Framework for Incorporation of Spalling in Design of Concrete Pavements

SANJAYA P. SENADHEERA AND DAN G. ZOLLINGER

A framework that can be used to incorporate crack spalling in the design of concrete pavements is proposed. Crack spalling is a common form of distress in concrete pavements. However, available literature on the modeling of spalling is limited to some regression-based models developed for jointed concrete pavements. On the basis of comprehensive field surveys and results from analysis of pavement condition survey data for continuously reinforced concrete pavements, several factors have been identified as excellent predictors of spalling, allowing the proposal of the design framework leading to a mechanistic spalling model to predict crack spalling. The design framework presented incorporates survival analysis, which is a statistical technique based on failure-time theory and reliability. The results obtained by the use of this technique provide the pravement engineer with the information required to assess the survivability of the pavement from spalling and the predicted level of spalling at a certain age, both simply and succinctly. Because the proposed statistical technique can be effectively used for other forms of pavement distress as well, a detailed description of the mathematical development of the model is also included for better understanding of the principles involved.

Spalling, which is an often encountered form of distress in concrete pavements, has not received the same attention in pavement design as the other distresses such as cracking and punch-outs in continuously reinforced concrete pavements (CRCPs) and joint failure in jointed concrete pavements (JCPs). It is a very important distress in concrete pavements from the standpoint of the road user because it results in a rough ride and gives a negative perception, that is, a lack of structural integrity in the pavement. From a technical standpoint, because spalling takes place at the transverse joints or random cracks in the pavement, it may take away from the load transfer efficiency that is important for minimizing stress levels in the pavement. Unless adequate load transfer is maintained, spalls may develop into more serious forms of distress such as punch-outs in CRCPs or joint failure in JCPs.

The lack of attention given to the spalling distress on a fundamental basis may have been caused by a lack of understanding of the mechanisms involved. At the Texas Transportation Institute (TTI) of the Texas A&M University System, research is currently under way to identify the mechanisms of spalling that would enable the modeling of spalling in concrete pavements by incorporating a number of factors that appear to influence spalling significantly.

The available literature on the modeling of spalling is limited to JCPs, and they indicate attempts to model spalling as a function of age. Field observations on CRCPs undertaken at TTI have indicated that spalling is not necessarily a function of age, but it is the culmination of the accumulation of fatigue damage starting with early-age delaminations that are extended by vehicle tire loads and repeated changes in pavement temperature. It is likely that this mechanism is applicable to JCPs as well.

In this paper a framework for mechanistically incorporating crack spalling as a design criterion for concrete pavements is introduced by incorporating the factors observed to influence spalling. The influences of these factors were further investigated by analyzing the available spalling data on CRCPs in Texas. The survival analysis technique, which is commonly used in medical research (*1*) and other industrial disciplines, is introduced, and its usefulness to pavement design is emphasized. Because of limitations in the currently available field data, a comprehensive spalling model can be only suggested at this point, but an illustrative model is developed to introduce the results that will be available to the pavement designer by using this technique.

OVERVIEW OF PRIOR RESEARCH

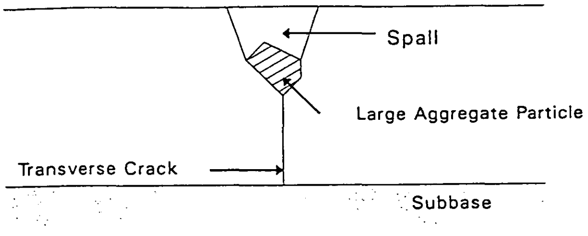
Several researchers have previously investigated spalling in concrete pavements. One definition defines spalling as the breakdown of the pavement along the cracks leading to the loss of concrete and the disintegration of the load transfer mechanism (*2*). Another definition indicates spalling in JCPs as any type of fracture or deterioration of the transverse joints, excluding corner breaks (*3*).

In CRC pavements spalling can take place on either one or both sides of a transverse crack (*4*). Spalls are generally categorized by their depth as either deep or shallow, with a depth greater than 2.5 cm generally being considered deep (Type II and Type III spalls; Figure 1). Spalls are also categorized as either minor or severe. In the CRCP spalling data base used for the development of spall models in this paper (*5*), minor spalling was defined as "edge cracking in which the loss of material has formed a spall of 0.5 in. wide or less."

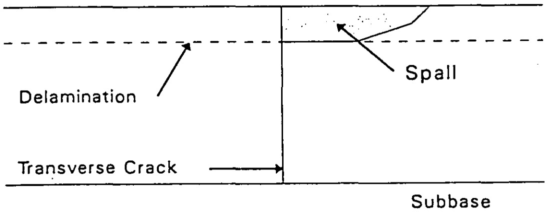
It would be appropriate at this point to note some observations indicated in previous work on spalling.

