

DEVELOPMENT OF A LONG-TERM MONITORING SYSTEM FOR TEXAS CRC PAVEMENT NETWORK UTILIZING EXPERIMENTAL DESIGN

Chia-pei J. Chou and B. Frank McCullough
Center for Transportation Research
The University of Texas at Austin
Austin, Texas

A network level performance condition survey to collect the distress information on continuously reinforced concrete pavements (CRCP) in Texas has been conducted bi-yearly since 1974 (except for 1976). From the recorded data, it has been observed that, while riding quality remains at an acceptable level from the user's point of view, some rigid pavement sections are approaching the ends of their lives from the structural viewpoint. Using distress conditions is, therefore, considered to be a more realistic way than serviceability index to evaluate the performance of a rigid pavement, and the condition survey should be continued in order to establish a long-term monitoring system on the CRCP network. In addition, more detailed information, such as pavement deflection, should be collected, along with visual distress manifestations, and some fundamental information, e.g., coarse aggregate type, temperature, and rainfall, for each project should also be collected for use with the condition survey data. However, it is not efficient and economical to conduct a condition survey on every pavement project. Thus, an experiment design covering the most important variables is considered to be the best method to achieve above purposes.

The primary objective of this study was to develop an experimental design for the network level condition survey for evaluating CRCP pavement performance in Texas. In addition to developing experimental design, other major contributions include (1) developing the distress and decision criteria indices for determining the current pavement distress condition and the time when a pavement reaches its terminal condition and (2) developing the data bank for fundamental information and historical distress manifestations for pavement networks. Figure 1 is a flow chart showing the research approach used in this study. The equation of distress index was indices were developed using discriminant analysis of the condition survey data and is a weighted combination of several distress manifestations occurring in a pavement section. The decision criterion index is a selected limiting value of the distress index. This developed equation was used to calculate the distress indices for the experimental condition survey sections. These distress indices were used to represent the pavement performance condition in the preliminary data analysis.

Several independent variables considered to influence pavement performance were selected as the experimental factors, based on the study of the AASHTO equations, field data analysis, and mechanistic models. These variables include pavement design and construction parameters, environmental parameters, traffic, and

pavement age. The information regarding these selected experimental factors was, then, collected from various sources for the entire CRCP network as the pavement fundamental information. This information and the data collected for the experimental condition survey have formed a very complete data bank of information for pavement evaluation and performance prediction.

Several experimental factorials were established based on the different levels of experimental factors which cover the wide range of conditions existing in Texas. Using in-service projects, test sections were chosen to satisfy the cells in these experimental factorials. A total of 425 test sections from 112 pavement projects were surveyed in this study.

A preliminary data analysis was performed to investigate the general relationship between the independent variables and pavement performance. This relationship can be used in further studies to develop the most applicable pavement performance prediction model.

SUMMARY

The primary objective of this research was to develop an experimental design for the network level condition survey in order to develop a long-term monitoring system for Texas continuously reinforced concrete (CRC) pavement.

The objectives of this paper are to provide an example for others for developing the experimental design and an analysis methodology and presenting results of a preliminary analysis. In addition to the experimental design, other major contributions include developing the distress index ($DI(t)$) and decision criteria index ($DCI(t)$) for determining the current pavement distress condition and the time when a pavement has reached its terminal condition. The distress index was developed using discriminant analysis of the condition survey data for 1974 to 1984. It is a weighted combination of several major distress manifestations occurring in a pavement section. For major rehabilitation, a pavement is classified as a candidate for overlay if its distress index is smaller than zero. Once the current pavement distress condition can be expressed as a single number, i.e., as a Zeta score, its future condition can be predicted from the relationship between the Zeta score and some independent variables considered to have an influence on pavement deterioration. However, this relationship can not be obtained unless sufficient distress information is available from a well-planned condition survey conducted periodically for years.

The approach adopted in this study for determining the relationship was to monitor existing in-service roads. A

factorial experiment permitting maximum use of data collected on a limited number of study test sections was designed. Several independent variables were selected as the experimental factors, based on the study of the AASHTO equations, field data analysis, and mechanistic models. The experimental factors possess control levels which cover a wide range of conditions existing in Texas. Since no information regarding these selected experimental factors is available in the existing distress data bank, data were collected from various sources for the entire CRCP network.

Eight experimental factorials were established, based on the different levels of experimental factors and whether the pavement project was overlaid or not. From the 355 projects in the CRCP network, 112 projects were selected. Definitions and methods for measurement of surveyed variables were presented in this study. A pilot study and training session were scheduled prior to the network experimental condition survey in order to investigate the feasibility of using the proposed measurement methods and survey forms. It was found that no change was necessary for either one.

Fourteen districts of the Texas State Department of Highways and Public Transportation (SDHPT) were included in the experimental condition survey. A total of 425 test sections were selected from the 112 pavement projects. The distress condition of each test section was calculated using the distress index equation. It was found, through the preliminary data analysis, that most design experimental factors or their interactions, e.g., roadbed profile characteristics, rainfall and soil type, coarse aggregate type, etc., have significant influence on the Zeta-score and pavement mean crack spacing. These significant effects implied that the applicable performance prediction model, in which distress is a function of the various experimental factors, should be developed in further data analysis.

BACKGROUND

The Texas SDHPT has about 5,600 lane-miles of CRCP currently in service, and present departmental tasks are focussed on the maintenance, overlay, and rehabilitation of many miles of CRCP. The expenditures required to maintain and rehabilitate pavements in Texas have been estimated to exceed \$400 million per year (1). Because of the large amount of money involved, any improvement in the management and technology for maintenance, overlay, and rehabilitation could result in significant savings. In addition, some of the existing CRCP were found to be either under or over designed. The development of a reliable design procedure for new roadways is considered to be one of the most important tasks at the present time. It is necessary to periodically collect condition and behavior data on the in-service highway so that the pavement performance can eventually be predicted, thus a design procedure can be developed and improved with continued observations.

A network level performance condition survey to collect the distress information on the CRCP in Texas has been conducted bi-yearly since 1974 (except for 1976) by the Center for Transportation Research (CTR) of the University of Texas at Austin. Every mile of each project was surveyed using 0.2-mile units. The collected information has formed a very complete data bank of historical CRCP distress condition. From the recorded data, it has been observed that, while riding quality remains at an acceptable level from the user's point of view, some pavement sections are approaching the ends of their lives from the structural or economic viewpoint (2). Therefore, the use of distress condition is considered to be a more realistic way than serviceability index to evaluate the performance of a CRCP.

It is also recognized that pavement distress manifestations are affected by an unlimited number of factors; however, no information regarding design and construction variables, environmental condition, and traffic data were recorded in the data bank. Since it is not possible and feasible to cover all variables, the most important factors should be evaluated, collected, and stored in the distress data bank for use in predicting pavement structure performance. These factors are called the fundamental information on pavement sections in order to distinguish them from the distress information in the data bank. A performance prediction model can be obtained through the development of the relationship between pavement distress condition and these influential factors. Since there are more than 350 pavement projects in the CRCP network in Texas, an experiment design factorial considering the influential factors as the variables and the observed distress manifestations as the observed measurements from samples of the network level survey is the most appropriate and economical method for establishing the relationship.

