National
Cooperative
Highway
Research
Program

RESEARCH RESULTS DIGEST

DIGEST 82 - JANUARY 1976

Design of Continuously Reinforced Concrete Pavements for Highways

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 1-15, "Design of Continuously Reinforced Concrete Pavements for Highways," by B. Frank McCullough, Adnan Abou-Ayyash, W. Ronald Hudson, and Jack P. Randall, The University of Texas at Austin.

THE PROBLEM AND ITS SOLUTION

Most of the thousands of miles of continuously reinforced concrete pavement (CRCP) that have been built in the United States have been performing adequately. Failures have been sufficiently numerous, however, to suggest a need for defining more quantitatively the influences of the design variables that affect performance and the relationships that exist between them if the potential of CRCP is to be fully realized. The failures that have occurred usually have manifested themselves as isolated areas of premature distress in the forms of (1) steel failure at transverse cracks, (2) edge pumping, (3) excessive spalling at transverse cracks, and (4) failure of the concrete. Most failures have appeared to be associated with irregular crack spacing, erratic crack pattern, and excessive deflection. The research that is reported herein was an effort to develop an improved structural design procedure to account more reliably for the variables affecting the performance of CRCP.

A three-directional approach consisting of a theoretical study, field surveys, and a laboratory investigation was used to attain the study objective.

Theoretical Study

The formation of transverse cracks at relatively close intervals is a distinctive characteristic of continuously reinforced concrete pavement. The frequency of crack occurrence depends on a complex interaction of environmental variables and material properties. The initial spacing of the cracks appears to be established primarily by the internal stresses induced by drying shrinkage of the concrete and changes in temperature. Other factors of influence include

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

the air temperature at concrete placement, type and amount of reinforcement, type of coarse aggregate, subbase friction, and depth of the reinforcement steel relative to pavement thickness. All of the foregoing factors affect crack width as well as spacing.

Results from numerous field studies, inclusive of the field surveys conducted under this project, have shown that transverse crack spacing and crack width have a profound influence on the ultimate performance of continuously reinforced concrete pavement. Although their importance has been recognized, neither has heretofore been included in design behavioral models because of the complexities involved. The theoretical study was designed to apply a concentrated effort toward overcoming this deficiency. All of the factors of influence mentioned, with the exception of the ratio of steel depth to pavement thickness, were considered in developing the behavioral model about which the theoretical study was centered. Selection of a line model with the steel located at the neutral axis prevented inclusion of this ratio in the theoretical analysis. However, empirical means are proposed for its inclusion in the pavement design process when the theoretical model is used.

Another factor of influence not included in the modeling is wheel load. This needs to be considered for a determination of the complete state of stress, but could not be included in the study because of time and funding limitations. Its inclusion is recommended as a subject of further research. Even in its absence, however, the mathematical model that was developed is considered to show encouraging agreement with available field measurement data.

Field Surveys

The field survey consisted of a general condition survey and a diagnostic survey. In the general condition survey, an experimental design was established for each state in which the survey was conducted, based on the number of design and construction variables and the miles of in-service CRCP present in the state. The study covered a total of 133 test sections, each 1200 ft long, in Texas, Arkansas, South Dakota, North Dakota, Minnesota, Iowa, Wisconsin, Illinois, Michigan, Indiana, Ohio, Mississippi, Georgia, and Connecticut. Crack spacing, crack width, depth of longitudinal reinforcement, various distress manifestations, present serviceability rating, and general observations of the field staff were recorded. Black-and-white photographs, slides, and 8-mm movies were taken of each of the test sections to give an over-all picture of a test section and its performance. A statistical analysis of replicate test sections on each project demonstrated the feasibility of obtaining representative data on a given project if care is used in selecting the sections. As a part of the general condition survey, background design and construction information was collected on each test section.

The diagnostic survey included a more extensive measurement program than that of the general condition survey, and was conducted only in Texas, Illinois, and Indiana. Observations and analyses in the general condition survey suggested the inclusion of pavements from these states in the diagnostic survey. The additional data acquisition program included in the diagnostic survey consisted of Dynaflect measurements of deflection, Mays Meter readings of surface roughness, and core samplings of the pavement structure.

Laboratory Investigation

The laboratory investigation focused attention on the influences of design variables on load transfer, water percolation, and spalling at transverse cracks in slabs undergoing repetitive loadings. A factorially designed experiment was used to examine the effects of percent reinforcement at two levels, depth of reinforcement at two levels, subgrade support at two levels, and coarse aggregate of two types. The design is shown in Fig. 1.