1. Aggregate type may have some influence on spalling (*6*).
2. Concretes made with coarse limestone aggregate showed less spalling than concretes with siliceous gravel aggregates (*7*).
3. Primary causes of spalling are entrapment of road debris in cracks, which causes a buildup of compressive stresses, a combination of shear and tensile stresses under wheel load, and poor concrete at the surface of the pavement, presumably because of overworking during the finishing process (*8*).
4. Minor spalling increases with age and traffic. Severe spalling does not seem to have a correlation to minor spalling or crack spacing (*8*).
5. Spalling increases with increasing crack width (*8*).

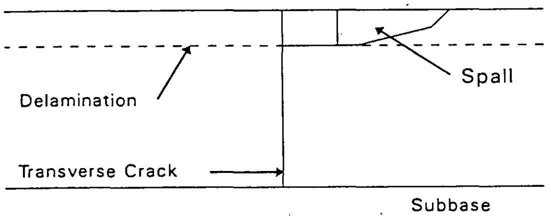
Texas Transportation Institute, Texas A&M University System, College Station, Tex. 77843.



(a) Type I-Deep Spall caused by Large Aggregate Particle



(b) Type II-Shallow,Wide Spall by Delamination & Traffic



(c) Type III-Shallow Spall, Initial Spalling away from Crack

FIGURE 1 Types of spalling in concrete pavements.

6. Severe spalling is usually a result of construction operations and is influenced by traffic, pavement age, and the location of the spall (*7*).

7. Spalling generally occurs in the wheelpath regions of the pavement (*9*).

8. Surface spalling associated with reinforcement results from the pressure exerted by corrosion products when the steel rusts. However, spalling over reinforcement is not a widespread problem in CRC pavements (*2*).

9. Deep spalls are generally related to structural weaknesses, and shallow spalls are related to weakened horizontal planes in the concrete (*10*).

10. Spalling is a result of discontinuities developed during propagation of cracks as the crack propagates along a path of least resistance (*11*).

11. Spalling develops because of restraint to volume change resulting from temperature variation through the slab depth (*12*).

12. Subgrade support conditions can influence spalling (*2*).

13. Crack width and depth to steel reinforcement have an influence on the stiffness and consequently will influence the spall stresses (*2*).

Except for Item 11 above, all other observations come from studies on CRC pavements.

A spalling model was first proposed for jointed pavements in the PEARDARP program in which spalling was modeled as a function of time (*13,14*). It was later found that the PEARDARP spalling model tended to overpredict transverse joint spalling for spalling data from certain environmental regions (*15*). Analysis of spalling data by Smith et al. (*15*) further indicated that in general spalling was observed on pavements of all ages and with different joint spacings in which material problems such as nondurable aggregates under harsh climates existed or the dowel bars had corroded or locked up the joints. On the basis of the analysis of the Michigan road test spalling data, Smith et al. (*15*) proposed spall models for jointed plain concrete pavements (JPCPs) and jointed reinforced concrete pavements (JRCPs) incorporating factors such as D-cracking, type of joint sealant, freezing index, and aggregate reactivity.

The model for JPCP had a coefficient of determination (R^2) of 0.59 and a standard error of estimate of 5 joints/mi. The model for JRCP had an R^2 of 0.47 and a standard error of estimate of 3 joints/mi. Smith et al. (*15*) believed that incompressible material inside the transverse joints is the major cause of joint spalling and postulated that preformed seals that seemed to reduce spalling at joints do so because of their ability to keep incompressible material away from the joints for a significant period of time.

FIELD SURVEYS

Extensive field surveys or spalling have been undertaken in concrete pavements in the state of Texas for a long period of time. Initial field surveys recorded the level of spalling in a large number of concrete pavement survey sections throughout the state. Recently, more field studies were undertaken by TTI with the idea of establishing the mechanisms involved in spalling (*4*). These field surveys have indicated the presence of several types of spalls (Figure 1). Types II and III appear to be the most widespread and to have the same type of distress development, that is, formation of delaminations that eventually lead to spalling because of fatigue loading from both traffic- and temperature-induced stresses.

Several important observations were noted from the field surveys conducted by TTI (*4*). These were that

1. Spalling is an extended form of delaminations at the transverse cracks.
2. Delaminations originate at transverse cracks (Figure 1).
3. Delaminations may be forming very early in the life of a concrete pavement, as early as when cracks initiate. This could be a matter of hours or days after the concrete is paved, depending on the environmental and curing conditions.
4. Most delaminations usually occur at depths ranging from 2.5 to 5.0 cm from the surface of the pavement, and they eventually propagate toward the surface, causing a visible spalling distress.
5. Most spalling distresses occur along the wheelpaths.
6. Higher levels of spalling were observed primarily in pavement sections constructed with siliceous river gravel coarse aggregate (Table 1 and Figure 2). Also at the spalling failure planes there is a high percentage of failure at the aggregate-cement paste interface (*4*).
7. Particularly in rural highways, inside lanes display more spalling than outside lanes.

