Selection of Milling Depth for Asphalt Pavement Rehabilitation

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Milling of an asphalt concrete (AC) pavement surface refers to the mechanical removal of a part of the pavement surface. The Kansas Department of Transportation (KDOT) and the Kansas Turnpike Authority (KTA) routinely mill some AC pavements before inlaying. KTA selects the milling depth based on engineering judgement. On some major projects where deep milling is involved, KDOT currently selects a mill-and-inlay depth so that the ratio of this depth to the remaining milled pavement thickness would be higher than 1.0. This somewhat insures that much of the full pavement thickness would consist of newer materials. These practices of KDOT and KTA were analyzed in a recent study and the findings are reported in this paper. Nine mill-and-inlaid pavement sections, selected on six different routes in Kansas, were studied. Falling Weight Deflectometer (FWD) tests were done on those sections at 15 or 30-m intervals before milling, after milling, and after inlaying. Laboratory fatigue tests were also done on the AC beams sawn from four test sections. The results show that in order to achieve higher fatigue life, the mill-and-inlay thickness should be at least 1.25 times of the thickness of the remaining milled pavement layer. Based on the mechanistic-empirical analysis procedure, it was found that the mill-and-inlaid pavement fatigue life also does not linearly increase with the inlay thickness. Key words: asphalt pavement, milling-and-inlay, fatigue life, rutting, serviceability, FWD.

INTRODUCTION

Milling of an asphalt concrete (AC) pavement surface refers to the mechanical removal of a part of the pavement surface. The Kansas Department of Transportation (KDOT) and the Kansas Turnpike Authority (KTA) routinely mill some AC pavements before inlaying. KTA selects the milling depth based on engineering judgement. On some major projects where deep milling is involved, KDOT currently selects a mill-and-inlay depth so that the ratio of this depth to the remaining milled pavement thickness would be higher than 1.0. This somewhat insures that much of the full pavement thickness would consist of newer materials. The assumption is that the existing AC and base layers are in good structural condition to provide extended service lives. However, little is known about the damage of these materials due to this rehabilitation action (mill and inlay) as these layers age and undergo repetitive loading while the top of the surface is being replaced. In most cases, the milling depth is selected based on the rule-of-thumb or experience of the agency for a specific surface distress, such as rutting, rather than on any engineering analysis. In fact, no design procedure is available for this rehabilitation since the mill and inlay pavements are not exclusively covered in the 1993 AASHTO Pavement Design Guide (*1*). Current practices of KDOT and KTA for mill-and-inlay strategy were analyzed in a recent study by Kansas State University and will be reported in this paper.

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TEST SECTIONS AND DATA COLLECTION

Test Section

Nine 300-m long mill-and-inlaid pavement sections, on six different routes in Kansas, were studied in this project. Table 1 shows the location and general features of these projects. The projects on the I-35 and I-335 are under the jurisdiction of the Kansas Turnpike Authority (KTA), and the rest belong to the KDOT network. Falling Weight Deflectometer (FWD) tests were done on those sections at 50 or 100-feet intervals before milling, after milling, and after inlaying.

Field Sampling and Fatigue Testing

Laboratory fatigue tests were done on the AC beams sawn from four test sections on I-35, US-59, and K-16. Tests were done in a third-point flexural loading fashion using a sinusoidal load of 10 Hz frequency. Constant stress mode was chosen in the flexural tests, and test temperature was controlled at 20^{o}C. The initial tensile strain was measured at the bottom fiber of the beams at the 200th repetition of the applied load, and the beams were then loaded to failure. The applied load was varied so that a range of tensile strains and corresponding varying cycles to failure would be obtained. Detailed discussions on the fatigue tests may be found elsewhere *(2)*.

Existing Pavement Condition

Most of the sites were visited before rehabilitation and quantitative distress data were obtained from the KDOT's pavement management system database. Common distresses were longitudinal or fatigue cracking, transverse cracking, and rutting. In general, rutting and transverse cracking were found on all sites. On average, each site had about 6.25 to 12.5 mm rutting. Fatigue cracking was observed on the sites on I-35, I-335, US-59, and K-92. Severe fatigue cracking was found on the US-59 and K-92 sites. K-16 and K-177 had a few longitudinal cracks. The former also had severe transverse cracking. These distresses contributed to the roughness shown in the last column of Table 1. Only K-177 had lower severity of all distresses mentioned, and that is well reflected in its lower International Roughness Index (IRI) value when compared with other sites.

