Estimation of Relative Performance of Overlaid Asphalt Mixtures against Reflection Cracking due to Mixed Fracture Mode

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ABSTRACT: Most of overlaid asphalt pavements on old and deteriorated Portland cement concrete (PCC) pavements are subject to reflection cracking in an early service life. To delay progression of the reflection cracking, many materials and techniques have been utilized to the overlay asphalt pavement by many researchers. In this study, an interlayer at the interface between old deteriorated PCC pavement surface and overlaid asphalt mixture layer was placed for retarding initiation and progression of reflection cracking, and polymer modifiers were used for strengthening asphalt mixture. An expedited reflection cracking test method was developed for mixed mode of fracture and applied to various asphalt mixture-interlayer-concrete test bodies. The results were compared one another with respect to the resistance characteristics of reflection cracking. Theoretical prediction model for fatigue life against reflection cracking was developed based on only effective stress intensity factor to compare relative performance of the material choices based on experimental test results. Most of the models showed very high coefficient of determination ($r^2 = 0.9$ or higher). Therefore, the fatigue life of each specimen can be estimated well with the prediction models developed in this study. These models can be used to select the best performing material combination by comparing many alternatives relatively for asphalt overlay on deteriorated concrete pavements at selected field sites.

Keywords: overlaid asphalt pavement, reflection cracking, interlayer, polymer modifier, asphalt overlay, fatigue life, mixed fracture mode

1 INTRODUCTION

As Portland cement concrete (PCC) pavement getting old and deteriorated, many types of damages, such as cracking, scaling, joint breakage, spalling, etc, appear on the surface. Asphalt concrete overlay is one of the most widely used choices for rehabilitation of the damaged PCC pavements. In most cases, however, reflection cracking begins to appear within a year or two as a premature damage in the overlaid asphalt pavement layer. Reflection cracking is a result of repeated vertical loading by traffic and horizontal movement (shrinkage) of base PCC slabs due to a drop of temperature.

A vertical wheel load creates bending stress at the bottom of asphalt layer when it is instantly applied to the asphalt layer on top of an existing crack in the underneath PCC slab. At almost the same time, the wheel load induces shear stress at perpendicular direction to the bottom face of asphalt layer when it is simultaneously moving across the crack. The former is responsible for mode I cracking (bending fracture mode), together with the shrinkage due to temperature down (Doh 2000, Doh et al. 2009). The later is responsible for mode II cracking (shear fracture mode). Therefore, the failure mechanism of the reflection crack should be considered as mixed fracture mode (Doh 2000).

Many studies have been performed in efforts of retarding progression of reflection cracking through the asphalt layer which is paved on top of existing cracks in old concrete pavement (Chang et al. 1998, Lim 1999, Kim et al. 1998, Kim et al. 1999). However, no complete crack-preventing technique has been developed yet, because of too much complication in the cause of reflection cracking. Only effective retardation is the best ways many researchers suggested. Some of the possible choices for effective retardation against reflection cracking include the application of an interlayer for retarding initiation of reflection cracking and the strengthening of the layer material for delaying progression of reflection cracking.

However, mathematical modeling of those techniques has been limited to mode I (bending) fracture and few models were applied to the mixed fracture mode (Kim et al. 1998, Doh et al 2009). In this study, progression of reflection cracking was considered as a result of mixed fracture mode. Therefore, the objective of this study is to estimate fatigue life of overlaid asphalt pavements from effective stress intensity factor considered only growth of reflection cracking. Many reinforcing materials were used for the overlay and these performances against reflection crack were relatively compared based on prediction results.

2 MATERIALS AND METHODS

Asphalt binder which has a penetration grade of 85-100 was used as a binder for mixture preparation. The asphalt was modified using a low-density polyethylene (LDPE) and a styrene-butadiene-styrene (SBS). Appropriate contents of LDPE and SBS were determined as 5% by weight of asphalt.

In addition, three reinforcing materials were used in this study and these include a polyethylene fiber (PF), a polyethylene film (vinyl: PV) and a glass fiber grid (GG). Table 1 describes the mixture name and materials used in this study.