These factors indicate that any design framework for spalling should be a two-tiered process. In Step 1 delaminations occur very early in the pavement life, most likely because of differential moisture loss across the depth of the pavement, and are accentuated by the low interfacial strength between the aggregate and the

TABLE 1 Summary of Observations on Sample Survey Sections

Highway	Coarse Aggregate Type	Modes of Distress	Remarks
SH-6	Siliceous River Gravel	Spalling	Extensive spalling. More spalling in the inside lane. 75 % of spalls downstream of crack. Spalling on wheel path. Plane of weakness at 2.5 cm depth at most transverse cracks.
BW-8	Siliceous River Gravel	Spalling	Isolated areas of extensive spalling. Spalling distributed among all 3 lanes. Concrete cores from pavement had planes of weakness at 2.5 cm depth.
US-59	Siliceous River Gravel	Spalling	Extensive spalling. More spalling in the inside lane. Most spalls were downstream of crack. Spalling in wheel path.
IH-10 Houston	Siliceous River Gravel	Spalling	Extensive spalling. Almost all spalling in 2 inside lanes.
IH-45	Crushed stone /siliceous gravel blend	Punchouts	Virtually no spalling.
IH-10 Gonzales	Crushed stone	Punchouts	Virtually no spalling.

cement paste at early ages. In Step 2 the subsequent development of the delaminations into spalls would be a process based on the accumulation of fatigue damage because of the action of vehicle tire load-induced stresses (*4*) and temperature change-induced stresses (*12*).

Spalling data for this analysis were obtained from the concrete pavement data base compiled by the Center for Transportation Research of the University of Texas at Austin. The condition surveys for spalling were performed in 1974, 1978, 1980, 1982, and 1984 (*16*). In this CRCP data base, each pavement section constructed at the same time is identified as a control unit. Each one of these control units is then divided into a number of survey sections, each of which is 305 m (1,000 ft) long, and spalling data are collected on each of these survey sections. Therefore there is a distribution of spalling data values for each control unit and for each survey period.

The spalling data base indicated minor and severe spalling for each pavement section surveyed. Minor spalling was defined in the data base as "edge cracking in which the loss of material has formed a spall of 0.5 in. wide or less" (*5*). All other spalling was considered severe. Because minor spalling as defined is not likely to fall into the Type II and III spalling, only severe spalling from the data base was considered in this analysis. The CRCP data base does not distinguish between the different types of spalls mentioned in this paper; however, because Type I spalls are few and far between, it is expected that they will not cause any significant bias in the analysis of the data.

The survey sections included in the data base had information such as pavement thickness, coarse aggregate type in the concrete, subbase treatment, type of subgrade soil (likelihood of swelling or shrinkage), average annual rainfall, and the estimated average daily traffic and its projected rate of growth.

Preliminary analysis of spalling data (*16*) indicated the following:

1. Eighty-five percent of survey sections were more than 5 years old at the time of the first survey.
2. Seventy-two percent of survey sections displayed no spalling whatsoever.

Field studies undertaken by TTI aimed at understanding the mechanism of spalling have revealed that there are a number of CRCP sections in the Houston area alone that have spalled within the first 2 to 4 years of service. Even though the development of spalls is caused by fatigue damage, the origins of these spalls (i.e., the presence of delaminations) are greatly influenced by the environmental conditions at the time of paving and immediately afterward (*17*). These conditions include the temperature and relative humidity profile during the first few days after the placing of concrete, wind velocity, and the method of curing. It is possible that these conditions dictate the number of delaminations in the pavement that are likely to develop into spalls, provided that the subsequent fatigue damage so dictates.

Typical spalling curves plotted against time for six survey sections in the data base are shown in Figure 3. An interesting feature

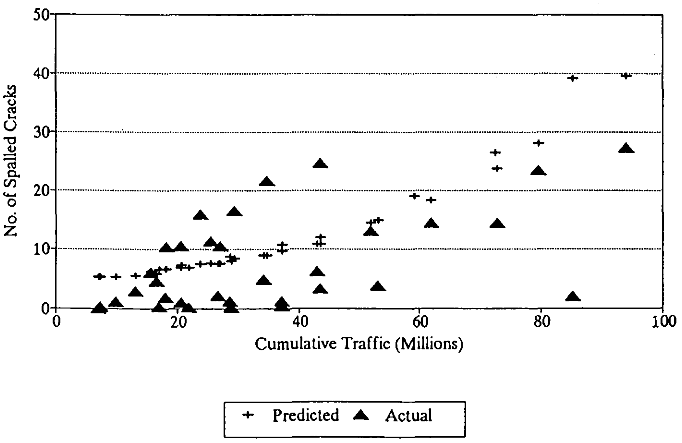


FIGURE 2 Actual and predicted spalling at 50th percentile level for pavements made with siliceous gravel.

