User's Guide for TxCRCP-ME Design Software Volumes I and II

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Texas Department of Transportation

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by

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A limited set of CRCP field performance data was used to develop the TxCRCP-ME punchout model, more accurate field performances are collected by Research project 0-6274 Project Level Performance Database for Rigid Pavements in Texas, Phase II. An updated worksheet will be developed under project 0-6274. The Spalling model has not been updated by field performances.

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User's Guide for TxCRCP-ME Design Software

<u>Ver. 0.1</u>

Volume I

User's Guide

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SECTION 1: Structural Design of CRCP

INTRODUCTION

This manual is organized to help users get accustomed to the operation modules of TxCRCP-ME, the structural design software for continuously reinforced concrete pavement (CRCP), which was developed under TxDOT research project 0-5832, Develop Mechanistic/Empirical Design for CRCP. An elaborate three-dimensional finite element analysis was conducted to identify the mechanisms of punchout distress in CRCP, and the critical component that may cause the punchout distress was mechanistically evaluated. A full factorial parametric study was performed for significant input variables to compile the database of the analysis results. A program was written using the 2007 version of Microsoft Excel to perform the analysis of the pavement system for given inputs in estimating the frequency of punchouts, the primary structural distress in CRCP. The conversion from mechanistic structural responses to pavement distress is achieved by a transfer function determined empirically, utilizing data collected from the TxDOT rigid pavement database project. The final results of the software are presented in the form of charts and tables. For more detailed information on how the program was assembled, consult the companion document, "User's Guide for TxCRCP-ME Design Software, Volume II."

EXECUTION SYSTEM

- The TxCRCP-ME design software is designed to be executed in Microsoft Office 2007 or later.
- The software requires a minimum free storage space of 300 MB.
- The execution time may take up to two minutes.
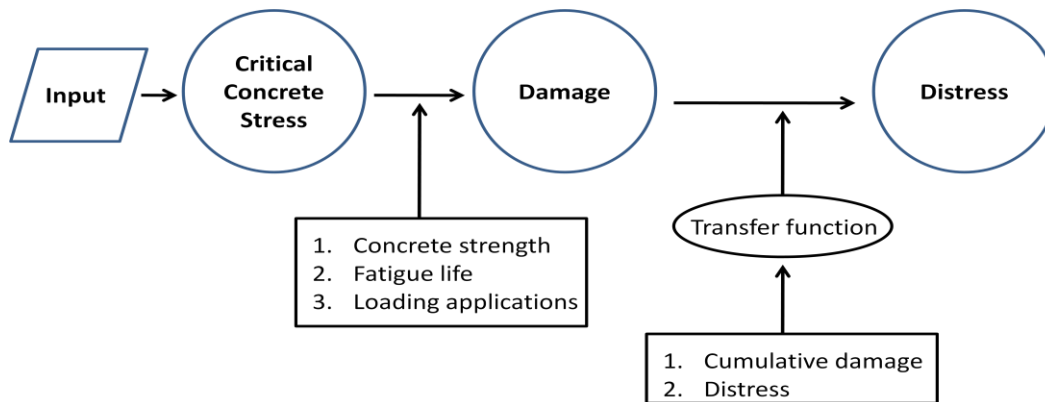
Figure 1.1 Framework of the TxCRCP-ME program

FRAMEWORK

The TxCRCP-ME design software is composed of four operational modules as illustrated in Figure 1.1.