Therefore, this study utilizes experiment design concepts for sampling the network condition surveys, pavement performance evaluation, and prediction analysis. Special emphasis is placed on the development of a network rehabilitation and maintenance scheme. In the following sections a detailed description of the development of experiment design is presented.

RESEARCH APPROACH

The approach adopted for determining pavement performance and the prediction model was to monitor existing in-service roads. Figure 1 is a flow chart showing the research approach used in this study. In general, the concepts of this research study can be briefly divided into three parts of developing: the distress index (DI), the decision criteria index (DCI), and the performance prediction model ($DI(t)$).

Figure 2 conceptually lays out the relationships among DI, DCI, and $DI(t)$. For a given pavement project at a point in time, t_k , the DI_k is calculated from the actual condition survey data. With time, Δt , that pavement's DI value decreases from DI_k to the critical DI_{LV} (limiting value), i.e., an observed performance model. The intersection of the DI_{LV} dash line and $DI(t)$ curve is considered as the point at which the pavement reaches its terminal condition, i.e., failure.

Since the prediction model is a function of time, well-planned condition surveys should be conducted periodically for years in order to obtain enough information for the development of the model. Therefore, in this study, a distress index and a decision criteria index were developed first, through an investigation of the historical condition survey data, and an experiment permitting maximum use of data collected on a limited number of study test sections was then designed for this purpose.

A preliminary data analysis was studied to investigate the general relationship between the most influential variables and pavement performance. This relationship can be used in further studies to develop the most applicable pavement performance prediction model.

DISTRESS INDEX (DI)

By reviewing existing schemes for maintenance and rehabilitation management, it was found that the pavement serviceability index (PSI) was used nationwide for major rehabilitation or overlay decisions. The PSI measure developed by Carey and Irick was used at the AASHTO Road

Test (3). The relationship revealed that pavement serviceability is largely a function of its roughness.

A study of the existing network level maintenance and rehabilitation prioritization methods (4) concluded that a prediction model considering only the serviceability index is not applicable to CRC pavements in Texas. The serviceability history of a pavement with heavy maintenance does not appear to change with time or traffic, while the distress condition does. Therefore, it is not uncommon for a pavement section to be approaching the end of its life from the structural or economical point of view while the riding quality remains unchanged. Thus, the use of distress measures may be a more realistic way to evaluate a pavement's terminal condition.

After several methods were reviewed, discriminant analysis (5, 6, and 7) was selected for the development of the distress index used in this study, because it appeared to be the most appropriate technique for the data available and because of the encouraging results.

Discriminant Analysis

Discriminant analysis is a statistical technique used to classify data into groups by maximizing the differences among group means. To distinguish among the groups, a collection of discriminant variables that measure characteristics on which the groups are expected to differ should be made. The mathematical objective of discriminant analysis is to weigh and combine linearly the discriminant variables in some fashion so that the groups are forced to be as statistically distinct as possible.

In this study, the historical data are separated into two groups, overlaid and non-overlaid pavements. Each datum point of each group consists of several distress manifestations, such as spalling, punchouts, and patches, which represent the distress condition of a specific section in a specific surveyed year. By using discriminant analysis, one or more composites, or discriminant functions, of the distress variables will be derived so that the composite(s) can construct a boundary which minimizes the overlap in the distribution of the discriminant scores of the different groups. The discriminant score is the value of the composite function for a particular datum. Ideally, the discriminant scores for the cases within a particular group will be fairly similar. The maximum number of discriminant functions which can be derived is either one less than the number of groups or equal to the number of discriminant variables, if there are more groups than variables. Since only two pavement groups are involved in this study, one function is derived.

The inputs for the discriminant analysis are historical condition survey data, including various distress types and their corresponding groups. The results of the analysis are the discriminant function, a mathematical equation, and its relative magnitude, which can be used as a distress index. In addition, the percentages of analyzed data which were correctly classified into either correspondent group are given. Once the equation is developed, data for any new project can be assigned to one of the predetermined groups by calculating its discriminant score and comparing it with the boundary between the groups (2).

Analysis

The discriminant function (equation) developed in the analysis to discriminate between groups is of the form

$$Z_i = \sum_{j=1}^m a_j z_{ij} ; (i=1, \dots, n, \text{ and } j=1, \dots, m) \quad (1)$$

where

- Z_i = discriminant score of the i^{th} observation (pavement project),
- a_j = weighting coefficient for the j^{th} discriminant variable,
- z_{ij} = standardized value for the i^{th} observation and the j^{th} discriminant variable (distress measure) used in the analysis,
- n = total number of observation, and
- m = total number of the discriminant variables.

The standardized values, z_{ij} , are calculated as follows:

$$z_{ij} = \frac{x_{ij} - \bar{x}_{.j}}{\sigma_{x_{.j}}} \quad (2)$$

where

- x_{ij} = value of j^{th} distress manifestation, for the i^{th} observation being classified;
- $\bar{x}_{.j}$ = mean value of the j^{th} distress manifestation; and
- $\sigma_{x_{.j}}$ = standard deviation of $x_{.j}$ which is equal to $\left[\sum_{i=1}^n (x_{ij} - \bar{x}_{.j})^2 / (n-1) \right]^{1/2}$

As may be seen in Eq 1, the discriminant function is linear, but it may not produce a realistic characterization. However, the statistical program requires a linear form and any non-linear transformation of the discriminating variables should be made before this program is used. Several transformation models have been tested, including multiple linear, second degree polynomial, and natural logarithm. The logarithm method shows the best analysis results. It is also the most commonly used transformation for "growth" type data, e.g., distress evolution, and cases where the mean is proportional to the standard deviation, which is the case in this study (2).

Based upon the findings of the above analysis, Eq 2 is modified to the following form while Eq 1 remains unchanged:

$$z_{ij} = \frac{\ln(x_{ij} + 1) - \bar{x}'_{.j}}{\sigma_{x'_{.j}}} \quad (3)$$

where

- x_{ij} = same as defined before,
- $\bar{x}'_{.j} = \frac{\sum_{i=1}^n \ln(x_{ij} + 1)}{n}$,
- n = data, both overlaid and non-overlaid groups, and
- $\sigma_{x'_{.j}}$ = standard deviation of $[\ln(x_{ij} + 1)]$.

Results

Table 1 summarizes the parameters to be used in Eq 3. The variable "patch" is the sum of asphalt concrete and portland cement concrete failure patches. It was decided that inclusion of the minor and severe spalling terms in the equation would be misleading because of their negative signs. In addition, the two terms have relatively small coefficient values compared to the other three variables. Thus, another equation of the same form as Eq 3 was developed without considering the terms of minor and severe spalling. Table 2 gives the values of parameters used in the new equation. After the introduction of the total means and derivation of the distress variables from Table 2 in Eqs 1 and 3 and several modifications, the final equation used to calculate the Distress Index, Zeta-score, is

$$Z = 1.0 - 0.0071 (\text{MPUNT}) - 0.3978 (\text{SPUNT}) - 0.4165 (\text{PATCH}) \quad (4)$$

where

$$\begin{aligned} Z &= \text{distress index or Zeta-score,} \\ \text{MPUNT} &= \ln (\text{minor punchouts per mile} + 1), \\ \text{SPUNT} &= \ln (\text{severe punchouts per mile} + 1), \text{ and} \\ \text{PATCH} &= \ln (\text{total patches per mile} + 1). \end{aligned}$$

There were 882 data points, the population of historical survey data for the CRCP network in Texas, included in the derivation of the discriminant equation. This data set is composed of 826 non-overlaid and 56 overlaid sections.