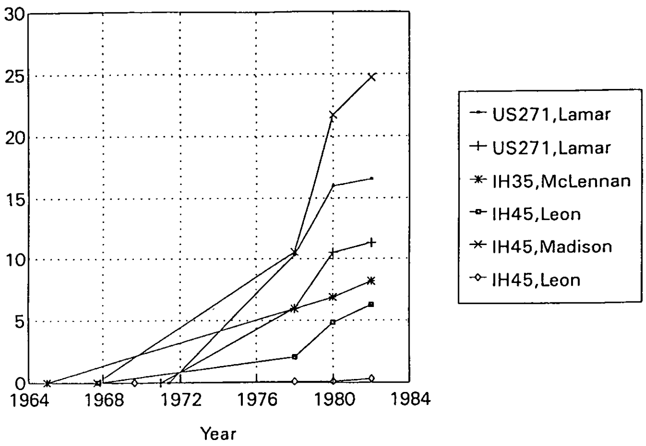


FIGURE 3 Typical spall development curves from survey sections.

about these curves is that they all have an S shape, which indicates a maximum asymptotic level of spalling, which these curves approach, in spite of a continuing increase in traffic volume. The shapes of these spalling curves are important criteria in selecting the mathematical distribution for representing spalling in the proposed spalling model. This maximum asymptotic level of spalling would be the level of delaminations present in the pavement.

A further analysis of a correlation of the spalling data was performed on some selected variables that were already identified as factors that influence spalling as a result of the TTI field survey (Table 1). The coarse aggregate type had the best correlation with the spalling data. Because of the unavailability of data on aggregate characteristics in the data base, separate correlation analyses were performed for the two primary aggregate types. These indicated that the following factors have the best correlation.

1. Cumulative traffic at the time of the survey,
2. Cumulative rainfall at the time of the survey, and
3. Interaction between the age of the pavement and subbase type.

FRAMEWORK FOR A SPALLING MODEL

To establish good design practices and maintenance strategies for spalling, it is important to estimate the time at which spalling first takes place and the level of spalling at different times during the service life of the pavement. If spalling were to be eliminated from concrete pavements, it would be necessary to make sure that no delaminations occur in the first place. This calls for extremely effective curing practices based on the ambient temperature and humidity profiles at the time of paving and immediately afterward. However, further study is required to assess the economic feasibility of such considerations associated with highway construction. In the meantime it may be important to predict the occurrence of spalling and its development with time on the basis of the factors identified to be the best predictors of spalling.

A design framework for spalling is proposed in this paper on the basis of a statistical method called the failure-time theory (*18*). In this method the failure time is a random variable and the dependence of failure time is assessed by using explanatory variables (covariates).

For pavements under the same conditions, the time that it takes for the pavement to spall will vary from one section of pavement to the other because of the random nature of spalling. Therefore the time to failure (spalling) can be represented by a probability density function. This is a situation in which extreme values of such a random variable (largest or smallest value, but in this case the smallest value for failure time) are of interest. These extreme values from samples with different numbers of datum points are also random variables nad have probability distributions of their own. These extreme values may be derived from the distribution of the initial variate.

Failure Time Theory and Concept of Survivability

Let T be a nonnegative random variable representing the failure time of a pavement section from a homogeneous population. The probability distribution of the failure time T can be specified by using one of three different functions, namely, the survivor function, the probability density function, and the hazard function.

The survivor function $S(t)$ is defined as

$$S(t) = P(T \geq t),\ 0 < t < \infty \tag{1}$$

The survivor function can be described as the probability of failure at time t provided that the pavement did not fail up to that time. Because of the aging of pavement, the survivability of the pavement should gradually decrease with time.

If the failure time T is a continuous variable, the probability density function $f(t)$ of the failure time T is given by

$$\begin{aligned} f(t) &= \lim_{\Delta t \to 0} \frac{P(t \leq T \leq t + \Delta t)}{\Delta t} \\ &= -\frac{dS(t)}{dt} \end{aligned} \tag{2}$$

In words, it is the proportion of pavements failing near time t within a very small time interval per unit time. $f(t)$ is a nonnegative function.

Also,

$$S(t) = 1 - F(t) \tag{3}$$

where $F(t)$ is the cumulative probability at time t.

The hazard function $h(t)$ of the failure time is defined as the probability of failure during a very small time interval (Δt) assuming that the pavement has survived up to the beginning of the time interval. Therefore, this gives the conditional failure rate.

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t \leq T \leq t + \Delta t | T \leq t)}{\Delta t} \tag{4}$$

The hazard function for a pavement is positive and increases with time.

Selection of a mathematical distribution to represent failure data is an important step in the survival analysis. There can be many different causes that lead to the failure of a pavement. It would be difficult, if not impossible, to isolate all of these causes and mathematically account for all of them. Therefore, selecting a theoretical distribution to approximate failure data needs to be done carefully by considering the type of hazard or survival function characteristics of the application at hand.

Commonly used mathematical distributions in failure-time theory are exponential distribution, lognormal distribution, and Weibull distribution. The simplest of these, the exponential distribution, provides a constant rate of hazard in which no aging effects are involved. If this distribution were to be used, failure (spalling) would be a random event independent of age. This is not suitable for representing spalling in a pavement in which the aging effect should be reflected by a monotonically increasing hazard.

The lognormal distribution shows an initially increasing and then decreasing hazard rate. This decrease takes place almost as soon as the median is passed and approaches zero as time approaches infinity. Therefore, it is unsuitable for modeling pavement distress.