I.   General Inputs

The first step in using this software is to estimate the values for input variables related to material properties, design parameters, climate, and traffic. The required fields are presented in red, and the optional fields are presented in yellow as shown in Figure 1.2. If all the modules operate properly, computed outputs will be presented in appropriate cells in green. For the input variables, a red triangle on the upper right corner of the cell indicates that further helpful information is available for that input variable. To access the information, move the cursor to the red triangle. After a value is typed for an input variable, press the "Enter" key. Once all the input values are provided, press F9 to execute the program.
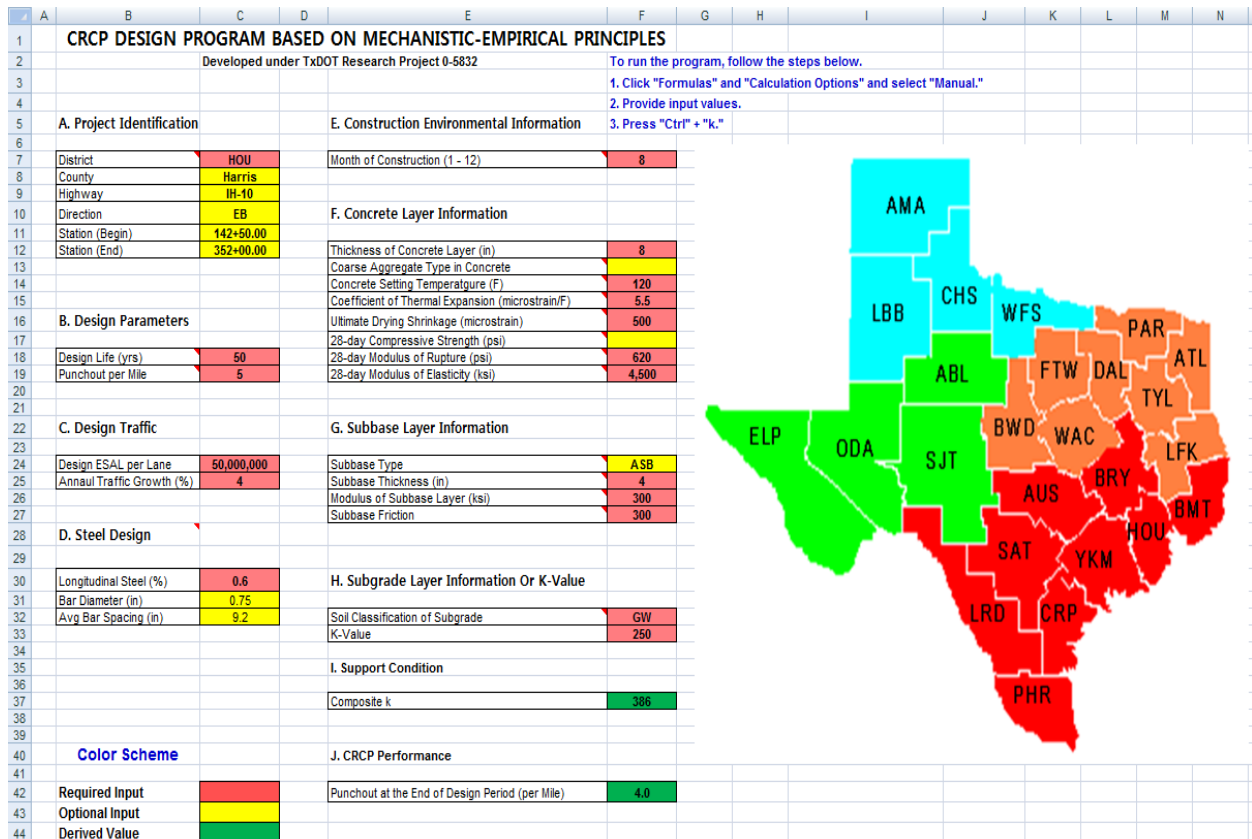
Figure 1.2 Input screen of TxCRCP-ME

The description of the general input variables are:

A. Project Identification

Provide general information of a project, i.e. district, county, highway, direction of construction, and stations. The "District" field is required to initiate the prescribed climatic data that will be used for the evaluation of stresses due to environmental loading. The input must be per the official abbreviation as shown in Table 1.1. All 25 TxDOT districts in the State of Texas are applicable to the district field. The other fields are optional. Once the design is completed, this screen can be printed for record in the project file.