Table 1: Description of various asphalt mixture

Mixture	Description
AP	Normal asphalt mixture
APG	Glass-fiber grid (GG) reinforced A mixture
APV	Polyethylene vinyl (PV) reinforced A mixture
APFG	Polyethylene fiber (PF) and GG reinforced A mixture
L	Low-density polyethylene modified asphalt mixture
LG	GG reinforced L mixture
LV	PV reinforced L mixture
LFG	PF and GG reinforced L mixture
S	Styrene-butadiene-styrene modified asphalt mixture
SF	PF-added S mixture
SG	GG reinforced S mixture
SV	PV reinforced S mixture
SFG	PF and GG reinforced S mixture
SFV	PF-added and PV-reinforced S mixture

Thickness of PV and length of PF are 0.2mm and 6mm, respectively. LDPE and SBS were blended with asphalt using a high shear mixer before mixing with aggregate. A 0.35% of PF by weight of total mixture was added into the mixture just before mixing. Single layer of PV and GG were place at the bottom of slab specimen mould before dumping loose hot mixture for roller compaction.

A gneiss aggregate, with maximum size 19mm, was used for a dense-graded asphalt mixture. Table 2 shows gradation of the aggregate. The gradation meets the specification limit given by the Ministry of Land, Transport and Maritime Affairs of Korea. Table 3 shows physical properties of aggregate.

Table 2: Gradation of gneiss aggregate

Sieve Size	25mm	19mm	13mm	#4	#8	#30	#50	#100	#200
Passing (%)	100	99.1	78.3	52.3	40.1	22.6	17.0	11.6	7.73

Table 3: Physical properties of gneiss aggregate

Classification	Specific gravity	Abrasion (%)	Absorption (%)
Spec. limit	> 2.5	< 35	< 3.0
Gneiss	2.72	18.1	0.7

Marshall mix design was carried out for each mixture combination to determine optimum asphalt content (OAC) (Asphalt Institute 1997). The slab specimen was prepared using the OAC for each mixture. Three beam specimens were obtained by saw-cutting a slab specimen which was made using a pneumatic pressure roller compactor. The size of the beam specimen was 340mm (length) x 80mm (width) x 53mm (depth). Figure 1 showed schematic illustration of beam test body for reflection cracking test.

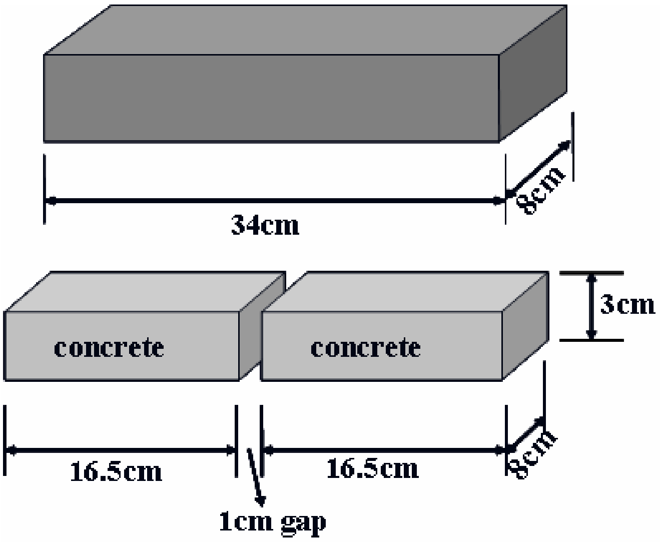

Figure 1: Schematic illustration of Preparation of test body

Methods

Marshall Stability, air void, flow, and indirect tensile strength (ITS) were measured for each mixture by appropriate standard methods. To simulate an overlaid asphalt pavement on top of a crack (or joint) in a PCC pavement, the beam was bonded using tack coating with two concrete blocks. The two blocks were separated 10mm to create a pseudo crack (gap) underneath the asphalt pavement layer. And 10mm-thick-rubber pad was laid out below test body to simulate elastic support.

Moving wheel loads were applied on top of the beam through a steel wheel (200mm diameter) at 0.5Hz using a wheel loading system. The specimen was covered with a thin plastic pad at the interface between loading wheel and specimen to simulate tire contact and to prevent asphalt from sticking to the wheel. A load of 981N (100kg) was applied to the specimen through the moving wheel. Test was carried out at 20°C in a temperature-controlled chamber (Lim 1999).