The two-parameter Weibull distribution is a generalized form of the exponential distribution. It is characterized by two parameters, shape and scale. This distribution can be used to model the survival distribution of a population with increasing, decreasing, or constant risk. It can provide a mnotonically increasing hazard and a Type III extreme value distribution. A Type III extreme value distribution is one in which its largest value has a finite upper bound and the smallest value has a finite lower bound, which is similar to the spalling distributions shown in Figure 3. Therefore, this is suitable for determining the minimum of a series of minima (i.e., failure times).

The survivor function $S(t)$ and the hazard function $h(t)$ of the two-parameter Weibull distribution are given by

$$S(t) = e^{-(\lambda t)^{\gamma}} \tag{5}$$

$$h(t) = \lambda\gamma(\lambda t)^{\gamma-1} \tag{6}$$

where γ is the shape parameter, and λ is the scale parameter.

These distributions can be generalized to incorporate a number of covariates. For illustrative purposes the case of a single covariate represented by Z is considered. Usually, the scale function selected is $\exp(Z\ \beta)$, where β is an unknown parameter.

If the effect of covariates is to act multiplicatively on the Weibull hazard, the conditional hazard may be taken as

$$h(t; Z) = \lambda\gamma(\lambda t^{\gamma-1} \exp(Z\beta) \tag{7}$$

A characteristic feature of the failure time data is that the response variable (such as the failure time) cannot be negative. This enables the use of a transformation such as log transformation before standard statistical methods can be applied. Log transformation is advantageous because it will reduce the presence of extremely large values in the distribution that can otherwise have a strong influence on the final fitting of the extreme value.

The survival functino $S(Y)$ and the hazard function $h(Y)$ for the natural logarithm of failure time Y are given by

$$S(Y) = \exp\left[-\exp\left(\frac{Y-\alpha}{\sigma}\right)\right] \tag{8}$$

$$h(Y) = \frac{1}{\sigma}\exp\left(\frac{Y-\alpha}{\sigma}\right) \tag{9}$$

where σ equals $1/\gamma$ and α equals $-\ln\lambda$.

With the addition of covariates, the survival function $S(Y)$ is given by

$$S(Y) = \exp\left[-\exp\left(\frac{Y-\alpha}{\sigma} + Z\beta\right)\right] \tag{10}$$

From Equation 10 the linear model can be obtained

$$Y = \alpha - (\sigma\beta)Z + \sigma \ln\left[\ln\left(\frac{1}{1-F(y)}\right)\right] \tag{11}$$

and for n number of covariates $Z_1, Z_2, \ldots Z_n$, the linear regression model

$$Y = \alpha + \sum_{i=1}^{n} Z_i\beta_i^* + \sigma W_p \tag{12}$$

where

n = number of covariates,
$\alpha = -\ln\lambda$,
$\sigma = 1/\gamma$,
$\beta^* = -\sigma\beta$, and
W_p = pth percentile of the extreme value distribution.

Although the failure-time theory and the survivability concept previously explained were in terms of the actual time response of failure time, often other variables can be used as the responsible variable. In spalling, for instance, the number of spalled cracks can be used as the response variable. This would enable the pavement engineer to perform the analysis without defining the level of failure in a pavement. Thus a prediction model that includes both the level of spalling and reliability can be developed. Because the spalling distress is being considered in this paper, the response variable is the natural logarithm of the number of spalled cracks. The *LIFEREG* procedure of the statistical analysis package SAS (*19*) can be used to obtain the regression parameters described in Equation 12.

Development of Spalling Model

On the basis of the previous discussions in this paper, the following factors can be earmarked for the modeling process.

Factors Influencing Formation of Delaminations

1. Ambient relative humidity and temperature during early days after paving.
2. Aggregate-cement paste interfacial strength in concrete.
3. Curing conditions.

Factors Relating to Strain Development Causing Fatigue Damage

1. Cumulative traffic volume.
2. Periodic fluctuations in temperature in the pavement.
3. Type of subbase, which influences the stresses in the pavement slab.

Factors Causing Restraint Necessary for Generation of Stresses

1. Cumulative rainfall as a means by which the restraint at the crack or joint faces are altered.
2. Tensile strength of concrete or the interfacial strength between the aggregate and cement paste, which influences the cohesion at crack faces.

All of this information is not available in the current data base. Only cumulative traffic volume and cumulative rainfall at the time of each condition survey can be calculated from the available data. Because these factors show a high correlation with the spalling data and the mechanisms of spalling identify these as two primary factors that affect spalling, a satisfactory spalling model can still be obtained by using them.

The importance of rainfall in this model is reflected in two ways. First, as mentioned earlier, in rural highways the debris inside cracks on the outside lane can get splashed along with the rainwater onto the inside lane. This will make spalling in the outside lane subject only to stresses from the vehicle tires. Now, with more debris inside the cracks in the inside lane, it can be subject to both the traffic-induced stresses and the temperature change-induced stresses. Second, the rainfall provides lubrication at the crack faces inside transverse cracks and delaminations. This will reduce or eliminate the cohesion between the crack faces, which plays an important role in reducing the stresses. When friction across the delamination faces are low, it will result in higher stresses (*4*).