FWD Data Analysis and Existing Pavement Damage

As mentioned earlier, three different sets of FWD data were collected on each test section— before milling, after milling, and after inlaying. A linear elastic backcalculation program EVERCALC, developed by the Washington Department of Transportation, was used to analyze the deflection data. The pavements were modeled as a four-layer structure (before milling and after milling) and a five-layer structure (after inlaying). A "stiff" layer was used whenever necessary for convergence. The backcalculated AC layer moduli were adjusted to a pavement temperature of 20° C. In general, the backcalculation results were judged to be good (root-mean-square error less than 2%). Details can be found elsewhere *(2)*.

The existing pavement damage was assessed by comparing two critical pavement responses corresponding to an 80 kN single-axle, dual tire load with a tire pressure of 690 kPa: 1) the horizontal tensile strain at the bottom of the AC layer, and 2) the vertical compressive strain on the top of the subgrade before milling, after milling, and after inlaying. The layered elastic pavement analysis program, ELSYM5, was used in this analysis. It was found that both tensile strains and vertical strains increased significantly after milling. However, after inlaying, both strain values decreased at least to the premilling level, thereby indicating that the critical pavement responses remain unaffected due to the mill-and-inlay action *(2)*.

DETERMINATION OF THE MILL-AND-INLAY THICKNESS

Equivalent Thickness Method (ETM)

The first methodology for determining mill-and-inlay thickness used in this study is ETM, which follows the "AASHTO Overlay Method Using NDT" as described in the Volume II, Appendix NN of the 1986 AASHTO Guide for Design of Pavement Structures *(3)*. This overlay design methodology uses nondestructive testing to evaluate the in-situ deflection basin characteristics of a pavement. A backcalculation technique is used to estimate the elastic moduli (E_i) of the pavement layers. The effective structural number (SN_{eff}) of the existing pavement from the following equation:

$$SN_{eff} = 0.0045\ \Sigma h_i\ (E_i)^{1/3} \qquad (1)$$

Where:

h_i is the thickness of the i-th layer above the subgrade; and

E_i is the elastic modulus of the i-th layer above the subgrade.

The overlay/inlay requirements can then be estimated by using the effective thickness concept. In this study, the structural numbers (SNs) of the pavements since last rehabilitation, available in KDOT and KTA data bases, have been taken as design SNs. The backcalculated moduli of the milled pavement and other layers (if any) were used to calculate the SN_{eff}. The deficiency in structural number because of milling was calculated by subtracting SN_{eff} from the design/historical SN. Finally, the inlay thickness was calculated by dividing this difference with 0.42, which is assumed to be the structural layer coefficient of the new inlay AC material.

TABLE 1 Test Section Features

Route	County	Last Rehab. Year	Present Mill and Inlay Thickness (mm)	Existing AC Thick. (mm)	Base Thick. (mm)	Current Annual ESAL's (on design lane)	Avg. Wheelpath IRI (before milling) (m/km)
I - 35 S	Sumner	1991	64	190	457	388,816	1.72
I - 35 N	Chase	1988	50	178	457	268,841	1.51
I-335 N	Osage	1992	50	178	457	146,000	1.67
US-59-1	Anderson	1988	25	127	152	12,775	1.67
US-59-2	Anderson	1988	50	100	152	22,630	1.81
K-16	Pottowatomie	1985	25	152	/	4,380	1.85
K-92-1	Jefferson	1990	50	89	203	6,205	1.17
K-92-2	Jefferson	1990	25	114	203	6,205	1.17
K-177	Riley	1992	150	114	229	39,055	1.15

Table 2 tabulates the required inlay thicknesses for all pavement test sections in this study. The results obtained were mixed. Apparently, there were no thickness requirements for I-35 South and I-335 for the given traffic whereas I-35 North sections required about 18 mm overlay. The results on US-59, K-16, and K-92-1 were very misleading presumably due to the very high existing AC moduli obtained in the backcalculation process. On K-177, 100 mm of inlay was required. Thus, this procedure does not appear to be applicable to the mill-and-inlaid pavements.

Regression Equation Method

In order to study the effect of the mill-and-inlay thickness on pavement structural life, multiple regression analysis was done where the tensile strain at the bottom of the AC layer (before milling or after inlaying) was taken as a dependant variable and several independent variables were investigated. The independent variables were ratio of the inlay thickness to the remaining pavement thickness, total pavement thickness above subgrade, ratio of the inlay modulus to the existing AC layer modulus, subgrade modulus, and effective pavement modulus above subgrade (E_p). E_p was backcalculated using the algorithms described in the 1993 AASHTO Guide for Design of Pavement Structures *(4)*. A linear regression equation was obtained using data from all sections except K-177. Data from K-177 was not included in the analysis since it had a much higher milling depth compared to other sections.