Horizontal expansion of each beam was measured using a demic gage from the points which were installed in one side of beam before testing. Vertical crack growth as load cycle accumulating was visually monitored every 500 cycles from the side at which white water color was pained (Figure 2). Test was conducted until the vertical crack length reached at 50mm (Kim et al. 1999).

3 PREDICTION MODEL FOR MIXED FRACTURE MODE

When the repeated load is applied to a structural member, which has a crack inside, the crack grows as the number of load cycle increase. In fatigue crack growing system, the crack growth rate due to load cycle is given by Paris law (Paris and Erdogan 1963).

$$\frac{da}{dN} = C(\Delta K)^m \qquad (1)$$

in which, C and m are material properties.

But Chang et at (1988) estimated fatigue life by thermal stress. Based on those studies, this study only estimated fatigue life from stress intensity factor only and considered growth of reflection cracking as.

$$N = C(\Delta K)^m \qquad (2)$$

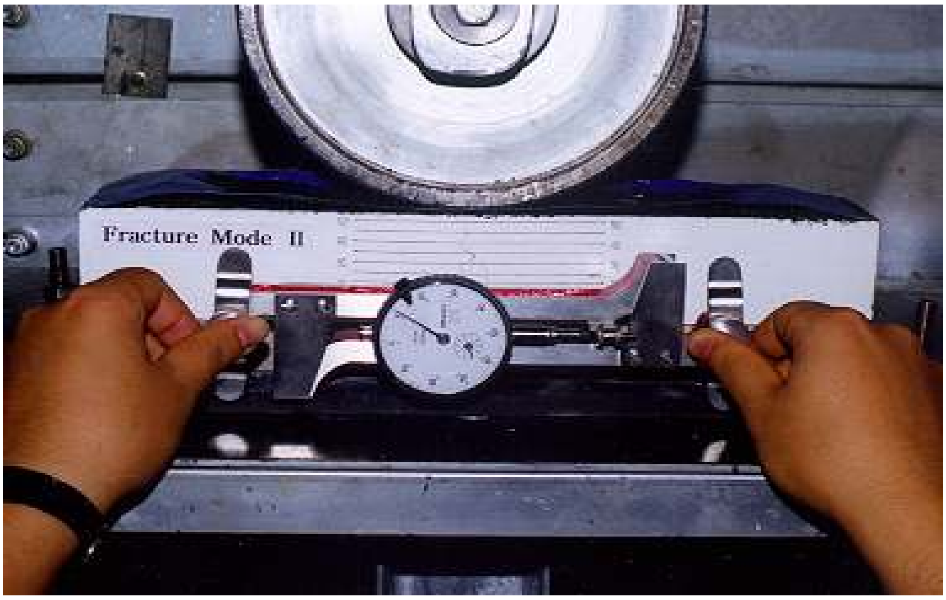

Figure 2: Horizontal expansion measurement in mode II Test system

ΔK is defined as the difference between maximum stress intensity factor (K_{max}) and minimum stress intensity factor (K_{min}).

$$K_{\max} = F\sigma_{\max}\sqrt{\pi a}, \quad K_{\min} = F\sigma_{\min}\sqrt{\pi a}, \tag{3}$$

$$\Delta K = K_{\max} - K_{\min} = F\Delta\sigma\sqrt{\pi a} \tag{4}$$

In equation 4, ΔK is used from bending fracture mode (mode I). To predict fatigue life against reflection crack under mixed fracture mode, the effective stress intensity factor must be calculated for mixed fracture mode (bending and shear fracture).

$$\Delta K_{eff} = (\Delta K_{\mathrm{I}}^4 + 8\Delta K_{\mathrm{II}}^4)^{0.25} \tag{5}$$

In calculation of ΔK_{eff}, K_{I} for mode I was given by equation 3, and K_{II} is calculated by

$$K_{\mathrm{II}} = f\tau\sqrt{\pi a} \tag{6}$$

In equation 6, the shear stress is given $\tau = P / (2A)$. The value of f, the geometric function of specimen is assumed to be 1. P is the applied wheel load and A is the vertical cross section area of the overlaid asphalt concrete.

4 FATIGUE LIFE PREDICTION UNDER THE MIXED FRACTURE MODE

Substituting equations 4 and 6 into equation 5, the effective stress intensive factor was calculated. The effective stress intensive factor, ΔK_{eff}, for each mixture and material properties C and m for fatigue life prediction based on growth of reflection cracking were determined from regression. Table 4 shows these values by mixture and Table 5 shows prediction model and predicted fatigue life against reflection cracking for each material.