Table 1.1 District inputs

District	Abbreviation
Abilene	ABL
Amarillo	AMA
Atlanta	ATL
Austin	AUS
Beaumont	BMT
Brownfield	BWD
Bryan	BRY
Childress	CHS
Corpus Christi	CRP
Dallas	DAL
El Paso	ELP
Fort Worth	FTW
Houston	HOU
Laredo	LRD
Lubbock	LBB
Lufkin	LFK
Odessa	ODA
Paris	PAR
Pharr	PHR
San Angelo	SJT
San Antonio	SAT
Tyler	TYL
Waco	WAC
Wichita Falls	WFS
Yoakum	YKM

B. Design parameters

Provide the design period in years and the design acceptable number of punchouts per mile. Currently, 10 punchouts per mile is a nationally accepted value for the terminal condition of CRCP, even though a designer could select a more appropriate value depending on the importance of the highway system under analysis. The design acceptability will be based on those design parameters; if the predicted number of punchouts at the end of the design period is more than the design value, modification of input(s) is required.

C. Design traffic

Design traffic information is used to estimate the cumulative fatigue damage in a concrete layer. Two inputs must be designated in this part of the spreadsheet: the ESALs in a single design lane, and an annual traffic growth rate to consider the number of load repetitions over the design period. Characterization of traffic loading in terms of ESALs is based on the research study conducted at the University of Illinois that shows the use of more detailed load spectra analysis does not improve the accuracy of pavement design (Bordelon, 2009).

D. Steel design

Longitudinal steel ratio is one of the most important factors determining the magnitude of the critical stress in the concrete layer. Any ratio between 0.5 to 0.7 % can be provided by the user. From a practical standpoint, users should start with 0.6 %. Once slab thickness is determined that will satisfy the limits for punchouts at the end of the design life, TxDOT CRCP Design Standards need to be consulted to get the steel design information. The program needs to run again with the steel design information from the TxDOT Design Standards to double-check the acceptability of the design selected. Either bar diameter or average spacing must be provided. The program calculates the other variable.

It should be noted that the inference space used for the development of a transfer function for steel design variables is quite limited. The accuracy of the CRCP design could be compromised if the ranges of the steel design variables are out of the normal ranges used in Texas. It is advised that steel design variables are not used to adjust the required slab thickness. Steel designs for transverse steel and tie bars are not included. They should be governed by TxDOT CRCP Design Standards.

E. Construction environmental information

   Provide the month of construction (1 to 12). The information will be used for the evaluation of environmental stresses. During the design phase, it might be difficult to project when the concrete placement will be made. Even in a single project, there could be different phases of construction. From a practical standpoint, it will be quite difficult to determine the month of concrete placement. If the concrete placement month is not known during the design phase, the selection of May or June is recommended as a default input.

F. Concrete layer information

   Provide the concrete layer information. The ranges of user-defined concrete properties are shown in Table 1.2.

Table 1.2 Ranges of concrete properties

Property	Range	Unit	Note
Thickness of Concrete Layer	6 to 14	in.	Required
Coarse Aggregate Type in Concrete[a]	SRG, CLS, or GRN	n/a	Optional
Concrete Setting Temperature	No restriction	°F	Required
Coefficient of Thermal Expansion	4 to 7	10^{-6} in./in./°F	Required
Ultimate Drying Shrinkage	300 ~ 700	10^{-6} in./in.	Required
28-day Compressive Strength	No restriction	psi	Optional
28-day Modulus of Rupture	No restriction	psi	Required
28-day Modulus of Elasticity	No restriction	ksi	Required

a. If this information is available during pavement design, provide the information: SRG for siliceous river gravel, CLS for calcareous limestone, and GRN for granite. If not available, leave blank.

   Concrete modulus of elasticity depends on concrete strength and coarse aggregate type used. However, the correlation is not precise and there is a large variability. In this version of the program, the modulus of elasticity of concrete is a direct input. For guidance on the selection of this value, contact the Rigid Pavements and Concrete Materials Branch of CSTMP in Austin. Slab thickness is an input and should be provided by the user. In that sense, this program is not a design program, but rather an analysis program. In a later version of the program, slab thickness could be an output and efforts will be made to achieve that capability.