The spalling model can be represented in the form of Equation 13:

$$\ln(\text{number of spalled cracks}) = \alpha + \beta_1^* \cdot CUMTR + \beta_2^* \cdot CRAIN + \sigma W_p \qquad (13)$$

where *CUMTR* is cumulative traffic in millions, and *CRAIN* is cumulative rainfall (in centimeters) at the time of the condition survey.

Using the *LIFEREG* procedure in the SAS statistical analysis package (*19*), the following linear regression models were obtained separately for pavements made with siliceous river gravel and crushed limestone. Because the natural logarithm of the number of spalled cracks per survey section was considered the response variable, to validate the model, left censoring was performed on the large number of sections that had not spalled at the time of the survey.

For pavements with siliceous river gravel coarse aggregate:

$$Y = 2.01 + 0.027 \cdot CUMTR - 5.3E{-}04 \cdot CRAIN + 1.34 \ln\left[\ln\left(\frac{1}{1 - F(t)}\right)\right] \qquad (14)$$

For pavements with crushed limestone coarse aggregate:

$$Y = 0.31 + 0.009 \cdot CUMTR - 2.31E{-}04 \cdot CRAIN + 0.85 \ln\left[\ln\left(\frac{1}{1 - F(t)}\right)\right] \qquad (15)$$

where *Y* is the natural logarithm of the number of spalled cracks.

Statistical data for spalling models in Equations 14 and 15 is provided in Table 2.

Illustrated in Figure 2 are the actual and predicted levels of spalling for pavements made with siliceous river gravel coarse aggregate. There is a certain amount of scatter evident in Figure 2. This scatter in the data may be a result of different initial conditions at the time of paving, variations in aggregate properties, and differences in temperature changes between pavements. It is hoped that more refinement, as discussed later in this paper, would eliminate this scatter.

Results from Proposed Spalling Model

The results from the models in Equations 14 and 15 are illustrated in Figures 4 and 5. These illustrations are given for a specific case of average daily traffic of 20,000, an annual traffic growth rate of 1 percent, and an average annual rainfall of 100 cm.

How the survivability (probability of survival) changes with time for pavements made with siliceous river gravel and crushed limestone coarse aggregates, respectively, is illustrated in Figures 4(*a*) and 4(*b*). As expected they display the aging effect of the pavement by giving probabilities of survival that decrease with time. It can clearly be seen from these curves how the probability of survival would change depending on the failure criterion selected. The failure criterion is the number of spalled cracks per survey section (305 m) that the pavement engineer would consider as failure. Therefore the pavement engineer need not decide beforehand what the failure criterion for spalling should be. Different design curves can be developed for different failure criteria (as shown in Figure 4), or the probability of survival can be directly calculated by using the model for each failure criterion. A survivability curve during the lifetime of a pavement that has a steep drop during the first few years would be inappropriate because it is an indication of possible fast deterioration (spalling) of the pavement.

TABLE 2 Statistical Parameters Pertaining to Model Development

Statistical Parameter		Model for Siliceous Gravel	Model for Crushed Limestone
Log Likelihood		2241	1019
α	Parameter Estimate	2.01	0.31
	Standard Error	0.14	0.12
	Chi-Square	201.0	6.3
	Pr>Chi	0.0001	0.0121
β_1	Parameter Estimate	0.027	0.009
	Standard Error	0.002	0.0046
	Chi-Square	176.7	3.39
	Pr>Chi	0.0001	0.0655
β_2	Parameter Estimate	-0.00053	0.000231
	Standard Error	0.0001	0.00027
	Chi-Square	15.73	0.75
	Pr>Chi	0.0001	0.39
σ	Parameter Estimate	1.34	0.85
	Standard Error	0.029	0.02