A test slab size of 3 ft x 6 ft x 4 in. was chosen using discrete element analysis techniques for a two-dimentional bending model and with consideration being given to laboratory space requirements. A weakened plane was established with a 1-in.-depth metal strip placed on the subgrade at mid-length of the slab before casting to help induce the crack at which observations were to be made. A pulling mechanism was devised to form and open the crack to the desired test widths. Crack widths of 0.01 and 0.04 in. were used in the load transfer and spalling studies. A series of crack widths varying from 0.002 in. to 0.04 in. were used in the water percolation studies. Hold-down beams were used at the slab ends to simulate additional slab length.

Loadings that oscillated between 500 and 5,000 lb at the rate of 5 cycles per second were applied vertically to the slab surfaces adjacent to the induced cracks through a steel plate approximating the size of a truck tire imprint. A theoretical stress prediction indicated that the 5,000-lb load would produce about the same stresses as a 9,000-lb load applied to an 8-in. pavement. Two million loading cycles were applied for each test condition. Slab deflections were measured at intervals during the loading process, as were the cracking and spalling that occurred during loading. Each slab was subjected to the loading series first with the crack width at 0.01 in. and then at 0.04 in. Preliminary studies showed the loadings at the 0.01-in. crack width to have a negligible effect on the results obtained at the 0.04-in. crack width.

The water percolation tests were conducted with and without repetitive loading. When repetitive loading was used, the load was applied at the rate of two cycles per second. Water was ponded at a depth of 3/4 in. over the pavement surface at the induced cracks to start the permeability tests. Salt and dye were added to the water. Electrodes were used to indicate water penetration to different depths in the cracks.

Rubber pads were used to represent the subgrade supporting the slabs. This was done to avoid the various problems that are associated with placing and maintaining uniformity in real subgrade material under laboratory conditions. Preliminary testing with steel plates indicated that subgrade support could be varied by changing the thickness of the rubber pads. On the basis of preliminary tests,modulus of subgrade reaction values of 225 pci and 500 pci were selected to represent poor and good subgrade support. As the laboratory study progressed, it became evident from test results that the differences between the two types of subgrade support were not nearly as great as indicated by the plate loading tests. A further investigation with larger plates verified the lack of much difference in subgrade support. This removed subgrade support as one of the study variables; however, the compression it caused in the factorial design permitted a better examination of the other variables and provided replicate slabs to measure experimental error.

FINDINGS

Theoretical Study

The theoretical study produced a design behavioral model that comes appreciably closer than earlier models in accounting for the factors that have major influence on the ultimate performance of CRCP. Due to the complexity of

Percentage of Reinforcement		.55%		.83%	
Type of Coarse Aggregate		Crushed Limestone	River Gravel	Crushed Limestone	River Gravel
Depth of Reinforcement	Type of Subgrade Support				
Mid-depth	Poor	L-1 L-2 L-3			L-4
	Good		L-5	L-6	
Upper Half	Poor		L-7	L-8	
	Good	L-9			L-10

L-1, L-2, etc. = individual test slabs

Fig 1. Factorial design for laboratory study.

the mathemetical model that was established and the solution time required, a computer program, designated CRCP-1, was developed. The basic concepts of the model were derived from field observations, prior studies, and experience. Because CRCP is a composite material, the model of necessity had to simulate the mechanistic interactive behavior of the materials that compose the pavement system. A generalized system of equations was developed with a capability of solving for the state of stress and strain in the pavement system resulting from drying shrinkage and temperature drop. An iterative numerical solution was adopted because of the nonlinearities involved in the CRCP problem.

The basic iterative consideration was that a concrete slab cracks whenever volume-change stresses exceed the strength of the concrete. After cracking, additional volume-change stresses in the slab result in attemped movement at the cracks, which is resisted by the longitudinal steel and subbase friction. This resistance to movement produces a stress buildup in the steel and the concrete that can result in additional cracking of slabs or possible overstressing of the steel reinforcement. During the mathematical modeling process, the best available information was used to simulate the transverse forces at the interface and the friction-force-and-movement relationship for the concrete-subbase interface.

During the modeling process, consideration was given to keeping the program inputs as simple as possible. Generally, material properties, with the exception of the subbase friction properties, can be determined, and environmental data can be obtained from weather service reports. The CRCP input for a typical problem is shown in Figure 2. Figure 3 is a summary of the CRCP output for the solution to the typical input. For any given day, the crack spacing, crack width, concrete stress, and steel stress can be evaluated by the designer. Also, the maximum value of each of the parameters is printed at the end of the analysis. If any of the output values exceeds limiting criteria that are established, a new set of design parameters can be tried. Figure 4 is a conceptual diagram showing the decreasing crack spacing as predicted by the program for the first eight days following placement.