G. Subbase layer information

   Provide the subbase type, subbase thickness, modulus of subbase layer, and subbase friction. Table 1.3 shows the input variables and acceptable ranges of the variables.

Table 1.3 Range of subbase properties

Property	Range	Unit	Note
Subbase Type[a]	ASB, CSB, or OTHER	n/a	Optional
Thickness of Subbase	2 to 6	in.	Required
Modulus of Subbase Layer	50 to 2000	ksi	Required
Subbase Friction	100 to 500	psi/in.	Required

a. Type ASB for asphalt stabilized subbase or CSB for cement stabilized subbase. Type OTHER for other types of subbase.

H. <u>Subgrade layer information</u>

Provide the soil classification per AASHTO or Unified Classification System as follows. If the modulus of subgrade reaction value of the soil is known, provide the number, instead of soil classification. If both soil classification and k-value are provided, k-value will be utilized.

Table 1.4 Classification of soil

Description	AASHTO	Unified
Gravel	A-1-a	GW or GP
Coarse Sand	A-1-b	SW
Fine Sand	A-3	SP
Silty Gravel or Sand	A-2-4 or A-2-5	GM or SM
Clayey Gravel or Clayey Sand	A-2-6	GC or SC
Clayey Gravel or Clayey Gravelly Sand	A-2-7	GC or SC
Silt or Silt/sand/gravel mixture	A-4	ML or OL
Poorly Graded Silt	A-5	MH
Plastic Clay	A-6	CL
Moderately Plastic Elastic Clay	A-7-5	CL or OL
Highly Plastic Elastic Clay	A-7-6	CH or OH

I. <u>Support condition</u>

Composite k-value is derived internally based on the input values provided for the subbase thickness, modulus of subbase layer and subgrade soil type or k value; the details of the composite k-value evaluation can be found in Chapter 4 and Appendix A of the research report, 0-5832-1. In this program, subgrade stiffness is characterized by modulus of subgrade reaction (k), and that of the subbase by modulus of elasticity. Once the subbase and subgrade layer information is provided in the spreadsheet, the composite k-value is computed internally.

J. CRCP performance

Combining all the information provided above, the number of punchouts at each month and at the end of the design period is estimated.

II. Critical Concrete Stress Evaluation

In this module, the concrete stresses due to environmental loads (temperature and moisture variations in concrete) and wheel loads are evaluated. Based on the three-dimensional finite element analysis, it was identified that the critical concrete stress due to wheel loading occurs in the vicinity of longitudinal steel reinforcement (Figure 1.3) at transverse cracked areas; the detailed scheme of the analysis can be found in Chapter 3 of the research report 0-5832-1. The combined concrete stresses due to wheel and environmental loads are used in the fatigue damage estimation in the concrete slab.
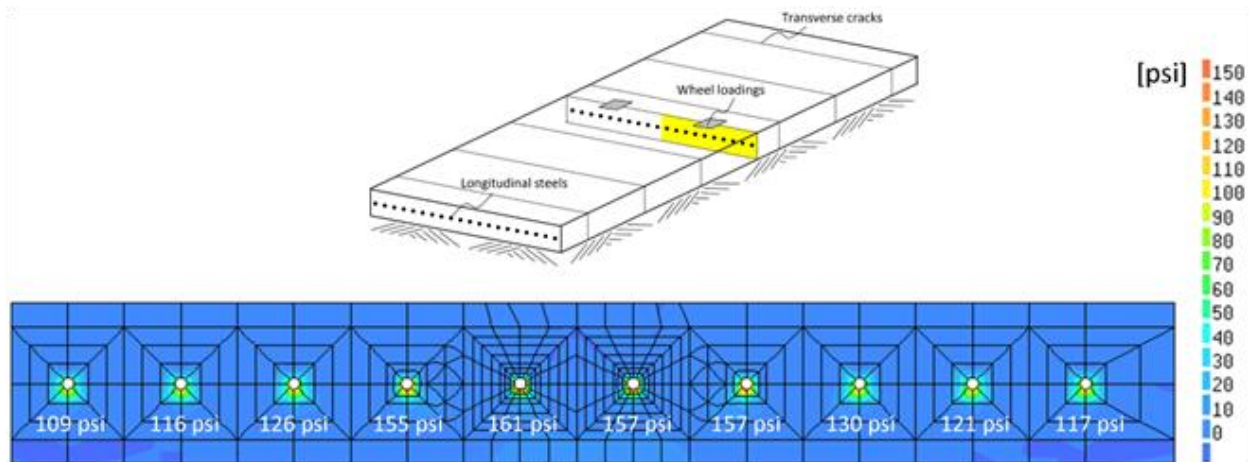
Figure 1.3 Principal concrete stress under wheel loading