A frequency distribution for each of the two groups is plotted (against the Zeta-score) on one continuous horizontal axis (Fig 3). It should be emphasized that the individual Zeta-score will not have the same distribution pattern about each group mean because of the different characteristics in nature. The historical distress record of any specific pavement project always starts from its best condition, i.e., no distress, and increases with time and traffic until the unacceptable condition before overlay. Thus, there exists a high bound, the best condition, in the Zeta-score distribution of the non-overlaid group, while the Zeta-score of the overlaid group tends to be normal distribution. The shadowed area indicates the overlap of the two distributions. The right half represents the probability (α) that a pavement which should be overlaid is misclassified into the non-overlaid group. Likewise, the left half indicates the probability (β) that a pavement is classified into the overlaid group while it is still above the acceptable level. In order to simplify the rehabilitation decision making about the Zeta-score, it was assumed the total costs, including agency and user costs, of overlaying a pavement when it should not be overlaid is equivalent to the total costs of not overlaying pavement when it should be. The Zeta-score of zero is, therefore, considered to be the appropriate value to separate the two groups in this study, since it can equally divide the shadowed area into two parts and make $\alpha = \beta$ = possible minimum value = 7.4 percent. Table 3 summarizes the probability of correct prediction for both groups by Eq 4.

In Eq 4 the most important variable that affects the Zeta-score is PATCH (patches), followed by SPUNT (severe punchouts) and MPUNT (minor punchouts). It was noted that approximately 11 patches or 12 severe punchouts, calculated from Eq 4, per lane-mile necessitates that a pavement project be overlaid when the other distress variables are all zeros. The final equation correctly classified 92.6 percent ($1 - \alpha$) out of the 882 cases. The cases used to test the prediction capability

of the discriminant equations were the same as the ones used to develop the equation. Hence, for any particular pavement, data on each distress manifestation should be substituted into Eq 4 in order to obtain a Zeta-score, the distress index for that pavement.

DECISION CRITERIA INDEX (DCI)

As defined earlier, DCI is the selected limiting value of distress index. Based on Eq 4, the criterion for major rehabilitation is that a pavement would be classified as a candidate to be overlaid if its distress index, Zeta-score, is smaller than zero. On the contrary, if a pavement's Zeta-score is equal to or greater than zero, the pavement is in good condition and does not need an overlay.

EXPERIMENTAL DESIGN

In order to carry out the network level performance condition survey for developing the relationship between CRCP performance and the various influential designated variables, an experiment was designed for this purpose. Variables which were considered to have significant influences on pavement performance should be included as experimental factors and various levels of each factor should also be assigned in order to obtain a complete factorial experiment.

Experimental Factors

A list of all the possible variables is prepared first. It includes variables of pavement design, construction, environment, traffic, and age. Evaluation of these variables from both empirical, (AASHTO equation, Ref 8 and field survey data), and theoretical, (CRCP mechanistic model, Ref 9), points of view was made in order to select the most significant variables out of the list. The empirical models usually involve statistical analysis to fit an equation to field data; that is, the data are used to generate the model. The theoretical models utilize established mechanical principles and variables to estimate a pavement response. An important difference between the two types of models is that mechanical models are bounded by the hypothesis used in its derivation, while empirical models are bounded by the maximum ranges of the data used in the analysis.

After the evaluation, the selected variables from either empirical or theoretical analysis were combined together, further analyzed, and reduced to a reasonable number. Since each design factor has two or more different levels, the number of experimental design factors should be kept as small as possible that the designed factorial will not be too complex.

Additional restrictions for all pavement projects were imposed upon the available variables in order to insure the quality and homogeneity of the information actually used. The initial quality control mechanism required that all data parameters utilized be common to every pavement project, so that pavement sections not included in the experimental design might make future use of the finding obtained from this study. Another imposed restriction required all experimental factors to be readily obtainable. Seven factors and one subfactor were finally chosen for this experimental design. Table 4 summarizes the final results of the experimental factors and the corresponding levels.

Variables to be Measured

Due to the different characteristics of distress manifestations between the overlaid and non-overlaid pavements, two sets of variables were generated from the empirical and the theoretical analysis as the items to be measured in the experimental condition survey. A brief description of each variable is given below.

Non-Overlaid Pavements.

- (1) **Crack Spacing.** The distance in feet between transverse cracks.
- (2) **Crack Width.** The width of opening of transverse cracks.
- (3) **Punchout.** Closely spaced transverse cracks linked by longitudinal cracks to form a block.
- (4) **Patch.** A repaired section of the pavement where the repair work has been carried out to the full depth of the concrete slab.
- (5) **Traffic (ESAL).** Number of accumulative 18 kip equivalent single axle loads per lane.
- (6) **Roughness.** Pavement surface profile information collected either by profilometer or Mays Ride Meter.
- (7) **Deflections.** Surface deflection measurements using the Falling Weight Deflectometer.
- (8) **Shoulder Condition.** General shoulder performance information

Overlaid Pavements.

- (1) **Reflected Cracks.** Cracks and joints of the underlying pavement reflected into the upper, overlay, layer.
- (2) **Bond Failure.** The condition in which the overlay has separated from the underlying layer of an area of the pavement, exposing the original pavement.
- (3) **Failure.** The condition in which punchouts and patches have reflected through and which will soon require patching.
- (4) **Patches.** Repaired failures found in the overlay are recorded as patches.
- (5) **Rut Depth.** Rutting is a form of permanent deformation in the wheel path caused by consolidation of one or more of the paving layers.
- (6) **Traffic (ESAL).** Number of accumulative 18 kip equivalent single axle loads per lane.
- (7) **Roughness.** Pavement surface profile information.
- (8) **Deflections.** Surface deflection measurements.
- (9) **Shoulder Condition.** General shoulder performance information.

Experimental Factorial

Once the factorial design factors and measured variables had been determined, the next step was to collect the

information about experimental factors for the entire CRCP network. These data were stored as a SAS data set (10). However, since only limited levels of each factor were chosen for the experimental factorial, data reduction became necessary in order to create the appropriate population for each factorial cell. It was found that 262 out of 355 pavement projects in the CRCP network qualified for the experimental design because of their corresponding levels of experimental factors.

Owing to the policies of the FHWA regarding roadway construction during the period from 1950 - 70's, a very large portion of the CRCP sections in Texas have slabs 8 inches thick. Despite the unbalanced distribution, pavement thickness remains a design parameter in the factorial in order to evaluate its effects on pavement performance.