CRCP-1 is written in FORTRAN computer language for the Control Data Corporation 6600 digital computer with a 60-bit word length. Loan copies of the deck are available from the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Avenue, NW, Washington, D.C. 20418.

General Condition Survey

An important result of the general condition survey is a series of regression models that were developed to predict crack spacing, crack width, and a "distress index." The distress index is a composite value representing a weighted score for ten performance characteristics observed during the general condition survey and includes crack spalling, localized cracking, pumping, patching, and other characteristics of similar nature. Each of the ten was rated on a severity scale of 0 to 100 during the field survey. The weighting factors selected were based on the engineering judgment of the senior research staff members.

The numbers of independent variables entered into the equations for crack spacing, crack width, and distress index were 19, 14, and 29, respectively. Most of the dependent variables, such as concrete strength, pavement thickness, percent steel, and average daily traffic, were measured values. Dummy variables were established to represent the differential effects of nonmeasurable variables such as aggregate type and steel type.

The three regression models offer the designer a procedure that may be used as an alternate to, or in conjunction with, the theoretically developed computer program CRCP-1 for evaluating selected pavement designs. When using the regression models, caution must be exercised in ascertaining that the input parameters are within the limits of the variables used in the model development. Due to the nature of their development, the theoretical models of CRCP-1 are considered to be less restrictive.

During the general condition survey, a number of special design techniques and field problems were observed. The following pertinent items may be useful to future CRCP users:

1. A bond breaker between the CRCP and the subbase layer was seen to reduce the reflected longitudinal cracking from the subbase, but may not significantly affect the transverse crack spacing.

2. Excessive reduction of the frictional resistance at the subbase-pavement interface was seen to result in excessive lateral slab movements in short-radius turning roadways.

3. Repairs of failures in areas experiencing pumping were seen to be only temporary and not to prevent expansion of the failure area unless steps are taken to reduce the pumping.

4. The three methods of placing longitudinal steel (i.e., chairs, double strike-off, and tubes) were seen to result in similar variations of the longitudinal steel's vertical position.

5. The presence or absence of transverse steel was seen not to affect the transverse crack width or spacing if all other variables are equal.

6. Where preformed crack spacings were used, the final crack spacing appeared to be independent of the original preformed spacing.

Diagnostic Survey

The diagnostic study of four projects in Texas showed the AASHO performance model to provide a reliable prediction of the change in serviceability during the pavement life. The study showed that vehicular traffic, as expressed in 18-kip axle load equivalencies, had a profound influence on the pavement condition. A study of concrete spalling at traverse cracks indicated that, where the tensile strength was below 400 psi, spalling was experienced.

The diagnostic studies in Illinois and Indiana showed that pavement deflection was reduced by increases in pavement thickness and percent longitudinal steel, but that it was not influenced by the type of reinforcing steel, the position of the steel, or the subbase type.

Laboratory Investigation

In the load transfer studies:

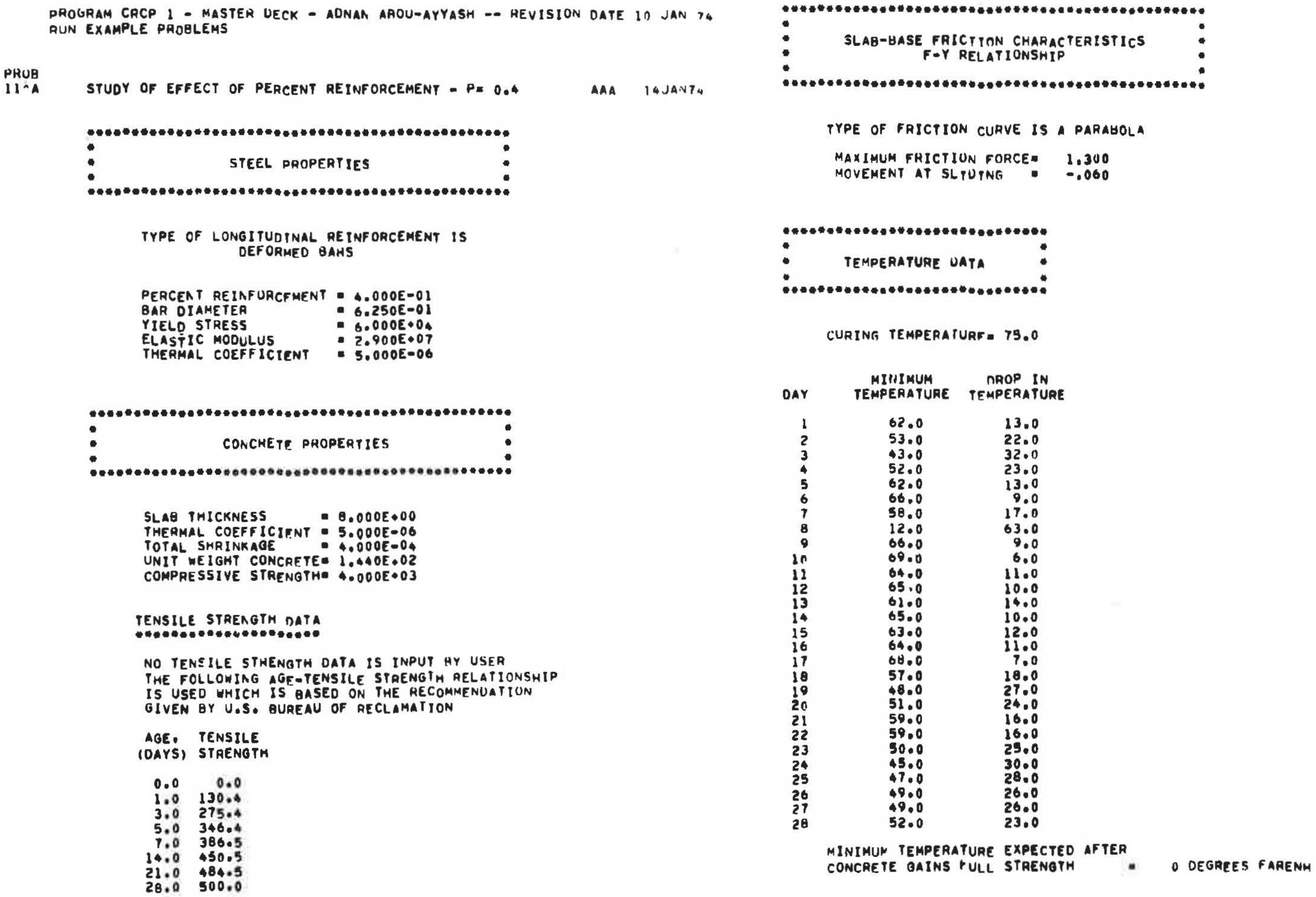
- Deflections increased with increasing numbers of load applications.
- Deflections increased with increase in crack width.
- Deflections were greater when the reinforcement was at mid-depth as compared with the upper half of the slab.

All of the foregoing are at the 95 percent level of confidence.

A regression analysis performed on the deflection measurement data with deflection as a function of load application produced an equation considered to be useful in the design and analysis of CRCP. A regression analysis conducted on the spall measurement data yielded an equation also considered to be useful in the design and analysis of CRCP.