Table 4: Effective stress intensity factor and material constant by growth of reflection cracking for various asphalt mixtures (mixed fracture mode).

Mixture	Effective stress intensity factor (ΔK_{eff}, kg. $cm^{3/2}$)	C	m	Note
AP	8.106	0.0021	6.9039	
APV	8.106	2.8773	3.6983	
APG	8.106	48.460	2.4648	
APFG	8.106	30.710	2.8642	
L	8.097	3.8479	3.9739	
LG	8.097	359.20	2.1175	
LV	8.097	47.303	3.0304	
LFG	8.097	36.376	3.4429	
S	8.097	12.212	3.1269	
SF	8.097	59.665	2.8248	
SV	8.097	35.763	3.0157	
SG	8.097	357.05	2.0584	
SFG	8.097	512.14	1.9954	

Table 5: Regression analysis of fatigue life of reflection crack by effective stress intensity factor for various asphalt mixtures (mixed fracture mode)

Mixture	Regression formula	r^2	Estimated life (cycle)	Note
AP	$N=0.0021 \cdot K^{6.9039}$	0.9892	3,949	
APV	$N=2.8773 \cdot K^{3.6983}$	0.9946	6,607	
APG	$N=48.460 \cdot K^{2.4648}$	0.9640	8,422	
APFG	$N=30.710 \cdot K^{2.8642}$	0.9963	12,311	
L	$N=3.8479 \cdot K^{3.9739}$	0.9890	15,661	
LG	$N=359.20 \cdot K^{2.1175}$	0.9732	30,110	
LV	$N=47.303 \cdot K^{3.0304}$	0.9934	26,759	
LFG	$N=36.376 \cdot K^{3.4429}$	0.9949	48,762	
S	$N=12.212 \cdot K^{3.1269}$	0.9891	8,453	
SF	$N=59.665 \cdot K^{2.8248}$	0.9833	21,956	
SV	$N=35.763 \cdot K^{3.0157}$	0.9921	19,619	
SG	$N=357.05 \cdot K^{2.0584}$	0.9706	26,450	
SFG	$N=512.14 \cdot K^{1.9954}$	0.9923	33,255	
SFV	$N=0.1214 \cdot K^{5.9186}$	0.9837	28,855	

According to the results, the most significant retardation effect was achieved from LFG combination. The estimated fatigue life of LFG mixture test body was 12.3 times longer than the normal asphalt (AP) mixture test body. This means that if the normal asphalt is modified with LDPE, mixture is reinforced with PE fiber and the glass-fiber grid is used as an interlayer, the overlaid asphalt layer will last 12.3 times longer than the normal (conventional) asphalt mixture overlay against reflection cracking.

Other strengthening combinations also showed 1.7 (AV) to 8.4 (SFG) times longer fatigue lives than normal asphalt mixture (AP), respectively. It was found that simply polymer modification with SBS (S) or LDPE (L) also showed relatively high effectiveness in retarding reflection cracking, showing 2 to 4 time longer fatigue lives than normal asphalt mixture, respectively. Between interlayer reinforcing materials, in general, the glass-fiber grid (G) was more effective than the PE film (V).

In general, very good correlations between effective stress intensity factor and fatigue life were found from regression analysis for all mixtures. Coefficient of determination (R^2) for the models was 0.99 on the average, ranging from 0.9732 to 0.9963. This high correlation is indication of effectiveness of the method developed in this study for prediction of the reinforced overlay of asphalt mixtures.

Figure 4 shows a relation of predicted life and measured life. The coefficient of determination was very high, as shown in Figure 3. Therefore, it was evidenced that the predicted fatigue lives from the model, which was developed in this study, were matched with mixed fracture mode test results well.