It was noted that 104 out of the 262 pavement projects had been overlaid once or more during their service lives. In order to compare the pavement performance of overlaid and non-overlaid sections, the pavement projects were separated into two categories, overlaid and non-overlaid. Hence, two sets of factorials were formed.

It should be noted that the procedure for factorial design used in this study is different from the conventional design procedure. The latter uses the completely randomized design method, in which the experimental units are drawn from the populations and randomly assigned to the treatment combinations of the levels of all the factors. The method developed in this study was similar to stratified sampling. The CRCP segments were first divided into groups based upon the properties of the experimental design factors, and then samples within each group or stratum were independently selected into factorial cells (treatment combinations).

As mentioned earlier, unbalanced factorials are unavoidable in this experiment design, and some factorial cells have more than ten highway sections while others have only one, two, or even no experimental units. The first criterion of test section selection is concerned with the number of sections that should be randomly selected from each factorial cell to represent that specific treatment combination. The following rules were determined in this study.

1. For factorial cells which have one to four highway projects, one project is selected.
2. For factorial cells which have five or more highway projects, two projects are selected.

The sample project must be random and without replacement. There were 112 pavement projects selected for the factorial design.

Test Section Selection

After the pavement projects are selected from the factorial cells, the next step is to select test sections from these projects. The test sections are the survey units on which the condition survey will be conducted. The criteria for selecting the test section are given as follows.

1. **Length of Test Section.** The unit length of sections for the condition survey was determined to be 1000 feet (0.2 mile) because that was considered to be the average distance that the roadbed construction is consistent as far as being cut, fill, or at grade.
2. **Number of Test Sections Selected from Each Project.** The number of test sections for each project is dependent on the length of that specific project. If its length is shorter than or equal to 3.0 miles, one cut, one fill, one at grade, and one transition section between a cut and a fill should be selected. If the project is more than

3.0 miles long, two cut, two fill, one at grade, and one transition should be selected. A test section with either cut, fill, at grade, or transition section can be in the tangent part or the horizontal curve of the highway section.

3. **Cut and Fill.** A cut and fill section is one where the pavement surface has a difference in height of 5 feet or more compared to the adjacent land. Figure 4 shows a typical longitudinal profile, which includes a cut, a fill, at grade, and a transition.

Each survey team consists of two persons. The surveyors check the length of each selected project and decide the number of test sections to be measured in that project, based on the above criteria.

CONDITION SURVEY

As described earlier, two categories of variables, non-overlaid and overlaid, are to be measured in the designed condition survey. In each category, many variables are amenable to measurement; for each variable there may be many alternative measurement procedures, and each of which provides a certain amount of information about the variable being measured. Several previous studies were reviewed (4, 6, 11, 12, 13, and 14), and then the measurement methods for this study were established. Because of the different degrees of complexity of these measurement methods, the field work was separated into two parts, a general condition survey and a diagnostic study. The general condition survey consists of items which need only visual measurements and/or some simple tools, such as a Rolatape. The measurement program of the diagnostic study is more extensive than the general condition survey and traffic control is required during the survey. Data collected for the diagnostic study consists of rut depth, crack width, deflection, and roughness. In this paper, only the measurement methods for the general condition survey are briefly described.

Measurement Methods

The numbers of punchouts and patches for non-overlaid sections and the bond failures, failures, and patches for overlaid sections were recorded separately for every 200 feet of the test section. The actual crack spacing of the first 200 feet of the test section is recorded, to the nearest 0.1 foot, using a Rolatape. For the remaining 800 feet, the number of cracks and reflected cracks are counted. Data collection is conducted only on the outside lane of the roadway, however, because it is assumed it has the poorest performance.

Besides the roadway, it is necessary to record the shoulder conditions: whether there is any distress on the shoulder, whether it has been repaired, and whether there is a difference in level between the shoulder and the pavement. Any occurrence of cracking and shoving on the shoulder should be noted. This information usually gives a good indication of any subsurface drainage problems.

PRELIMINARY DATA ANALYSIS

Data collected from the experimental condition survey can be analyzed on a number of levels, but the approach used in this pilot study consists of isolating each of the different experimental factors and also combining some of the factors, such as soil type and rainfall, to define qualitatively the effect of each variable parameter or of combined parameters on the

performance of the pavement. Although several distress manifestations and crack data were recorded, the distress index (Zeta-score) and crack spacing were selected as the indicators of pavement performance in the analysis, since the Zeta-score is the weighted combination of punchouts and patches.

The first step was to select the parameters which may have an important influence on the deterioration of the pavement sections. Past experience and the available data constrain the analysis to the following parameters:

1. roadbed profile characteristics: cut, fill, at grade, and transition;
2. geographical location: this encompassed temperature, rainfall, and soil type;
3. concrete material type: limestone and silicious river gravel; and
4. pavement age.

It is apparent that a true isolation of the variables is not possible due to the interactions among them; thus, conclusions are drawn regarding the subject variable only from observations made under the same conditions. A more detailed analysis, taking into account the effects of all variables at different levels, should be considered in further studies.

Analysis of Distress Index

Effect of Profile Characteristics. It is not surprising to see that the profile characteristic has a significant effect on the pavement performance, particularly when it interacts with other factors, i.e., rainfall, subbase drainage, and age. In Fig 5, the average Zeta-score for different profile characteristics and different age categories in two geographical locations, Districts 3 and 13, are shown. Pavement is defined as "young" if its age is less than 15 years and "old" if it is equal to or over 15 years.

It is obvious from Fig 5 that the pavement section in the transition area, between cut and fill, has the lowest Zeta-score. In other words, the performance in the transition area is the worst among the other gradeline types. Sections with cut grading show the best performance and those at grade show the next. The fill gradeline type has a Zeta-score smaller than that at grade type, but greater than the transition. This trend is true for pavements at different geographical locations and at different ages. In addition, if a comparison is made of the various types of gradeline types by geographical location, a larger variability in performance is noted in District 13 than in District 3, which implies that other factors, such as rainfall, are influencing the results. It may be noted that District 13 is a higher rainfall area and experiences greater traffic.

Effect of Climatic Condition and Pavement Age. Climatic condition encompasses temperature and rainfall. The eastern part of the state has the highest annual rainfall and ground water, west Texas is the driest area in the state, and the lowest temperatures are recorded in the north.

In Fig 6, the mean Zeta-scores for four typical climatic conditions (Districts 4, 13, 20, and 24) for different survey years are shown. It is noted that the distress condition is worst in the eastern part of Texas (District 20), while the district located in west Texas (District 24) has the best performance. Districts 4 (north) and 13 (southeast) have similar quantitative performances; the former has the lowest temperature but little annual rain, and the latter has a higher temperature, but more rainfall. A trade-off exists between these two environmental factors.

It is noted from Fig 5 that pavement age has an important influence on pavement performance. Old pavement always has

a lower Zeta-score than young pavement for the same gradeline type in the same district. It is also observed, from Fig 6, that pavement distress condition deteriorates with age. The districts having higher moisture show a faster deterioration rate than districts in the dry area.