APPLICATION

In summary, the study produced eight mathematical models for characterizing CRCP performance that can be used in CRCP design. From the theoretical study came:



```
PROGRAM CRCP 1 - MASTER DECK - ADNAN ABOU-AYYASH -- REVISION DATE 10 JAN 74
RUN EXAMPLE PROBLEMS

PROB
11^A     STUDY OF EFFECT OF PERCENT REINFORCEMENT - P= 0.4         AAA   14JAN74

        ***********************************************
        *                                             *
        *              STEEL PROPERTIES               *
        *                                             *
        ***********************************************

            TYPE OF LONGITUDINAL REINFORCEMENT IS
                      DEFORMED BAHS

            PERCENT REINFURCFMENT = 4.000E-01
            BAR DIAMETER          = 6.250E-01
            YIELD STRESS          = 6.000E+04
            ELASTIC MODULUS       = 2.900E+07
            THERMAL COEFFICIENT   = 5.000E-06

        ***********************************************
        *                                             *
        *            CONCHETE PROPERTIES              *
        *                                             *
        ***********************************************

            SLAB THICKNESS       = 8.000E+00
            THERMAL COEFFICIENT  = 5.000E-06
            TOTAL SHRINKAGE      = 4.000E-04
            UNIT WEIGHT CONCRETE= 1.440E+02
            COMPRESSIVE STRENGTH= 4.000E+03

           TENSILE STRENGTH DATA
           *********************

            NO TENSILE STHENGTH DATA IS INPUT HY USER
            THE FOLLOWING AGE-TENSILE STRENGTH RELATIONSHIP
            IS USED WHICH IS BASED ON THE RECOMMENDATION
            GIVEN BY U.S. BUREAU OF RECLAMATION

            AGE.  TENSILE
           (DAYS) STRENGTH

             0.0     0.0
             1.0   130.4
             3.0   275.4
             5.0   346.4
             7.0   386.5
            14.0   450.5
            21.0   484.5
            28.0   500.0
```

```
***********************************************
*                                             *
*      SLAB-BASE FRICTION CHARACTERISTICS     *
*             F-Y RELATIONSHIP                *
*                                             *
***********************************************

    TYPE OF FRICTION CURVE IS A PARABOLA

     MAXIMUM FRICTION FORCE=   1.300
     MOVEMENT AT SLIDING   =   -.060

*****************************
*                           *
*     TEMPERATURE DATA      *
*                           *
*****************************

    CURING TEMPERATURF= 75.0

           MINIMUM       DROP IN
DAY     TEMPERATURE   TEMPERATURE

  1         62.0          13.0
  2         53.0          22.0
  3         43.0          32.0
  4         52.0          23.0
  5         62.0          13.0
  6         66.0           9.0
  7         58.0          17.0
  8         12.0          63.0
  9         66.0           9.0
 10         69.0           6.0
 11         64.0          11.0
 12         65.0          10.0
 13         61.0          14.0
 14         65.0          10.0
 15         63.0          12.0
 16         64.0          11.0
 17         68.0           7.0
 18         57.0          18.0
 19         48.0          27.0
 20         51.0          24.0
 21         59.0          16.0
 22         59.0          16.0
 23         50.0          25.0
 24         45.0          30.0
 25         47.0          28.0
 26         49.0          26.0
 27         49.0          26.0
 28         52.0          23.0

    MINIMUM TEMPERATURE EXPECTED AFTER
    CONCRETE GAINS FULL STRENGTH        =     0 DEGREES FARENH
```

Fig 2. Typical input data sheet for CRCP-1 computer program.

- A model to predict average crack spacing (CRCP-1).
- A model to predict average crack width (CRCP-1).
- A model to predict the average state of steel reinforcement stress (CRCP-1).

From the general field survey came:

- A regression model to predict average crack spacing.
- A regression model to predict average crack width.
- A regression model to predict a "distress index."

From the laboratory study came:

- A regression model to predict average surface spall at cracks.
- A regression model to predict average deflection under traffic loading at cracks.

```
        PROGRAM CRCP 1 - MASTER DECK - ADNAN ABOU-AYYASH -- REVISION DATE 10 JAN 74
        RUN EXAMPLE PROBLEMS


PROB
110A      STUDY OF EFFECT OF PERCENT REINFORCEMENT - P= 0.4          AAA    14JAN74


                                                                       MAXIMUM
 TIME    TEMP      DRYING    TENSILE   CRACK        CRACK       CONCRETE      STRESS IN
(DAYS)   DROP    SHRINKAGE   STRGTH   SPACING       WIDTH        STRESS       THE STEEL

   .39   10.0    1.415E-06    55.2    1281.3    2.572E-03     4.481E+01     1.118E+04
   .50   13.0    1.814E-06    69.8    1281.3    4.781E-03     6.551E+01     1.593E+04
  7.50   63.0    2.559E-05   391.6     160.2    3.958E-02     2.999E+02     7.602E+04
  8.50    9.0    2.876E-05   401.5     160.2    5.786E-03     1.159E+02     2.881E+04
  9.50    6.0    3.187E-05   411.0     160.2    4.585E-03     1.040E+02     2.566E+04
 10.34    6.0    3.445E-05   418.8     160.2    4.907E-03     1.076E+02     2.650E+04
 10.50   11.0    3.493E-05   420.3     160.2    7.696E-03     1.348E+02     3.342E+04
 11.50   10.0    3.794E-05   429.3     160.2    7.556E-03     1.336E+02     3.301E+04
 24.50   28.0    7.300E-05   492.4     160.2    2.415E-02     2.394E+02     5.874E+04
 25.50   26.0    7.542E-05   494.6     160.2    2.317E-02     2.345E+02     5.741E+04
 26.50   26.0    7.780E-05   496.8     160.2    2.352E-02     2.363E+02     5.779E+04
 27.50   23.0    8.015E-05   498.9     160.2    2.186E-02     2.278E+02     5.556E+04



                        AT THE END OF THE ANALYSIS PERIOD

                        CRACK SPACING        = 6.673E+00 FEET
                        CRACK WIDTH          = 5.580E-02 INCHES
                        MAX CONCRETE STRESS= 3.612E+02 PSI
                        MAX STEEL STRESS     = 8.089E+04 PSI
```

Fig. 3. Summarized output data sheet for CRCP-1 computer program.