Excellent R^2 value was obtained by including all five variables. However, the students' t-values of the moduli ratio and total thickness above subgrade were too low, implying that those two variables were not highly correlated with the independent variable. After dropping those two variables, the following equation was obtained:

$$\varepsilon_r = 21.55 * r_0 - 0.03813\, E_p + 4.203\, M_r \quad (R^2 = 0.91) \qquad (2)$$

where

ε_r = horizontal tensile strain at bottom of the AC layer after inlaying/ before milling (microstrains);
r_0 = thickness ratio of the inlay layer to the remaining milled AC layer;
E_p = effective pavement modulus above subgrade, ksi (backcalculated using the AASHTO algorithm); and
M_r = subgrade modulus, ksi (backcalculated using the AASHTO algorithm).

The limitations of Equation (2) include a smaller database and possible hidden auto- correlation of r_0, E_p, and M_r with the horizontal tensile strain taken as a dependent variable. Equation (2) was used to compute the horizontal tensile strains at the bottom of the AC layer for the I-35 South and US-59-1 sections for different mill-and-inlay thickness ratios. Figure 1 shows the relationships obtained. It appears that the fatigue lives of these pavements could be doubled by choosing thickness ratios of 1.25 for US-59 and 1.50 for I-35, respectively. Thus, it is apparent that in order to achieve a very high fatigue life, the mill-and-inlay thickness should be at least 1.25 times the thickness of the remaining AC layer after milling. However, in some cases, the increase in thickness ratio may not significantly decrease the tensile strain at the bottom of the AC layer (or in other words, may not increase the fatigue life significantly) since it also depends upon the existing pavement layer moduli.

Mechanistic-Empirical (M-E) Method

The M-E design method for asphalt pavements commonly include estimation of pavement damages due to traffic and environmental loading by using distress prediction models or transfer functions that relate a critical structural response to specific distress damage (e.g., fatigue cracking or rutting). In this study, both fatigue lives and lives corresponding to limiting rutting of the test sections were estimated.

The functional lives were predicted from the AASHTO serviceability equations were compared to the fatigue lives predicted from the laboratory fatigue equations for the sites on I-35, US-59, and K-16. The results show that the fatigue lives on most sections are usually equal to or more than the functional lives. This indicates that the pavement sections in this study will most likely be rehabilitated due to excessive roughness. However, in some cases, the fatigue lives will be exhausted before the functional lives. Thus, in order to safeguard against premature fatigue cracking, the mill-and-inlay strategy selection must also consider the fatigue life.

The rutting potential of the mill-and-inlaid pavements was studied. Based on the results from the rut depth equation developed by LTPP *(5)*, no significant change of rutting potential of the mill- and-inlaid AC pavements was evident no matter what mill-and-inlay thick-

TABLE 2 Computed Inlay Thicknesses by the Equivalent Thickness Method

No.	Section	Design SN	Existing AC		BASE		SN_{eff}	Inlay Thickness (mm)
			E_{AC} (MPa)	Thickness (mm)	E_{AC} (MPa)	Thickness (mm)		
1	I-35 S	4.2	1,090	191	200	457	4.31	-8
2	I-35 N	5.1	2,310	178	234	457	4.81	18
3	I-335	5.0	1,545	178	138	457	5.20	-13
4	US-59-1	3.3	2,351	127	483	152	4.11	-46
5	US-59-2	3.3	3,354	102	221	152	3.55	-48
6	K-16-2	2.3	5,791	140	0	0	4.44	-109
7	K-92-1	3.8	2,952	89	696	203	3.94	-130
8	K-92-2	3.8	4,366	114	634	203	3.36	-8
9	K-177	4.4	1,010	114	490	229	2.74	100

ness is selected. Since this thickness is usually smaller compared to the total AC thickness, and the overall pavement structure is not being changed, the rutting potential of this type of pavements can be considered insignificant. However, this analysis assumes that the mixture and construction process would not contribute to the rutting on the inlays *(2)*.

Figure 2 shows the relationships between the mill-and-inlay thickness and the allowable ESALs for I-35 South and US-59-1 using the laboratory fatigue models developed in this study. The figure shows that on I-35 South, with an increase in mill-and-inlay thickness, the allowable ESALs first increased to a maximum value, then decreased. The allowable ESALs to fatigue failure did not vary much for 25 to 75 mm of milling thickness. This means that the milling thickness has a critical range of values on I-35 South, outside which the fatigue life will decrease. The above analysis implies that since rutting potential does change on mill-and-inlaid pavements before and after inlaying, the pavement fatigue life should be selected in a such a way that it may safeguard the pavement functional life. Thus the critical mill depth range obtained from the fatigue life analysis should be used to estimate the optimum mill-and-inlay depth.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support for this study provided by the Kansas Turnpike Authority and Kansas Department of Transportation under the Kansas Transportation and New Developments (K-TRAN) program.