Effect of Rainfall and Soil Type. From the plots in Fig 7, where the influence of rainfall and soil type on the distress index is presented, it is seen that pavements, whether with swelling clay or non-swelling soil, have lower Zeta-scores if they are located in the high rainfall regions. However, the drop of Zeta-score is more rapid with increasing rainfall if pavement is constructed in a swelling clay area. The difference in the Zeta-scores of the two soil types is not significant unless the moisture factor is interacting.

Analysis of Crack Spacing

One of the most important responses of a continuously reinforced concrete pavement to the impact of traffic and environment is its crack pattern. The design methods of CRCP are based on the precept of keeping the crack pattern within certain limits in order to avoid distress leading to the failure of the pavement.

Pavement cracking usually starts right after the completion of construction, due to the temperature and moisture changes. Several other factors and their interactions affect the crack formation. In this section, some of the most important factors, i.e., coarse aggregate type, rainfall, temperature, and pavement age, are examined.

Effect of Coarse Aggregate Type. Two of the most available aggregates used in concrete slab were selected for this analysis. Concrete properties, such as tensile strength and thermal coefficient, are highly influenced by the coarse aggregate type. An overall distribution of crack spacing for the coarse aggregate types, limestone (LMS) and silicious river gravel (SRG), for the entire state is given in Figure 8. Both aggregate types have bell shaped distributions for crack spacing, on the natural log basis. It is obvious that the mean crack spacing for pavement using limestone is double that for pavement using silicious river gravel. This is primarily due to the fact that the former has a much lower thermal coefficient than the latter.

Effect of Climatic Condition. From Fig 8, it is apparent that both temperature and rainfall have drastic effects on crack spacing for LMS and SRG concrete pavements. The average annual lowest temperature (AALT) was used here with the assumption that all pavement sections were cured at the same temperature. Theoretically, crack spacing is a function of temperature drop, and temperature drop is defined as the difference between the curing temperature and the lowest temperature which the pavement experienced in the same year cycle. AALT was used in this analysis as a substitute for real temperature drop since the curing temperature is assumed to be the same for all pavement sections. A lower AALT indicates a large temperature drop. The crack spacing shows a tendency to reduce with the reduction in AALT.

Pavement sections were divided into two groups based on the rainfall. It was noted from Fig 9 that pavement located in the high rainfall area has a crack spacing smaller than that of pavements located in the low rainfall area. It was concluded that the SRG concrete pavement located in the cold, humid area has the smallest crack spacing, 2.3 feet, if the other factors are fixed.

Effect of Age. In Fig 10, the effect of pavement age on crack spacing for LMS and SRG concrete pavements is presented. In this figure, it is observed that age has more effect on crack spacing of SRG concrete than of LMS concrete. LMS concrete pavement crack spacing ranged from 5.5 feet to 6.3 feet, while the crack spacing of SRG concrete

pavement decreased from 4.5 to 2.5 feet with age. Data for this analysis are available only for ages from 10 to 24 years, but, studies done by McCullough and Chesney on specific projects showed that the crack pattern develops quickly in the first months and only a slight decrease in the mean crack spacing is seen in the following years (15). Since there are no available data to show the process of the crack spacing decrease in the early stage of pavement life, no sound conclusion can be made regarding the effect of age on crack spacing here.

CONCLUSIONS

The principal conclusions concerning the development of the distress and decision criteria Indices for the CRC pavement network are summarized as follow:

Three conclusions were drawn from the development of the Distress and Decision Criteria Indices.

1. From the historical condition survey record, it was found that, for CRC pavements, distress gives a better indication of the pavement performance condition than riding quality.
2. The distress index (Eq 4) was developed using 10 years of condition survey data with the discriminant analysis method. Punchouts and patches were the primary distress manifestations included in the distress index equation.
3. The distress index equation provides a method for ranking the rehabilitation needs for a network analysis and maintenance programming. Zeta-scores ranged from +1.0 to -1.8, with zero as the decision criterion, with a confidence level of 92.6 percent.

In relation to the development of the experimental design and pavement performance condition survey, the following conclusions have been derived.

1. Eight independent variables were selected to be the experimental factors, based on an investigation from both the empirical and the theoretical viewpoints.
2. Information regarding the experimental factors for all the CRCP network projects was collected from various sources and stored in the existing distress data bank as fundamental pavement information.
3. There were 112 pavement projects selected for the condition survey from a set of experimental factorials, using the random sampling method. Most of them were 8-inch-thick pavements. The criteria of test section selection were also established.
4. The general performance condition survey was completed in the summer of 1987. A total of 425 test sections were selected and surveyed. Distress data and other information were processed and combined with the previous distress data and pavement fundamental information.

Through the preliminary data analysis, conclusions regarding the application of the distress manifestation data base formed from the condition survey are summarized below.

1. the subgrade gradeline type has a significant influence on the distress index, the Zeta-score. In general, a pavement section in a cut shows the best performance during its life. The distress indices of the other gradeline types

decrease in the order of at-grade, fill, and transition between cut and fill.

2. The Zeta-score decreases with pavement age. In some cases, the data are confounded, because the highly distressed sections were overlaid between two adjacent surveys.
3. Climatic condition has a definitive effect on distress deterioration. Districts located in East Texas, the highest rainfall area, show the worst distress condition, while Districts located in West Texas, the dry area, have the best performance.
4. Pavements built on swelling clay have lower Zeta-scores than those on non-swelling soil. The difference becomes more significant if they are located in the high moisture region.
5. Coarse aggregate type plays an important role in the cracking pattern. Limestone concrete pavement has double the mean crack spacing of pavement with silicious river gravel.
6. No sound conclusion can be made regarding the effect of age on crack spacing for either LMS or SRG concrete pavements.