The foregoing models were used as the basis for development of a new procedure for design of continuously reinforced concrete pavements. The proposed procedure adheres to the basic principle of separating the reinforcing steel design and the pavement thickness design as accepted in the past. As heretofore, it is assumed that if the cracks are held to very limited openings continuity will be preserved within the pavement structure. This presumes that the prime purpose of the reinforcement is to maintain this condition. The advantages of the new design procedure are application of better limiting criteria and more sophisticated techniques.

Only parts of the full procedure are ready for immediate application by designers. Additional information must be acquired, especially on values to assign to several of the limiting criteria, before the full procedure can be employed.

The input data for the new procedure may be considered in three basic categories: environmental variables, fixed variables, and designer options. The values for the first two categories are fixed parameters; hence, the designer has no tolerance for adjustment in design. The flexibility comes with the designer options, such as percentage of longitudinal steel, steel type, and steel spacing. Concrete shrinkage may also be considered as a designer option because revisions in the curing procedure, cement factors, etc., may alter the shrinkage history, thus affecting the crack spacing, the crack width, and the

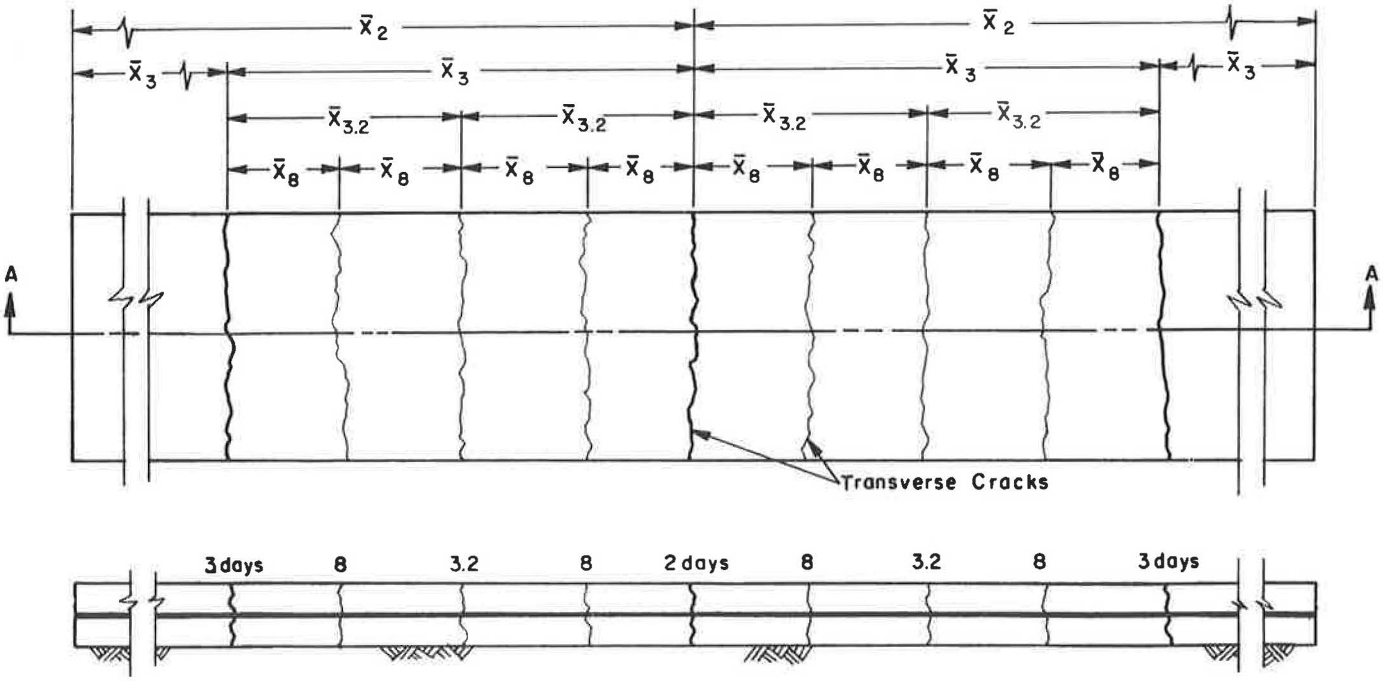


Fig 4. Typical occurrence of transverse cracks on a daily basis.

state of stress in the steel and the concrete. The design steps are outlined in the flow chart of Figure 5. In each of the procedural boxes, the step number of the procedure is indicated. It will be seen that the procedure is an iterative process that requires several trial-and-error steps. Computations of average crack width, average crack spacing, the state of stress, and the distress manifestations are made and checked against limiting criteria. Certain of these criteria were developed in the project or adapted from previous work; others remain to be developed. The report contains suggestions on how the missing criteria might be established.