III. Damage Estimation

In this module, cumulative damage in the concrete slab due to environmental and traffic load applications are evaluated as shown below.

1. Fatigue damage evaluation: To predict the allowable fatigue number of the concrete layer, the fatigue relationship developed by Vesic [1] was employed. As can be seen in Equation (1.1), the fatigue number of concrete is dependent on the stress-strength ratio.

$$N_i = 225{,}000 \left(\frac{\sigma}{MR}\right)^4 \qquad \text{(Eq 1.1)}$$

where, N_i is the fatigue number;

MR is the modulus of rupture (psi); and

σ is the tensile concrete stress (psi).

This equation was developed using the modulus of rupture for plain concrete. The fatigue behavior of concrete near longitudinal steel might be slightly different. There are no equations available for the fatigue behavior of concrete near reinforcement due to static and dynamic loading. However, as long as there is no large difference in the shape of the fatigue equations, errors due to not using the exact fatigue equation will be minimized by the selection of a proper transfer function.

For concrete stress, the value in the vicinity of longitudinal steel reinforcement derived from three-dimensional analysis was used for Equation (1.2). To consider the rate of concrete strength development over time, the model proposed by ACI 209 was employed.

$$f'_{c(t)} = f'_{c(28)} \left(\frac{t}{4 + 0.85t} \right)$$ (Eq 1.2)

where, $f'_{c(t)}$ is the compressive strength at age t (psi);

$f'_{c(28)}$ is the compressive strength at 28-day (psi); and

t is the age in day.

Since the modulus of elasticity of concrete is proportional to the square root of the compressive strength, the rate of increase in modulus of elasticity over time takes the form of the square root of the time factor in Equation (2).

2. Cumulative damage estimation: This allowable load repetitions number (fatigue number) in turn, was used for the damage prediction. The damage ratio – the ratio between the number of load repetitions and the allowable number of load repetitions – was calculated for each month and summed over every month, up to the end of the design period, to estimate total cumulative damage. To estimate the number of load repetitions over the design period, the design ESALs and an annual traffic growth rate input values were used. Damage was computed using Equation (1.3).

$$D = \sum \frac{n_i}{N_i} \qquad\qquad \text{(Eq 1. 3)}$$

where, D is the damage;

N_i is the number of load repetitions to failure at the ith specified stress level (psi); and

n_i is the number of load repetition at the ith specified stress level (psi).