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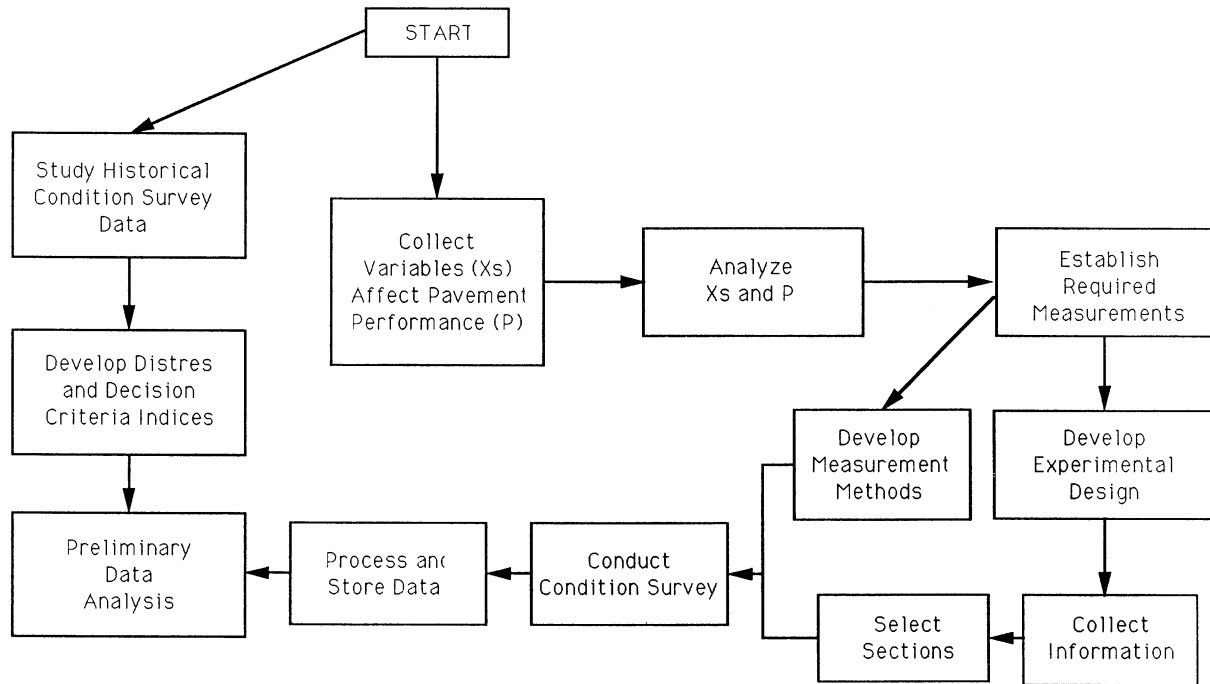


Figure 1. Flow chart of the experiment design development.

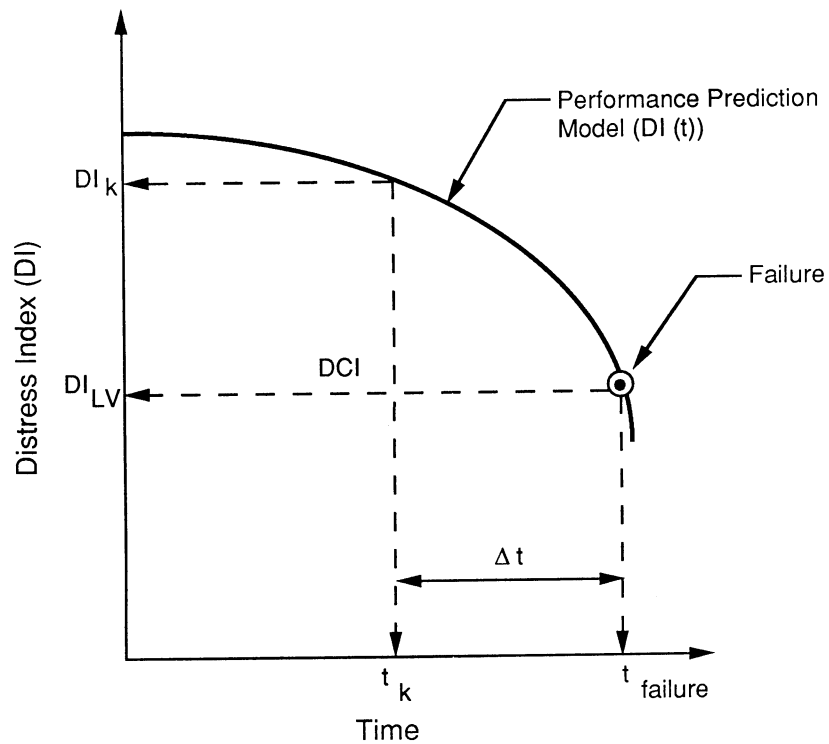


Figure 2. Failure criterion for continuously reinforced concrete pavement.

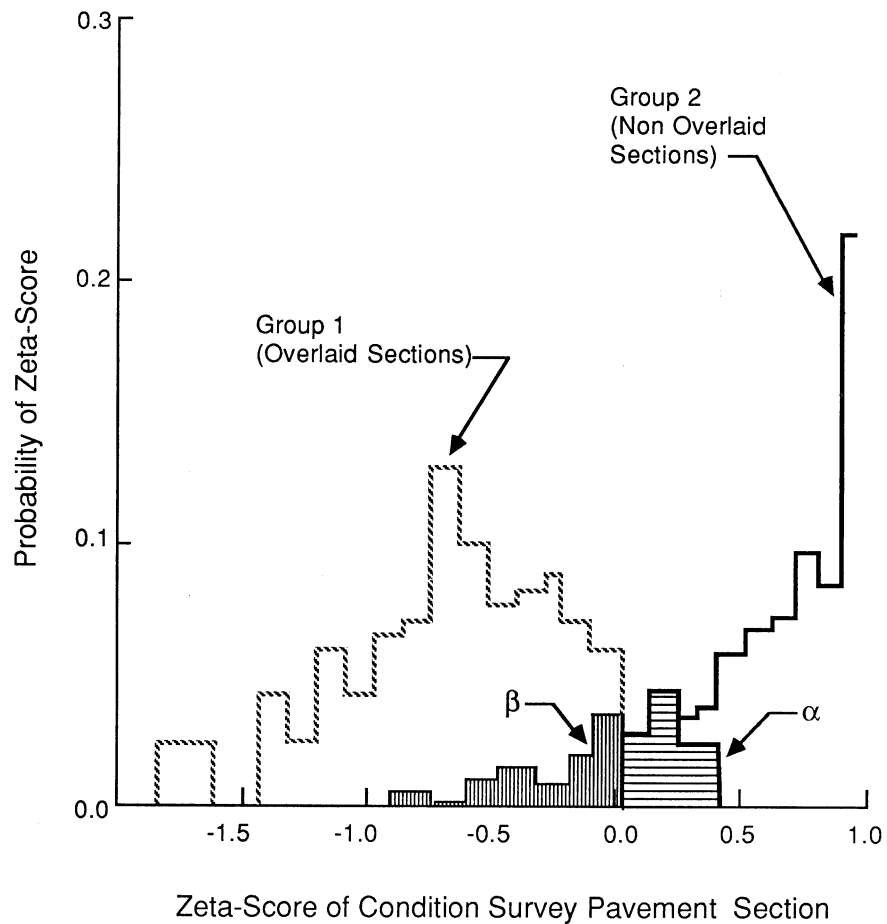


Figure 3. Modified frequency distribution of Zeta-scores based log equation for the non-overlaid and overlaid groups.

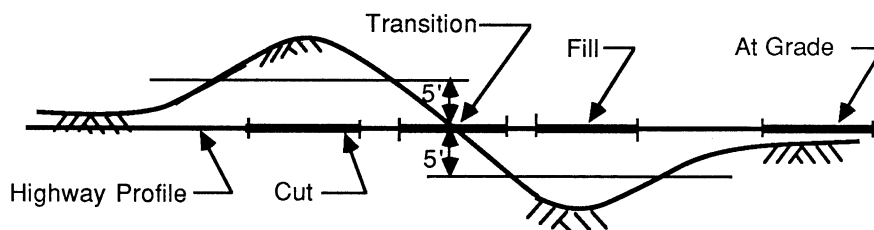


Figure 4. A highway project with cut, fill, at grade, and transition sections.

