Distress as Function of Age in Continuously Reinforced Concrete Pavements: Models Developed for Texas Pavement Management Information System

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In 1989 FHWA required all states to implement a formal pavement management system by February 1993. To comply with this mandate the Texas Department of Transportation (TxDOT) is developing the Pavement Management Information System (PMIS). PMIS will assist Texas planners in providing cost-effective maintenance of the state pavement inventory. To correctly priority rank pavement rehabilitation and predict future needs, PMIS must accurately predict the development of pavement distress with time under Texas conditions. By using a data base containing 20 years of historical condition survey data taken on continuously reinforced concrete pavements across the state, models were developed for the following distress types: punchouts (minor and severe), patches (asphalt and portland cement concrete), crack spacing, loss of ride quality, and spalling. The significance of additional extrinsic factors relating to traffic, pavement structure, and environment was also investigated. These factors may be incorporated into the distress models at a later date, when the data base currently supporting the PMIS is expanded.

In 1989 FHWA mandated that all states have a formal pavement management system in place by February 1993. To comply with this mandate the Texas Department of Transportation (TxDOT) will implement the Pavement Management Information System (PMIS). PMIS will allow TxDOT administrators to monitor statewide trends in pavement condition. It will also assist in the monitoring, selecting, and priority ranking of paving projects and in estimating future needs (*1*).

A rehabilitation strategy for a given pavement section may consist of doing nothing, applying preventive maintenance, or performing light, medium, or heavy rehabilitation. A decision to do nothing in the current year may result in the need for more costly rehabilitation later. For PMIS to perform a multiple-year optimization it must be able to predict the development of pavement distress as a function of age and other possibly significant factors such as traffic, structural design, and the environment.

A literature survey was made to determine the important distress manifestations for continuously reinforced concrete pavements (CRCPs) In Texas. At the same time existing pavement performance data bases were examined to determine what type of distress data had been collected. The principal data bases considered were the Pavement Evaluation System data base maintained by TxDOT, the Rigid Pavement Data Base developed by the Center for Transportation Research (CTR) at the University of Texas, and the COPES data base (FHWA) (*2*).

The CTR Rigid Pavement Data Base was selected for this phase of the analysis because it was the only source of CRCP performance data available that directly addressed Texas conditions and provided sufficient historical depth for the analysis. The CTR data base (*3*) contains condition survey data taken on a regular basis since 1974 as well as associated traffic, environmental, and structural data for the pavement sections.

The seven distress indicators selected for CRCP are minor punchout, severe punchout, asphalt patching, Portland Cement Concrete (PCC) patching, transverse crack spacing, loss of ride score, and crack spalling.

INFERENCE SPACE FOR MODELS

The CTR rigid pavement data base was used for the analysis. The first step was to examine the inference space in the data base used for developing the models. This inference space, of course, determines the applicability of any model derived from the data.

Pavement Age

Because the desired models all predict distress as a function of age, several frequency distributions relating to pavement age were examined. Figure 1 shows the basic age distribution of the condition survey data. Every observation in the data base from 1974 to 1987 (the last year a survey was performed) is considered separately. Thus, a section built in 1964 and surveyed in 1974 and 1984 would produce two observations and be counted in the 10-year and 20-year bars on the graph. As can be seen from Figure 1 many observations are available over a wide range of pavement ages.

Using the date of first overlay field in the data base, a rough indication of CRCP performance can be plotted. Figure 2 shows the distribution of pavement life as indicated by years to first overlay. The mean time to first overlay was 16.7 years; most of the pavements were overlaid after 20 years.