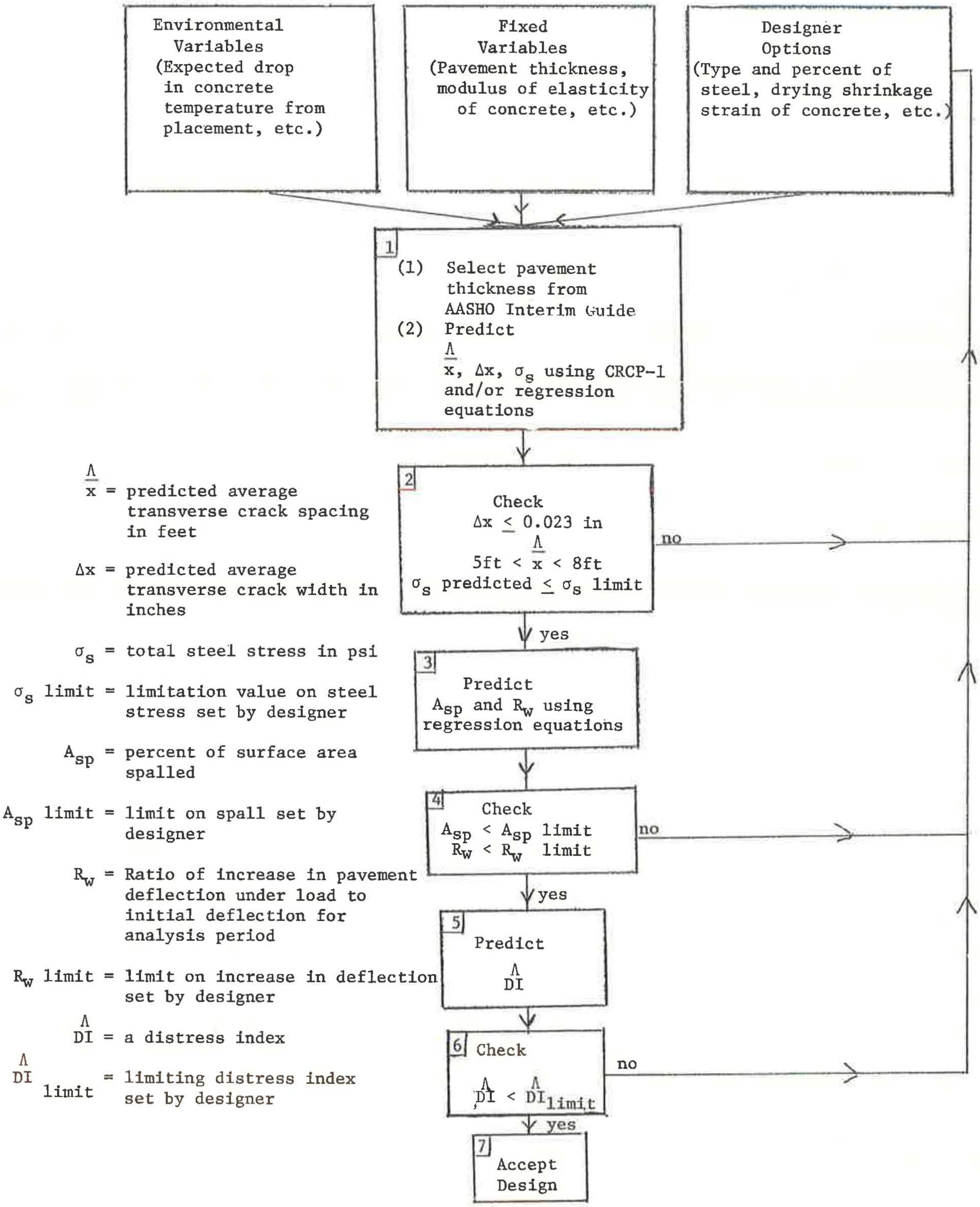
Following is a step-by-step description of the proposed new design process.