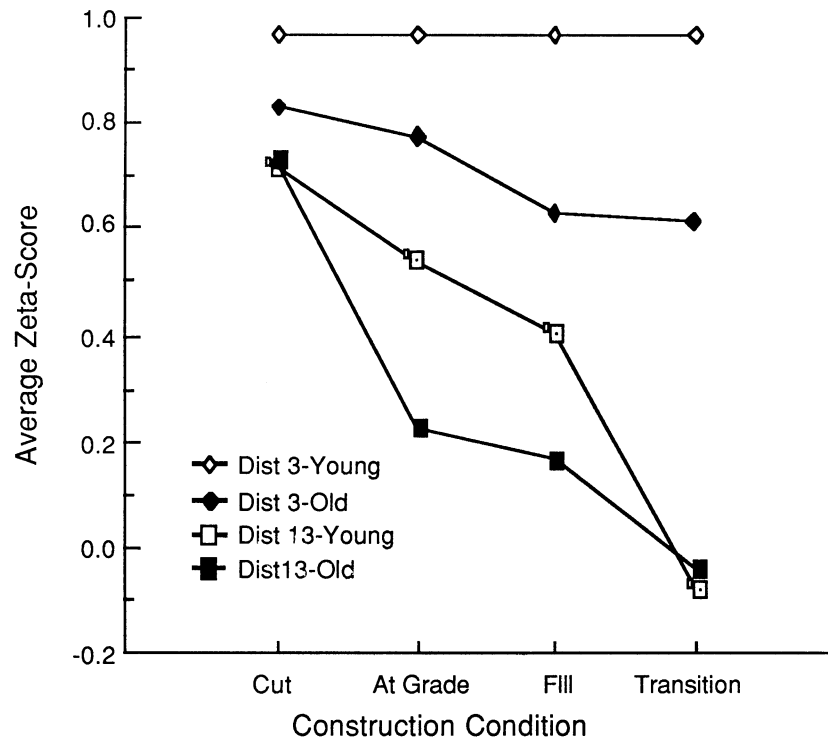


Figure 5. Effect of profile grading type and pavement age on distress index, Zeta-score.

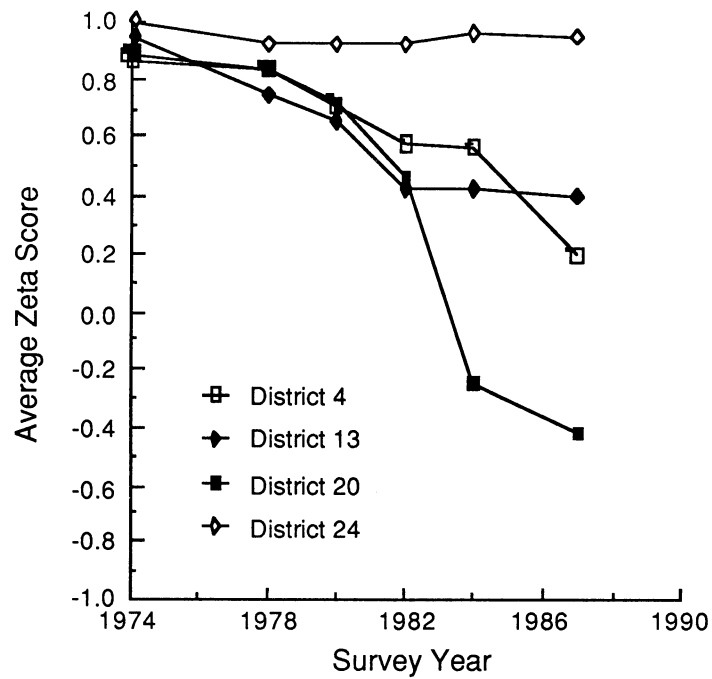


Figure 6. Effect of geographical location and pavement age on distress index, Zeta-score.

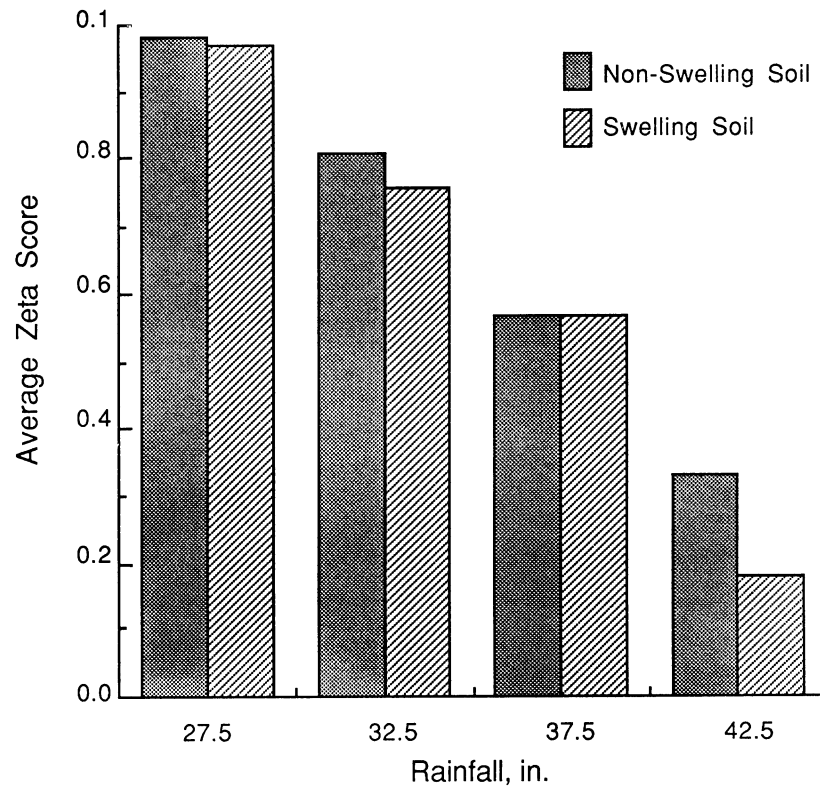


Figure 7. Effect of rainfall and soil type on distress index, Zeta-score.