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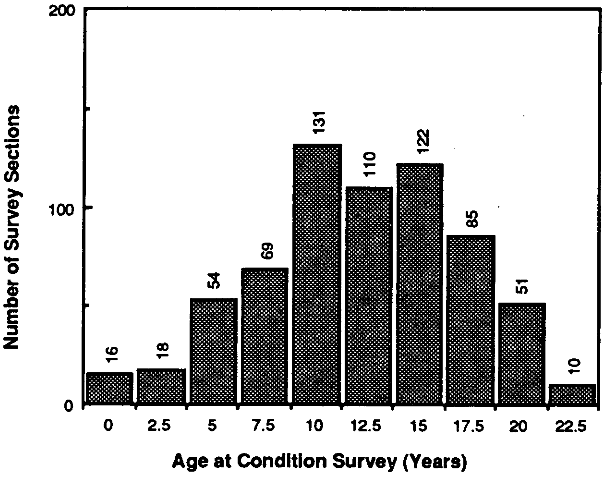

FIGURE 1 Age distribution of model inference space.

Temperature

Because environmental factors are expected to have an impact on the distress curves, a distribution of average annual minimum temperature (AAMT) was plotted. The AAMT (*4*) is the yearly minimum temperature recorded at the weather station nearest the pavement segment, averaged over the years 1951 to 1980. This is a potentially important variable, because the interaction of temperature with rainfall (freeze-thaw cycling) and the interaction of temperature with coarse aggregate type (thermal expansion in the aggregate) may play a role in cracking and punchouts. As shown by Figure 3, low temperatures in Texas vary greatly, from a minimum of 7.5°F to about 60°F (−9 to 15°C). A median low temperature of 30°F (−1°C) was selected as a separator level to differentiate "low" temperature conditions from "high" temperature conditions.

Rainfall

In a similar manner the distribution of rainfall was examined (Figure 4). A separator level of 30 in./year (75 cm) was chosen (*5*) to distinguish between high and low rainfall conditions in Texas; the median rainfall amount of 33 in./year (83 cm) found in this analysis agreed with that finding. Rainfall amount may also interact with soil type (swelling or nonswelling), which is already available in the data base.

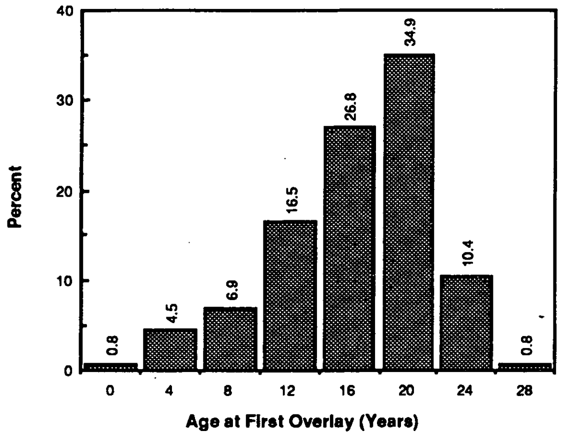

FIGURE 2 Pavement age at first overlay.

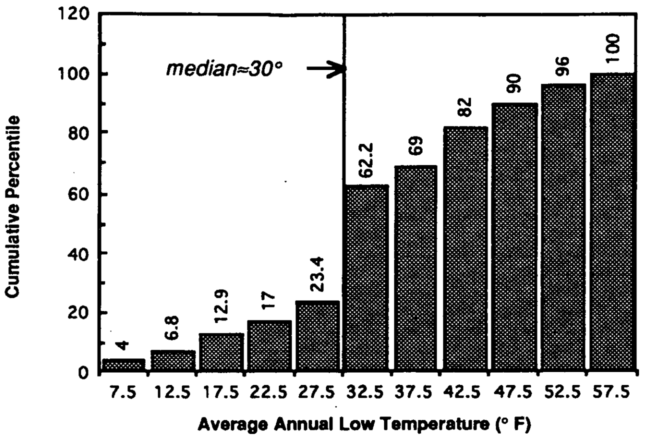

FIGURE 3 Average minimum temperature distribution (30°F = −1°C)

Pavement Thickness

It is expected that thicker pavements will exhibit distress later (in terms of time and loading) than thinner pavements. Unfortunately, most survey sections in the data base are 8-in. (20-cm). Some thicker sections have been added recently and are being monitored. At this time, however, there are too few thick sections to contribute significantly to the analysis.