Step One

A pavement thickness is selected based on the alternate procedure for the design of rigid pavements given in the AASHO Interim Guide for Design of Pavement Structures (1972). Values are assigned to the other recognized variables of influence, and the average crack spacing and crack width that can be expected under the given set of conditions are then determined, either through application of computer program CRCP-1 developed in the theoretical portion of the study, or the regression equations derived from field data of the study, or both. As stated previously, the computer deck is available on loan from NCHRP. The regression equations are presented in the agency report. The computer program also is used to estimate the state of tensile stress in the steel.

The diagnostic field survey made as a part of the present study indicated that the AASHO Interim Guide procedure can be used with a high degree of reliability to predict required pavement thickness. Fundamental to its application is the assumption that adequate load transfer is provided and good construction practices are observed.

Results from the computer program have been checked against field data and have been found to give reliable and reasonable answers. For extrapolations outside the limits considered in the project, a higher degree of reliability should be attached to solutions from the computer program as compared with the regression analysis. A table is provided in the report to guide users of the regression



$\hat{x}$ = predicted average transverse crack spacing in feet

Δx = predicted average transverse crack width in inches

σ_s = total steel stress in psi

σ_s limit = limitation value on steel stress set by designer

A_{sp} = percent of surface area spalled

A_{sp} limit = limit on spall set by designer

R_w = Ratio of increase in pavement deflection under load to initial deflection for analysis period

R_w limit = limit on increase in deflection set by designer

$\hat{DI}$ = a distress index

$\hat{DI}$ limit = limiting distress index set by designer

Fig. 5. Proposed steel reinforcement design procedure for CRCP

equations with regard to the ranges of values used in the regression analysis. The computer model assumes the steel to be placed at the neutral axis; directions are given in the report for adjusting the output if the steel is to be located elsewhere.

Step Two

This step consists of comparing the average crack spacing predicted in Step One with limiting values that are provided. If the limiting values are not met, the designer must return to Step One and select other values for the variables over which he has control; if the limiting criteria are met, he proceeds to Step Three.

The report recommends that the average transverse crack spacing as indicated by the process of Step One lie somewhere between 5 ft and 8 ft. The results of studies elsewhere are cited as showing that spacings within this range provide optimum load transfer, acceptable deflections under load, and resistance to steel corrosion. A maximum allowable crack width of 0.023 in. is proposed based on the results of the laboratory water percolation tests made during the course of the project, and to some extent on the results of the diagnostic field survey where little spalling indicative of inadequate load transfer was found at crack widths of less than 0.020 in. No limiting criterion is applied to concrete stress because it is an independent function. It is, however, considered indirectly by the procedure. The designer is referred to the AASHO Interim Guide for the selection of a limiting criterion for stress in the steel.

If all limiting criteria are met, the designer proceeds to Step Three; if not, he returns to Step One to make the necessary adjustments and to repeat the design process.

Step Three

This step consists of predicting the amount of spall likely to take place at cracks, and the increase in deflection under loading that can be expected during the estimated life of the pavement. Regression equations developed from the tests of model slabs in the laboratory study are provided for the predictions.

Step Four

No limiting criteria are currently available from the project or elsewhere for the amount of spall and increase in deflection under loading that can be tolerated. Information is provided in the report on procedures that might be used to acquire the missing data. If the designer has access to limiting criteria, he proceeds to the next step if the criteria are met, or returns to Step One to change input values if they are not.

Step Five

This step consists of predicting a distress index using the results of the regression study of data obtained in the general condition survey. The distress index is a composite value representing a weighted score for performance characteristics. The weighting factors for the observed distress manifestations were assigned by the research staff members based on engineering judgment and experience.

Step Six

This step consists of comparing the predicted distress index with a limiting distress index whose value is yet to be determined. It is recommended that the designer use in-service pavements to establish a limiting value. If the limiting value is known, and is not satisfied, the iterative process continues.

Step Seven

If the requirements of Step Six are satisfied, the design may be considered an acceptable one.

DISCUSSION

As indicated previously, only parts of the proposed design process are ready for immediate practical use. Application of the full design process as outlined requires further study to provide values for several limiting criteria about which not enough is now known. Additional sensitivity analyses are also needed to determine whether some of the variables that are considered in the present process can be eliminated from further consideration because of a lack of significant impact on design selection. Finally, design charts or nomographs must be prepared to remove the present cumbrousness from the design operation. Research activity in these areas is currently in progress at the University of Texas at Austin under other contracts.

TRANSPORTATION RESEARCH BOARD
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 42970