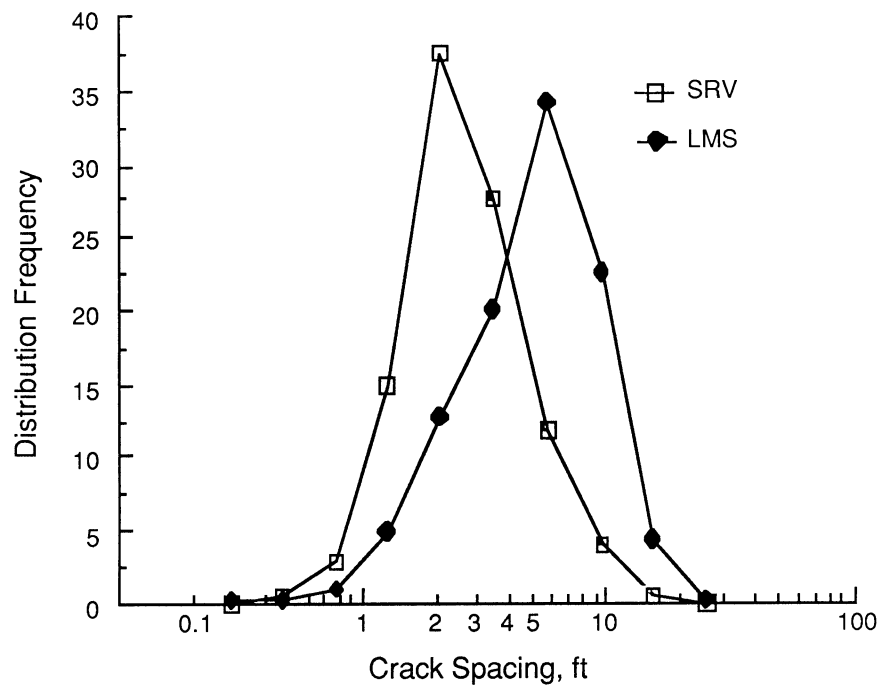


Figure 8. Overall distribution of crack spacing for LMS and SRG.

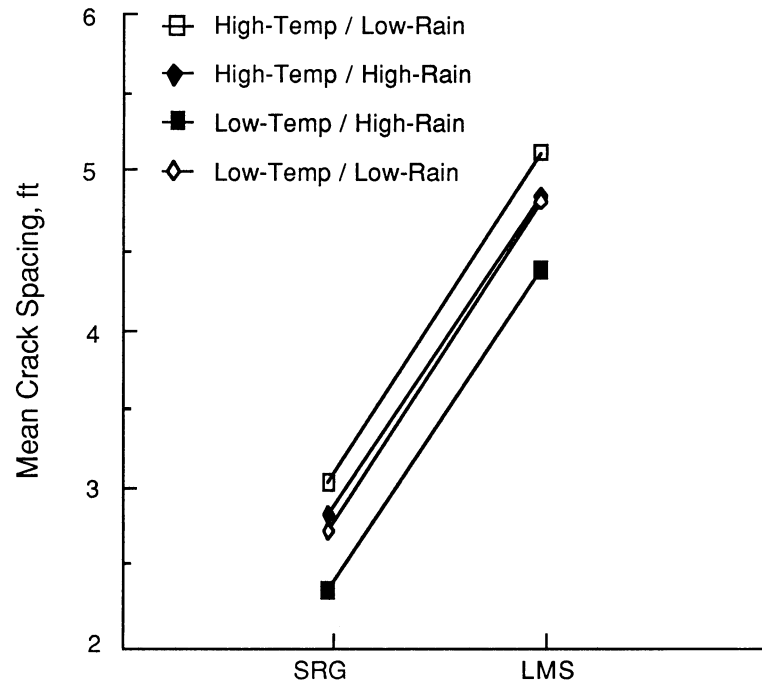


Figure 9. Effect of the temperature and rainfall on crack spacing for LMS and SRG concrete pavements.

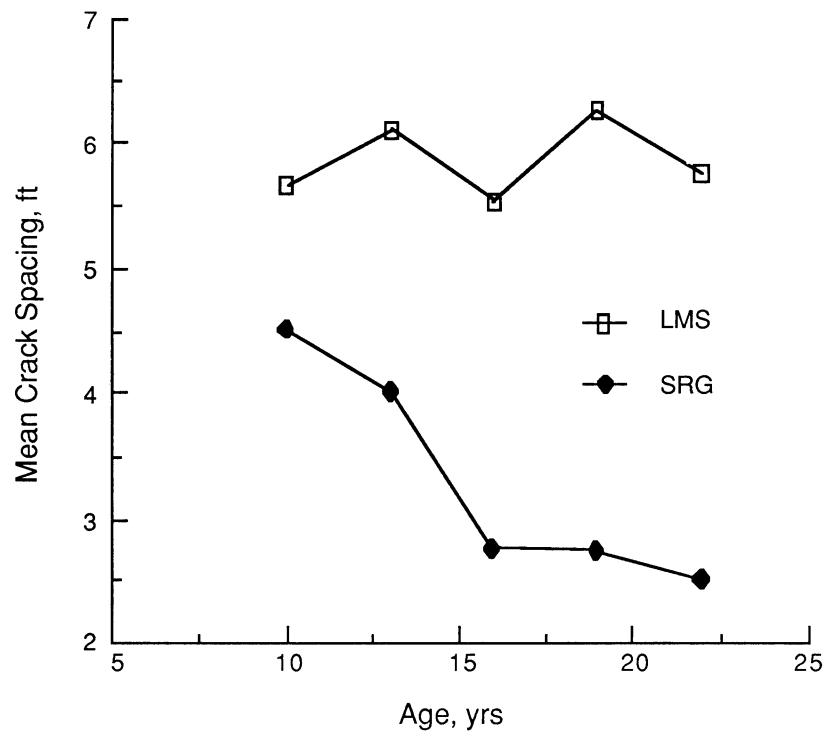


Figure 10. Effect of coarse aggregate type and pavement age on crack spacing.

i	Distress Manifestation	a_j	$\bar{x}_{.j}$	$\sigma_{x_{.j}}$
1	Minor Spalling (MPS)	-0.04248	3.558	2.5075
2	Severe Spalling (SSP)	-0.09866	1.4191	1.6301
3	Minor Punchout (MPUNT)	0.05373	1.0853	1.05002
4	Severe Punchout (SPUNT)	0.47223	0.3015	0.5044
5	Patch (PATCH)	0.72323	0.6313	0.8281

TABLE 1. CONSTANTS TO BE USED IN EQS 1 AND 3 (WITH MINOR SPALLING AND SEVERE SPALLING)

i	Distress Manifestation	a_j	$\bar{x}_{.j}$	$\sigma_{x_{.j}}$
1	Minor Punchout (MPUNT)	0.01869	1.0853	1.5020
2	Severe Punchout (SPUNT)	0.44885	0.3015	0.50444
3	Patch (PATCH)	0.72391	0.6313	0.8281

TABLE 2. STATISTICAL PARAMETERS USED IN EQS 1 AND 3 (WITHOUT MINOR SPALLING AND SEVERE SPALLING)

		Levels			
	Parameters	1	2	3	4
1	Slab Thickness	6"	8"	9"	13"
2	Coarse Agg.Type	Silicious River Gravel	Limestone		
3	Subbase Type	Cement Treatment	Asphalt Cement Treat.	Crush Stone	Lime Treat
4	Roadbed Soil	Swelling	Non-Swelling		
5	Average Annual Rainfall	High	Medium	Low	
6	Average Annual Lowest Temp.	High	Low		
7	Age	≤ 15	> 15		

TABLE 3. NUMBER OF CASES CORRECTLY PREDICTED BY THE DISCRIMINANT EQUATION (EQ 4)

Group	Number of Cases	Number of Correct Classification	Percent
Overlaid	56	52	92.9
Non-Overlaid	826	765	92.6
Total	882	817	92.6

TABLE 4. FACTORS AND LEVELS USED IN THE EXPERIMENT DESIGN