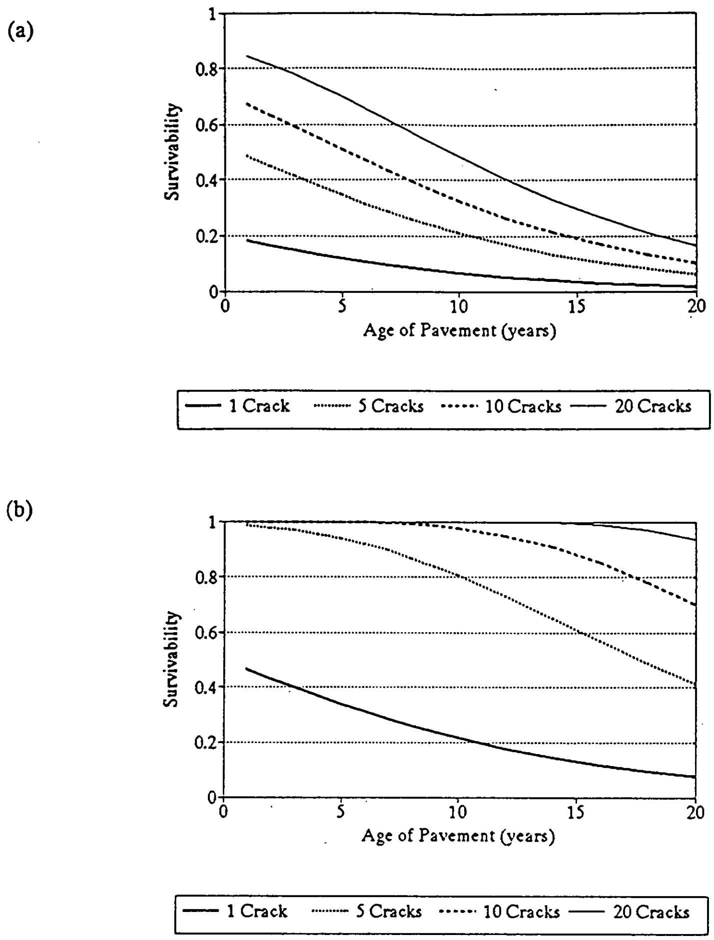


FIGURE 4 Survivability curves for different failure criteria for concrete pavements made with (*a*) siliceous river gravel and (*b*) crushed limestone coarse aggregate.

Shown in Figures 5(*a*) and 5(*b*) are the predicted number of spalls per survey section for pavements with siliceous river gravel and crushed limestone coarse aggregate types, respectively. Different curves are provided for three levels of reliability (50, 90, and 99 percent). It should be noted that a 90 percent reliability would mean that 90 percent of the original field data would fall below this level.

CONCLUSION

Preliminary analysis of spalling data identified the coarse aggregate type, level of traffic, rainfall, and subbase type as the best predictors of the level of spalling. Parameters such as ambient relative humidity and temperature, periodic temperature fluctuations, and concrete strength are not available in the data base but are nevertheless considered important predictors of spalling. Even though this lack of available data prevents the use of all of these parameters in the modeling process, a more complete model could be developed by accommodating all of these variables.

The proposed modeling method that uses survival analysis appears to be a promising tool for predicting the occurrence of spalling and the level of spalling at a certain time. This technique can be used not only for spalling but for other pavement distresses as well.

The proposed mechanistic model can be extended to incorporate damage as a covariate instead of having separate covariates in the form of cumulative traffic and temperature change. This can be achieved by developing a method of calculating fatigue damage primarily from the application of wheel loads and restraint stresses because of daily temperature changes while incorporating the effects of rainfall and subbase type as well.

Once damage is included in the spalling prediction model, two other important steps need to be taken. First, calibration of the model to account for local pavement conditions is important. The scatter visible in Figure 5 is an indication that more refinement of the data, particularly the calibration of the data to relate design parameters to local conditions, is necessary. This can be done once data such as initial environmental conditions at the time of paving are known. Also allowance must be made for variability in the design parameters by using statistical techniques (Lyton, R. L., and D. G. Zollinger. Modeling Reliability in Pavement. Presented at 72nd Annual Meeting of Transportation Research Board, Washington, D.C., 1993).

The design framework proposed in this paper incorporates data that can be easily measured or that are readily available. Thus,

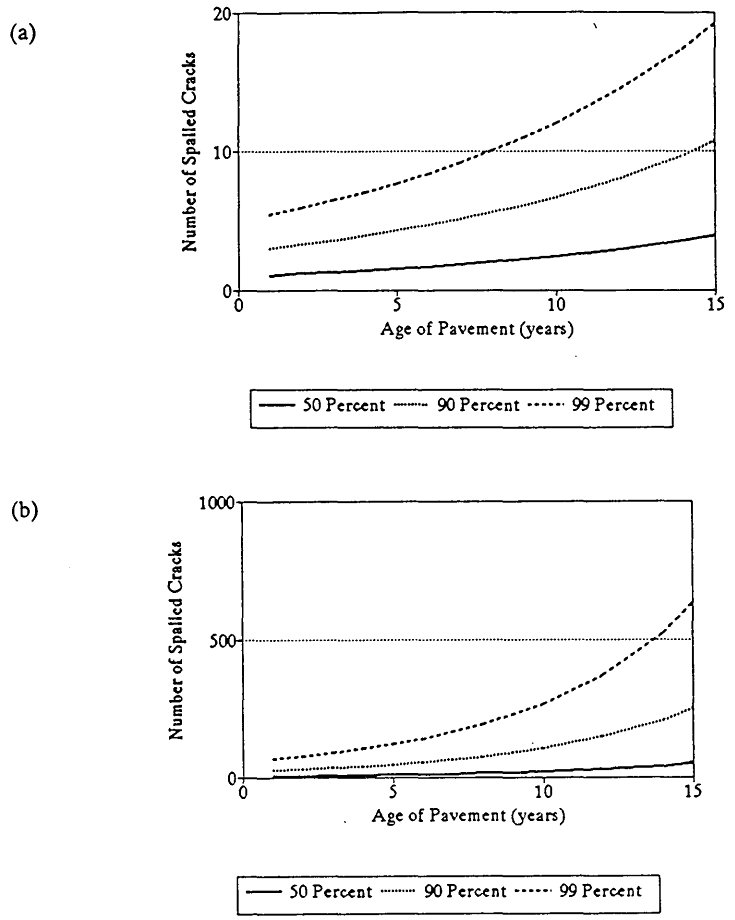


FIGURE 5 Predicted number of spalled cracks for different levels of reliability in pavements made with (*a*) siliceous river gravel and (*b*) crushed limestone coarse aggregate.

models such as those in Equations 14 and 15 can be developed for different localities and climatic conditions.