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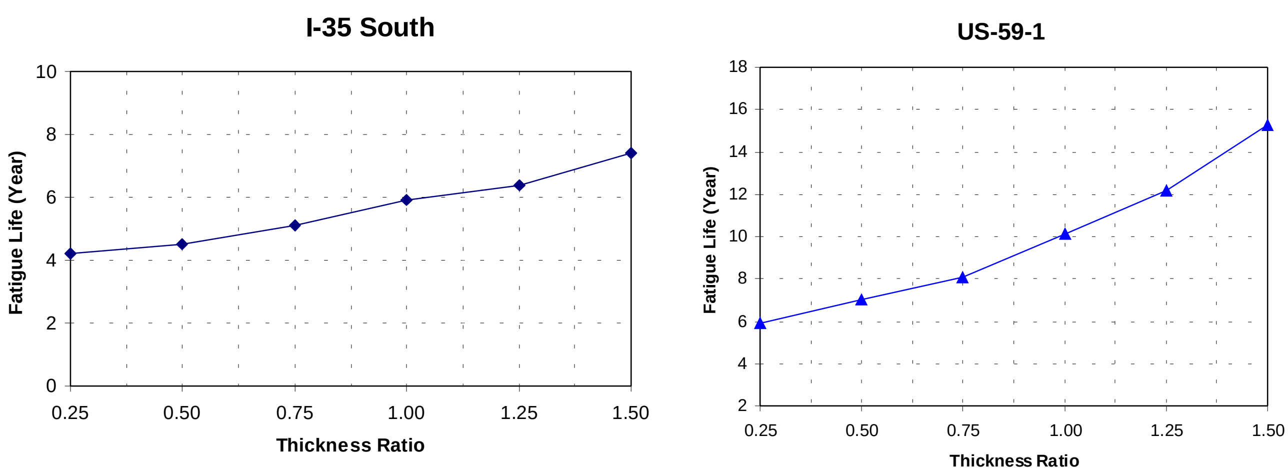

Figure 1 Thickness ratio vs. fatigue lives on I-35 South and US-59-1

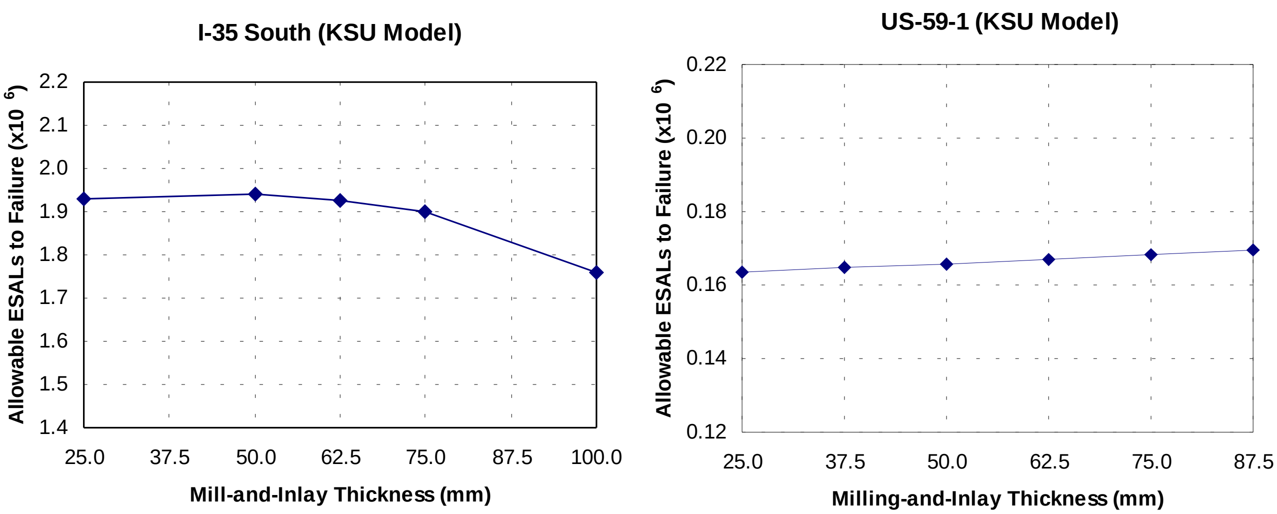

Figure 2 Mill-and-inlay thickness vs. the allowable ESALs for I-35 South and US-59-1