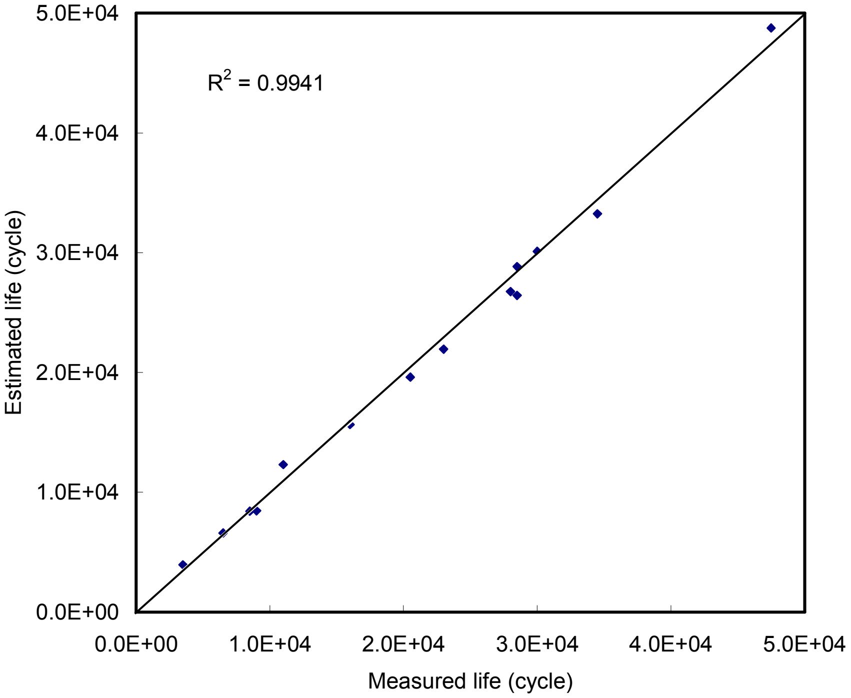

Figure 2: Correlation between estimated life by effective stress intensity factor and measured fatigue life of all asphalt mixtures (mixed fracture mode)

5 CONCLUSIONS

This study showed that the relative performance of overlay asphalt concrete systems with various materials and interlayer reinforcement on top of the old PCC could be predicted in terms of fatigue life under mixed fracture mode (bending and shear fracture mode). The experimental technique also developed for applying wheel load to induce bending stress and shear stress in asphalt layer (mixed fracture mode). Prediction models were developed by using stress intensity factor only to consider growth of reflection cracking. The predicted fatigue lives showed high correlations with experimentally tested fatigue lives, showing coefficient of determination over 0.9. Therefore, the study result can be used for estimation of relative performance of overlay asphalt mixture materials and to select the best combination from many choices before field application.

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REFERENCES

Asphalt Institute. 1997. Mix design methods for asphalt concrete and other hot-mix types. *MS No. 2 (MS-2),* pp 22～25.

Chang, D. T. T,., Lai, R. Q., Chang, J. Y. And Xang, Y. H. 1998. Effects of geo-grid in enhancing the resistance of asphalt concrete to reflection cracks, Flexible Pavement Rehabilitation and Maintenance, ASTM STP 1348, pp 39-45

Doh, Y. S. 2000. Estimation of fatigue life against reflection cracking of reinforced overlay asphalt concretes, *Ph.D. dissertation,* Graduate School, Kangwon National University, Chunchon, Korea.

Doh, Y. S., Baek, S. H. and Kim, K. W., 2009. Estimation of relative performance of reinforced overlaid asphalt concretes against reflection cracking due to bending mode fracture. Construction and Building Materials, 23(5), May, 1803-1807.

Lim, S. B. 1999. Development and evaluation of accelerated reflection cracking test system in shear mode. *M.S. thesis,* Graduate School, Kangwon National University, Chun Cheon, Korea.

Kim, K. W., Doh, Y. S., Rhee, S. K., Lim, S. B. and Park, T. S. 1999. Evaluation of resistance against mode II reflection cracking in reinforced asphalt pavements, *Proceedings, 7th Conference on Asphalt Pavements for Southern Africa,* Victoria Falls, Zimbabwe.

Kim, K. W., Rhee, S. K., Doh, Y. S., Lim, S. B. and Li, X. F. 1998. Retarding effect of reflection cracking in overlaid asphalt concrete using modified asphalts and reinforcements, *Proceedings, Advanced Technologies in Asphalt Pavements,* Center for Advanced Mineral Aggregate Composites, Kangwon National University, Chun Cheon, Korea.

Paris, P. C. and Erdogan, F. A. 1963. Critical analysis of crack propagation laws. *Transactions of the ASME, Journal of Basic Engineering, Series D, No.3.*