Traffic

It is expected that traffic history will have a significant effect on pavement distress. For the purposes of this analysis 18-kip equiva-

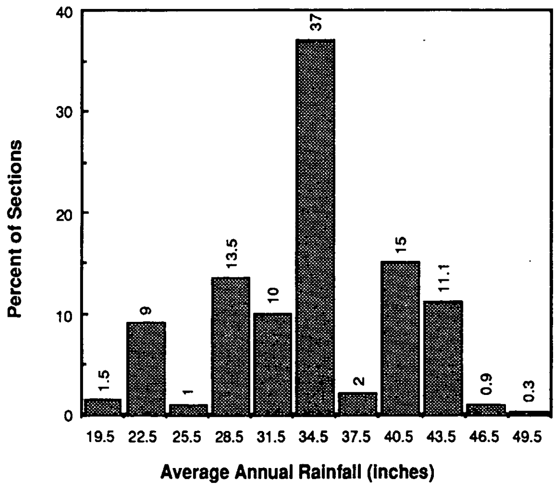

FIGURE 4 Distribution of average annual rainfall (1 in. = 2.56 cm).

lent single axle loads (ESALs) will be used. To fit into the predetermined PMIS scheme, traffic will not be treated as a continuous variable but as an adjustment to the time-distress curve in terms of high or low traffic.

Because loading has a cumulative effect on pavement performance, cumulative ESALs were calculated for each section from the time of construction to the date the section was surveyed. These detailed data were available only for a limited number of sections. At this point the data were analyzed only to determine a breakpoint for ESALs per year, which could be used to differentiate high traffic from low traffic. Figure 5 shows the average cumulative ESALs versus age for all the sections in the data base with detailed traffic data. From this analysis 1.4 million ESALs per year was chosen as the dividing line between high and low traffic.

ESAL figures given thus far are two-way ESALs across all lanes. Because only outside lanes were surveyed, a traffic distribution factor must be assumed. Approximately 75 percent of the data is for pavement with two lanes in each direction.

ANALYSIS OF VARIANCE

An analysis of variance (ANOVA) was performed to determine which factors were significant predictors for each distress type (Table 1). Age, cumulative ESALs since construction (CTRAF), average annual minimum temperature (TEMP), average yearly rainfall in inches (RAIN), coarse aggregate type (CAT), subbase treatment (SBT), swelling content of soil (SOIL), and their two-way interactions were examined. HT is highway type [Interstate highway (IH) or US highway] and is significant in terms of maintenance. On the basis of that analysis the following factors (in addition to age) were determined to be highly significant.

DISTRESS CURVES

Because pavement age was highly significant for every distress type and because few predictors may be available in the early implementation of the state PMIS, a preliminary analysis was performed by using only age as a predictor. Pavement sections older than 15 years were not used in the analysis, because after 15 years more than half of the sections had been overlaid and the remaining sections began to exhibit a "survivor effect." That is, any remaining data in the data base are nonrepresentative, because those 8-in. pavements that were weaker than average have already been overlaid. The NLIN procedure of SAS, a nonlinear least-squares analysis (*6*), was used to find the best-fit coefficients for the generalized sigmoidal function specified by TxDOT.

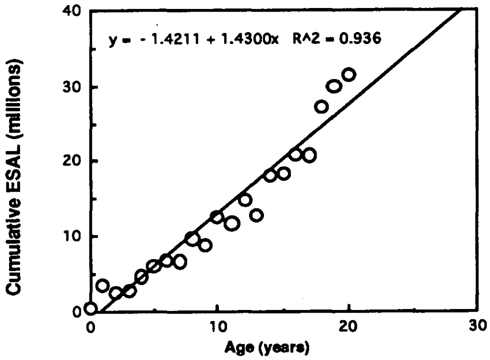

FIGURE 5 Average cumulative ESALs for data base sections.