IV.   Estimation of Number of Punchouts

To make a conversion from the accumulated damage to the actual number of punchout distresses in CRCP, a transfer function, which provides a relationship between accumulated damage and the number of punchouts per mile, was empirically derived based on the information from the TxDOT rigid pavement database. Figure 1.4 shows the transfer function developed in this study. A transfer function is one of the most important elements in any mechanistic-empirical (ME) pavement design procedure. Reasonableness of any ME pavement design procedure depends to a great extent on the accuracy of a transfer function. Small errors in the estimation of concrete stresses in the "mechanistic" portion of ME design procedures do not necessarily cause inaccuracy in the output of ME designs. Development of a proper transfer function will minimize any errors associated with inaccurate estimation of concrete stress. On the other hand, inaccuracies in a transfer function ("empirical" portion of ME design procedures) will have a direct and pronounced impact on the reasonableness of pavement designs from ME design procedures.
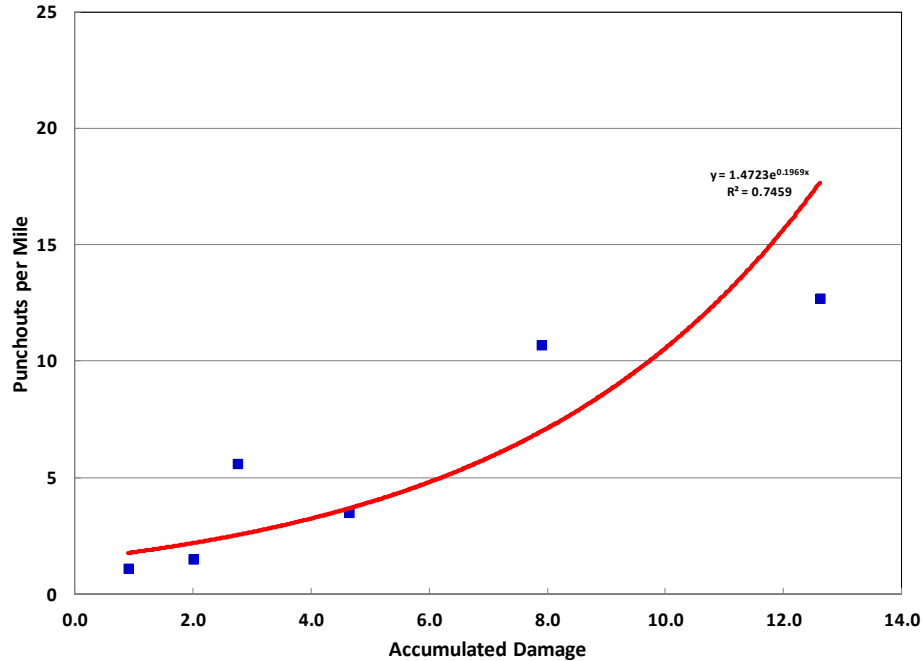
Figure 1.4 Transfer function

The transfer fuction developed in this research study at the time of the writing of this Guide is as follows:

$$y = 1.5801 \cdot e^{0.1871x} \qquad \text{(Eq 1.4)}$$

        where, y is the number of punchouts per mile; and
                x is the accumulated damage over the period.

The derivation of the transfer function is described in Chapter 4 of the report 0-5832-1. Considering the importance of the accuracy of a transfer function in overall reasonableness of ME pavement design procedures, efforts will continue to collect accurate information on traffic loading and punchout distress and, when an improved transfer function is developed, it will be incorporated into the TxCRCP-ME program and this Guide will be updated.

V.   Output Presentation

The last module of this program is the output presentation. The primary output result of this software is to assess the potential of punchout distress in CRCP over the design period. Table 1.5 and Figure 1.5 show examples of the output results.

Table 1.5 shows output results and is divided in the following columns:

1) 1st & 2nd columns: the pavement age in month and year scales, respectively.
2) 3rd & 4th columns: the development of modulus of rupture and modulus of elasticity, respectively.
3) 5th column: concrete stresses which were obtained from the 3-dimensional finite element analysis. As described earlier, the concrete stress was evaluated in the vicinity of longitudinal steel reinforcement and transverse cracks.
4) 6th column: maximum stress ratio, the ratio between the critical concrete stress and the modulus of rupture.
5) 7th column: the number of allowable load repetitions to fatigue failure from equation (4).
6) 8th column: the number of actual load repetitions calculated from data provided by the user.
7) 9th column: pavement damage estimated for a specific month
8) 10th column: accumulated pavement damage up to that month
9) 11th column: the number of punchouts estimated from a transfer function in (4)

The output information is also presented in a graphical form for the number of punchouts per mile for various time periods up to the end of the design life. An example is shown in Figure 1.5.