ACKNOWLEDGMENTS

This paper is based on the results of a cooperative study between the Texas Department of Transportation and the Texas Transportation Institute of the Texas A&M University System. The study is sponsored by the Texas Department of Transportation and FHWA.

REFERENCES

1. Lee, E. T. *Statistical Methods for Survival Data Analysis*, 2nd ed., John Wiley & Sons, Inc., New York, 1992.
2. Zollinger, D. G., and E. J. Barenberg. *Continuously Reinforced Pavements: Punch-outs and Other Distresses and Implications for Design.* Research Report FHWA/IL/UI 227. Department of Civil Engineering, Illinois Department of Transportation, University of Illinois, Urbana, March 1990.
3. Darter, M. I., and K. T. Hall. *Structural Overlay Strategies for Jointed Concrete Pavements*, Vol. IV. *Guidelines for the Selection of Rehabilitation Alternatives.* Report FHWA-RD-89-145. FHWA, U.S. Department of Transportation, Jan. 1990.
4. Zollinger, D. G., S. P. Senadheera, and T. Tang. Spalling in Continuously Reinforced Concrete Pavements. *Journal of Transportation Engineering, ASCE,* Vol. 120, No. 3, May–June 1994.
5. Dossey, T., and A. Weissmann. *A Continuously Reinforced Concrete Database.* Research Report 472-6. Center for Transportation Research, University of Texas at Austin, Nov. 1989.
6. Shelby, M. D., and B. F. McCullough. Experience in Texas with Continuously Reinforced Concrete Pavement. *Bulletin 274,* HRB, National Research Council, Washington, D.C., 1960.
7. Gutierrez de Velasco, M., and B. F. McCullough. *Summary Report for 1978 CRCP Condition Survey in Texas.* Research Report 177-20. Center for Transportation Research, University of Texas at Austin, Jan. 1981.
8. McCullough, B. F., J. C. M. Ma, and C. S. Noble. *Limiting Criteria for the Design of CRCP.* Research Report 177-17. Center for Transportation Research, University of Texas at Austin, 1979.
9. Tracy, R. G. *Deterioration of Continuously Reinforced Concrete Pavement in Minnesota—An Overview.* Research and Development Section, Minnesota Department of Transportation, Aug. 1978.
10. *NCHRP Synthesis of Highway Practice 60: Failure and Repair of Continuously Reinforced Concrete Pavement.* TRB, National Research Council, Washington, D.C., 1979.
11. McCullough, B. F., A. Abou-Ayyash, W. R. Hudson, and J. P. Randall. *NCHRP Report 1-15: Design of Continuously Reinforced Concrete Pavements for Highways.* TRB, National Research Council, Washington, D.C., Aug. 1975.
12. Tayabji, S. D., and B. E. Colley. *Improved Rigid Pavement Joints.* FHWA Research Report FHWA/RD-86/040. Construction Technology Laboratories, Skokie, Ill., 1986.

13. van Wijk, A. J. *Purdue Economic Analysis of Rehabilitation and Design Alternatives for Rigid Pavements: A User's Manual for PEARDARP*, FHWA Contract DTFH61-82-C-00035. Final Report. FHWA, U.S. Department of Transportation, Sept. 1985.
14. Kopperman, S., G. Tiller, and M. Tseng. *JCP-1: Interactive Microcomputer Version, User's Manual: IBM-PC and Compatible Version.* Report FHWA-TS-87-205. FHWA, U.S. Department of Transportation, Jan. 1986.
15. Smith, K. D., A. L. Mueller, M. I. Darter, and D. G. Peshkin. *Performance of Jointed Concrete Pavements*, Vol. II. *Evaluation and Modification of Concrete Pavement Design and Analysis Models.* Research Report FHWA-RD-89-137. ERES Consultants, Savoy, Ill., 1990.
16. Dossey, T., and W. R. Hudson. *Distress Curves for CRCP Crack Spalling.* Technical Memorandum 1908-12. Center for Transportation Research, University of Texas at Austin, Oct. 1992.
17. McCullough, B. F., and D. G. Zollinger. *Compendium of Research Activities To-Date: Evaluation of the Performance of Texas Concrete Pavements Made with Different Coarse Aggregates.* Texas Department of Transportation, Center for Transportation Research of the University of Texas at Austin, and Texas Transportation Institute of the Texas A&M University System, May 1993.
18. Kalbfleisch, J. D., and R. L. Prentice. *The Statistical Analysis of Failure Time Data.* John Wiley & Sons, Inc., New York, 1980.
19. *SAS/STAT® User's Guide*, Release 6.03 Edition. SAS Institute Inc., Cary, N.C., 1988.

Publication of this paper sponsored by Committee on Rigid Pavement Design.