TABLE 1 Significant Factors from ANOVA

	SIGNIFICANT FACTORS
Minor PUNCHOUT	SOIL, SOIL*CAT, TEMP*CAT, RAIN*SOIL
Severe PUNCHOUT	CAT*AGE, AGE*TEMP, SOIL, TEMP*RAIN
Port. Cmnt. PATCHES	AGE*CAT, AGE*SBT AGE*RAIN, AGE*HT
Asphalt PATCHES	AGE*TEMP, AGE*RAIN AGE*HT
CRACK SPACING	TEMP*CAT, CTRAF*RAIN, RAIN, RAIN*AGE
Loss of RIDE	* ANOVA not performed
SPALLED Cracks	AGE*CAT, AGE*RAIN, AGE*SBT

$$D = \alpha\, e^{-\left(\frac{\chi\epsilon\sigma\rho}{N}\right)^{\beta}}$$

where?

D = predicted level of distress,
N = age of the pavement,
α, β, and ρ = shape parameters estimated by regression,
χ = a factor to adjust for traffic,
ϵ = a factor to adjust for environment, and
σ = a factor to adjust for pavement structure.

To more clearly show the trend with time, weighted average values were used for the analysis. For all the following analyses χ, ϵ, and σ were fixed at 1.0, because it was expected that data would not be available in the initial implementation of PMIS to determine their values. Table 2 gives the best-fit coefficient values calculated for each distress type.

DISCUSSION OF RESULTS

Minor Punchouts

Figure 6 shows the fit for minor punchouts. A punchout is considered minor when several cracks have intersected but have not yet totally isolated a block of pavement. Data for punchouts (minor and severe) do not include repaired punchouts (patches). Considerable scatter is still evident (presumably because of extrinsic environmental, structural, and loading factors), but a clear trend with age is visible. This model will give a reasonable estimate when age is the only available predictor.

TABLE 2 Best-Fit Coefficients for Sigmoidal Function

	α	β	ρ
MPO/mi	82.9	1.33	18.6
SPO/mi	35	.577	144
ACP/mi	9.72	0.86	36.2
PCP/mi	146	1.23	40.3
CRACK SP SRG	34.9	1.00	0.06
CRACK SP LS	19.79	1.06	0.05
Loss of RIDE	0.269	1.00	1.00
Spalling (SRG)	2.02	6.06	10.0
Spalling (LS)	0.325	1.00	20.0

Severe Punchouts

Figure 7 shows the fit for the severe punchout model. A punchout is considered severe only if the affected block is completely detached from surrounding pavement. In contrast to minor punchouts, the data show that severe punchouts take longer to begin development, but once they are started their development accelerates rapidly.

Asphalt Patches

Figure 8 shows the fit for the asphalt patch model. As for severe punchouts, the onset of patching is slow to begin, but once it has started it increases rapidly after 5 to 6 years.

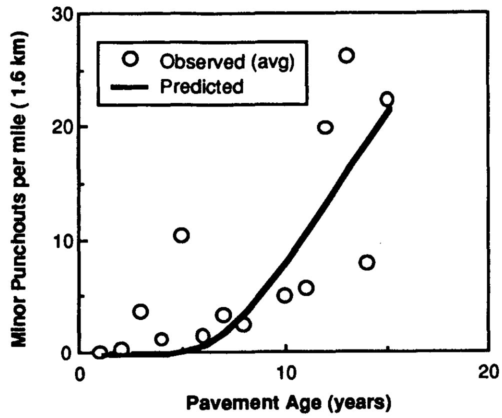

FIGURE 6 Prediction curve for minor punchouts.

PCC Patches

Figure 9 shows the prediction model for PCC patches. A very clear trend with age is evident; no pavements in the sample were patched within the first 5 years, and an inflection point is present around 10 years, after which the rate of patching increases steeply. Punchout and patch models give the number of occurrences per mile; multiply by 0.625 to find the number per kilometer.

