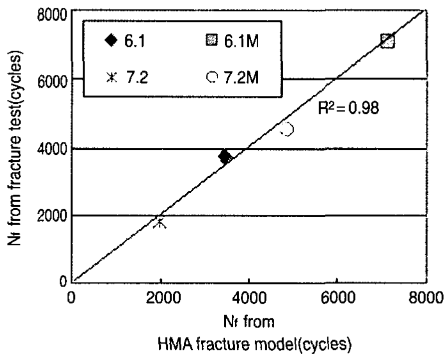

Figure 5. Comparison of measured and predicted N_f

4. Summary and Conclusions

A laboratory investigation was conducted to evaluate the cracking resistance of coarse-graded Superpave mixtures. The investigation also focused on identifying mixture properties and/or characteristics, as well as specific test methods that can be used to properly characterize the cracking performance of asphalt mixtures. The findings of this study is summarized as follows:

- It was found that the polymer used in this study appears to improve the cracking performance of asphalt mixtures by reducing the rate of creep accumulation, which has been shown to be directly related to the rate of micro damage development, without reducing the threshold fracture energy of the mixture. Therefore, one must determine both the creep properties and the fracture energy limit of mixtures to accurately characterize the cracking performance of asphalt mixtures.

- It is possible to characterize the cracking performance of asphalt mixtures by evaluating the post-peak stress-strain behavior of the mixture during a tensile strength test performed with the Superpave IDT. This finding is particularly useful for quality-control purposes, where relatively simple test is required to assure that the right type and level of modification was used during production.
- The HMA fracture model appears to accurately reflect the beneficial effects of polymer modification on the cracking performance of asphalt mixtures. The model uses creep compliance parameters determined from a 1000-second creep test and the threshold fracture energy determined from a tensile strength test, both of which are performed with the Superpave IDT, to predict crack initiation and growth in asphalt mixtures.

In conclusion, the key to characterize the cracking resistance of asphalt mixture is in the evaluation of the combined effects of creep and failure limits.

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