Crack Spacing

An increase in the number of cracks per 100 ft (decrease in crack spacing) indicates poor pavement condition. Unlike the other distresses crack spacing does not vary drastically with age. Typically, most early-age cracking occurs within days of slab placement, and nearly all cracking has taken place by the end of the first winter after placement (*7*). Consequently, several other factors have as much or more influence than age, particularly coarse aggregate type. Be-

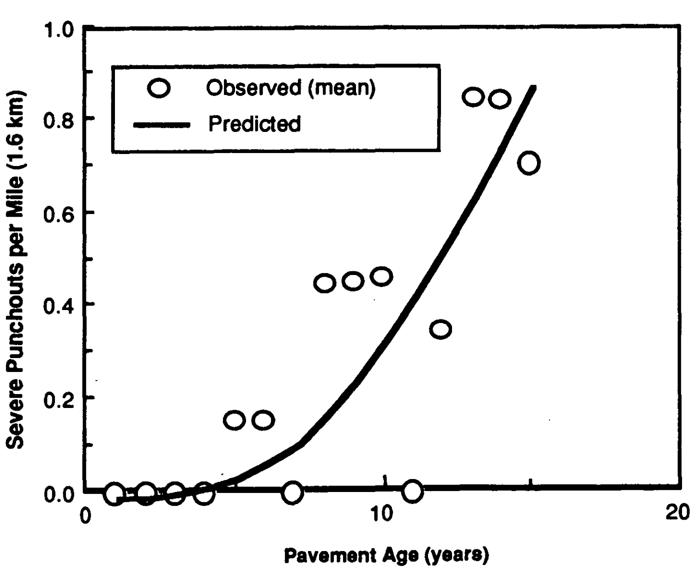

FIGURE 7 Prediction curve for severe punchouts.

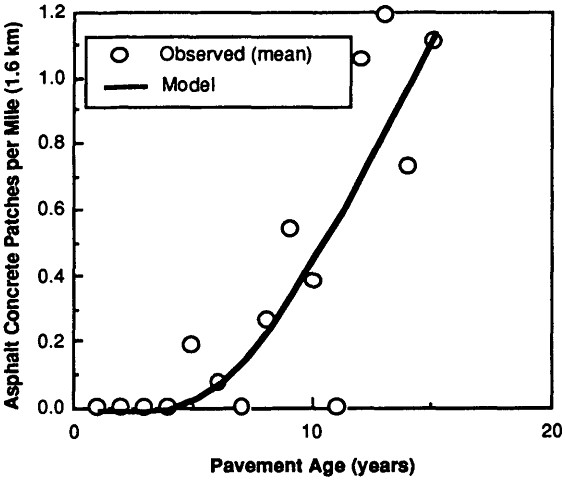

FIGURE 8 Prediction model for asphalt patching.

cause of this two separate curves were fitted, one for limestone (LS) aggregate and another for siliceous river gravel (SRG) aggregate. The results are shown in Figure 10.

Figure 10 shows that crack spacing in LS aggregate pavements tends to decrease from around 8 ft to 5 ft (2.4 to 1.5 m) (20 cracks/100 ft) in a fairly short period of time and then stay basically constant thereafter. SRG pavement crack spacing often decreases with time to under 3 ft (0.9 m; 33 cracks/100 ft). Because 3 ft is the critical level for this distress, the slight rise in SRG crack spacing observed from 9 to 15 years is probably an early-age survivor effect because many of these pavements are overlaid at an early age. Additional scatter in the plot may be explained by other extrinsic factors, such as temperature and season of placement (especially if the peak temperature coincided with peak heat of hydration), which are only approximately known. Subbase friction, percent steel, and slab thickness may also play a role. Minimum temperature is included in the data base, and its interaction with aggregate type was found to be significant. This is probably because of the large difference in thermal coefficient between the two aggregate types (*5*). The crack spacing model predicts the number of cracks per 100 ft; this would be the same as the number per 30 m.

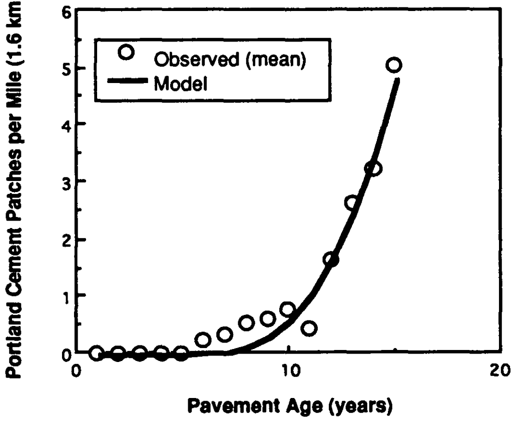

FIGURE 9 Prediction model for PCC Patches.

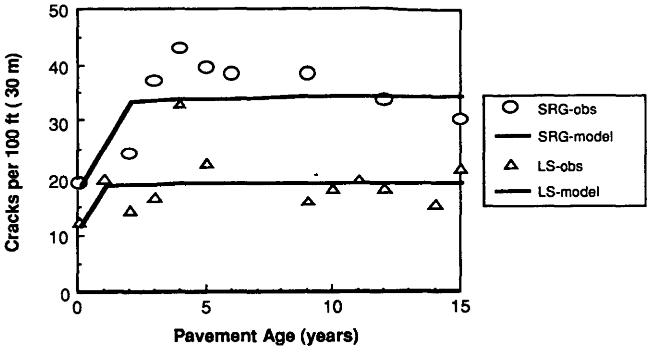

FIGURE 10 Crack spacing performance curves for LS and SRG aggregates.

Ride Score

Additional data for ride score (and spalling) were available from archives of historical condition surveys conducted periodically by CTR in 1974, 1978, 1980, 1982, and 1984 (*8*). Approximately 300 projects were selected across the state. A project consists of a continuous length of pavement with homogeneous properties such as pavement thickness, coarse aggregate type, and traffic.

Figure 11 shows the distribution of the data relative to pavement age. Of the total of 8,878 sections surveyed, most were between 6 and 9 years old when surveyed. Although the distribution was skewed toward middle-age pavements, a sufficient number of younger and older pavements were available to proceed with the analysis.

Ride score was modeled as serviceability index (SI) *loss* versus age, normalized to a hypothetical initial SI of 4.5. The normalized SI loss (NSL) was calculated as follows:

$$NSL = (4.5 - PSI)/4.5$$

where PSI is present serviceability index. NSL ranges from 0 ($PSI \geq 4.5$) to 1 ($PSI = 0$). For example, if the PSI of a section is 3.5, then the section is assumed to have lost 1 SI unit of ride quality, giving an NSL of 0.22. This means that the section has lost 22 percent of its initial smoothness. Figure 12 shows the fit to the data.

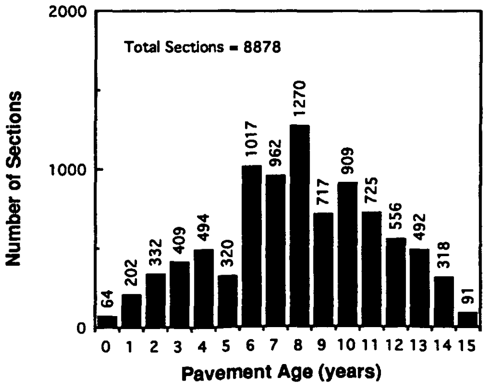

FIGURE 11 Age distribution of ride scores at time of survey.

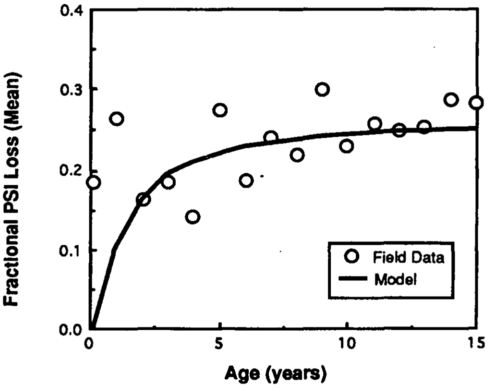

FIGURE 12 Best-fit model for loss of ride score.

When examining Figure 12 it should be remembered that the model was fit to the *weighted* average values of PSI; many more datum points were available for medium-age pavements than for 14- and 15-year old pavements (see Figure 11). Thus, the curve shown in Figure 12 passes through the 12- and 13-year points, which are heavily weighted, but is pulled down from the 14- and 15-year points, for which there were very few observations, and thus they had less of an effect on the regression.

Spalled Cracks

Data for spalling were obtained from the same source as the ride data. Spalling data were divided into two categories, minor and severe. Minor spalling was defined as "edge cracking where the loss of material has formed a spall of one half inch wide or less" (*9*). Because the PMIS definition of spalling (*10*) specifies spalling of "at least 1 inch (25 mm) wide," a decision was made to consider only the CTR severe spalling in the analysis.

As shown in Table 1 the interaction of age with coarse aggregate type was the best predictor for crack spalling; this was followed by the cumulative rainfall on the section (AGE · RAIN), the age of the section, and the interaction of age with the type of subbase treatment.

Figure 13 shows the development of severe spalling with age for several commonly used coarse aggregates. It is clear from Figure 13 that spalling develops with age, apparently at an exponential rate. Pavements constructed with SRG coarse aggregate exhibited an average rate of spalling more than 10 times the rate of LS pavements. The aggregate type "other" in Figure 13 consists of blended LS and river gravel or sometimes slag blended with LS or gravel. These are grouped together because there are relatively few of them compared with the number of LS and SRG pavements. Because they often include some SRG material, it is reasonable that their rate of spalling would lie somewhere in between "pure" LS and SRG aggregates.

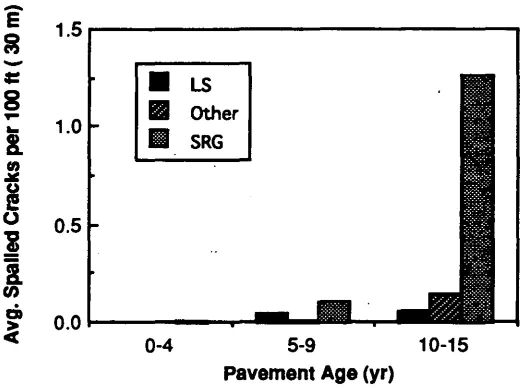

FIGURE 13 Spalled cracks by age and coarse aggregate type.

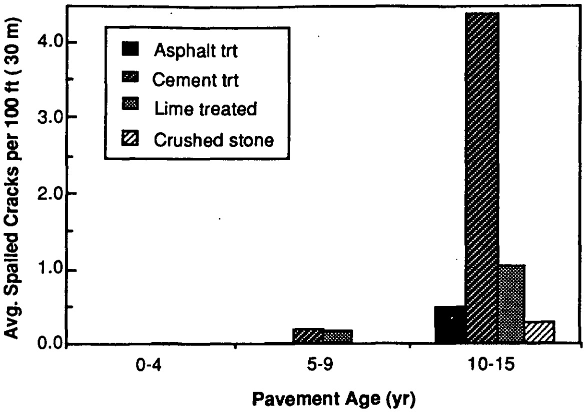

FIGURE 14 Effect of subbase treatment on spalling in SRG Pavements.

Figure 14 illustrates the relative effectiveness of the various subbase treatments, which were identified by the ANOVA as significant in predicting spalling rate. From the limited data available crushed stone gave the best performance; this was followed by asphalt-treated subbase. The worst choice by far was cement-treated subbase. However, the design of pavements in the field is not a controlled experiment; consequently, the choice of subbase treatment is not evenly distributed. If more study in this area is desired, a closer examination of the inference space in terms of subbase treatment is needed.

These extrinsic factors, aggregate type, rainfall, age, and subbase treatment, explain in part why many pavements exhibit no crack spalling at all whereas others are severely spalled. Because of the extremely different performances of LS- and SRG-based pavements, at least two curves are needed to adequately model spalling.

Spalling for CRCPs was expressed as the number of spalled cracks per 100 ft (30 m) of pavement. Weighted average values were used for the analysis. A composite curve modeling both aggregates would do justice to neither, so separate curves are suggested. Figure 15 shows the fit to the SRG pavement data.

Pavements made with LS coarse aggregate were much less prone to spalling. Figure 16 shows the fit to the LS pavement data.

CONCLUSIONS AND RECOMMENDATIONS

For the seven distress types modeled, all but two can be adequately described as functions of pavement age. In the cases of crack spacing and spalling the choice of coarse aggregate used is so important that it overwhelms age as a consideration and must be included in the model. Results from the ANOVA show that all the models could be improved by considering additional environmental, structural, and loading variables; the sigmoidal equation suggested by TxDOT

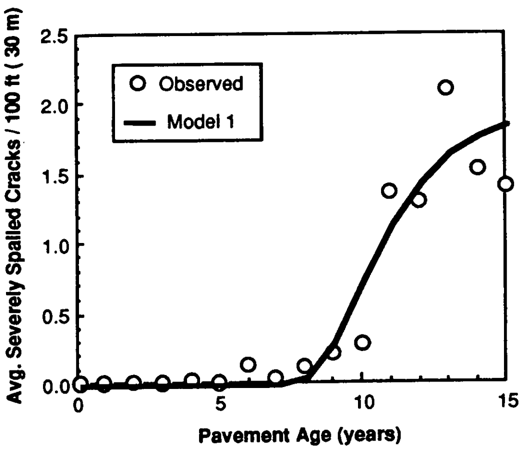

FIGURE 15 Spalling model (SRG).

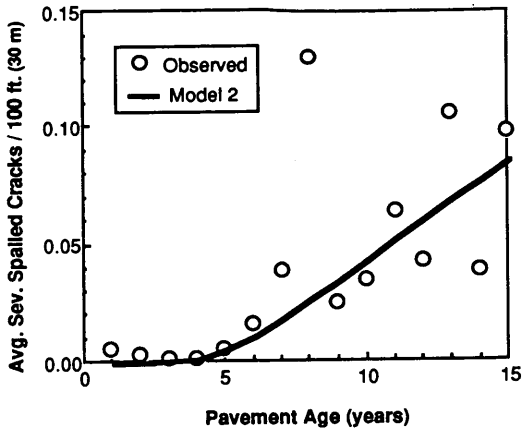

FIGURE 16 Spalling model (LS).

provides these factors. At the present time supporting data for the Texas PMIS are limited, and simple age-dependent models are all that is required. More work is needed to quantify the influences of these additional factors so that the models can be refined and improved as the data base expands.

REFERENCES

1. *Managing Texas Pavements.* Pavement Management Section (D-8PM). Division of Highway Design, Texas Department of Transportation, Austin, Jan. 1993.
2. Singh, N., T. Dossey, J. Weissmann, and W. R. Hudson. *Preliminary Distress and Performance Prediction Models for Concrete Pavements in Texas.* Report 1908-1 (preliminary). Center for Transportation Research, Austin, March 1993.
3. Dossey, T., and A. Weissmann. *A Continuously Reinforced Concrete Pavement Database.* Report RR 472-6. Center for Transportation Research, Austin, Tex., Nov. 1989.
4. Chou, C. *Development of a Long-Term Monitoring System for Texas CRC Pavement Network.* Report RR 472-2. Center for Transportation Research, Austin, Oct. 1988.
5. Suh, Y. *Early Age Behavior of Continuously Reinforced Concrete Pavement and Calibration of the Failure Prediction Model in the CRCP-7 Program.* Report RR 1244-3 (preliminary). Center for Transportation Research, Austin, Tex., March 1992.
6. *SAS User's Guide: Statistics.* Version 5 edition. SAS Institute Inc., Cary, N.C., 1985.
7. Won, M., K. Hankins, and B. F. McCullough. *Mechanistic Analysis of Continuously Reinforced Concrete Pavements Considering Material Characteristics, Variability, and Fatigue.* Report RR 1169-2 (preliminary). Center for Transportation Research, Austin, Tex., April 1990.
8. McCullough, B. F., and P. J. Strauss. *A Performance Survey of Continuously Reinforced Concrete Pavements in Texas.* Research Report 21-1F, Nov. 1974.
9. Gutierrez de Velasco, M., and B. F. McCullough. *Summary Report of 1978 CRCP Condition Survey in Texas.* Research Report 177-20, Jan. 1981.
10. *1991 Pavement Evaluation System Rater's Manual.* SDHPT, May 2, 1991.