Table 1.5 Output results

| Pavement Month	Age Year	Concrete Modulus of Rupture (psi)	Concrete Modulus of Elasticity (ksi)	Concrete Stress (psi)	Maximum Stress Ratio (psi/psi)	Number of Load Repetitions to Failure	Number of Load Repetitions	Pavement Damage	Cumulative Damage	Number of Punchouts per Mile
1	0.08	620	4.50E+03	258.32	0.417	7.47E+06	1.15E+05	1.54E-02	1.54E-02	1.58E+00
2	0.17	676	4.91E+03	274.70	0.406	8.27E+06	1.16E+05	1.40E-02	2.94E-02	1.59E+00
3	0.25	693	5.03E+03	284.37	0.410	7.94E+06	1.16E+05	1.46E-02	4.40E-02	1.59E+00
4	0.33	702	5.09E+03	292.29	0.416	7.48E+06	1.16E+05	1.56E-02	5.96E-02	1.60E+00
5	0.42	707	5.13E+03	297.79	0.421	7.16E+06	1.17E+05	1.63E-02	7.59E-02	1.60E+00
6	0.50	711	5.16E+03	299.96	0.422	7.10E+06	1.17E+05	1.65E-02	9.24E-02	1.61E+00
7	0.58	713	5.18E+03	298.64	0.419	7.33E+06	1.18E+05	1.60E-02	1.08E-01	1.61E+00
8	0.67	715	5.19E+03	295.08	0.412	7.77E+06	1.18E+05	1.52E-02	1.24E-01	1.62E+00
9	0.75	717	5.20E+03	291.93	0.407	8.18E+06	1.18E+05	1.45E-02	1.38E-01	1.62E+00
10	0.83	718	5.21E+03	287.67	0.401	8.74E+06	1.19E+05	1.36E-02	1.52E-01	1.63E+00
11	0.92	719	5.22E+03	284.32	0.395	9.21E+06	1.19E+05	1.29E-02	1.65E-01	1.63E+00
12	1.00	720	5.23E+03	283.22	0.393	9.40E+06	1.20E+05	1.27E-02	1.77E-01	1.63E+00
13	1.08	721	5.23E+03	283.73	0.394	9.37E+06	1.20E+05	1.28E-02	1.90E-01	1.64E+00
14	1.17	721	5.24E+03	286.19	0.397	9.08E+06	1.20E+05	1.33E-02	2.03E-01	1.64E+00
15	1.25	722	5.24E+03	291.92	0.404	8.41E+06	1.21E+05	1.44E-02	2.18E-01	1.65E+00
16	1.33	722	5.24E+03	297.84	0.412	7.78E+06	1.21E+05	1.56E-02	2.33E-01	1.65E+00
17	1.42	723	5.25E+03	302.09	0.418	7.37E+06	1.22E+05	1.65E-02	2.50E-01	1.66E+00
18	1.50	723	5.25E+03	303.38	0.420	7.26E+06	1.22E+05	1.68E-02	2.67E-01	1.66E+00
19	1.58	723	5.25E+03	301.40	0.417	7.47E+06	1.22E+05	1.64E-02	2.83E-01	1.67E+00
20	1.67	724	5.25E+03	297.33	0.411	7.90E+06	1.23E+05	1.55E-02	2.99E-01	1.67E+00
21	1.75	724	5.25E+03	293.80	0.406	8.30E+06	1.23E+05	1.48E-02	3.13E-01	1.68E+00
22	1.83	724	5.26E+03	289.25	0.399	8.84E+06	1.24E+05	1.40E-02	3.27E-01	1.68E+00
23	1.92	724	5.26E+03	285.67	0.394	9.31E+06	1.24E+05	1.33E-02	3.41E-01	1.68E+00
24	2.00	725	5.26E+03	284.40	0.392	9.49E+06	1.24E+05	1.31E-02	3.54E-01	1.69E+00
25	2.08	725	5.26E+03	284.78	0.393	9.44E+06	1.25E+05	1.32E-02	3.67E-01	1.69E+00
26	2.17	725	5.26E+03	287.14	0.396	9.15E+06	1.25E+05	1.37E-02	3.81E-01	1.70E+00
27	2.25	725	5.26E+03	292.80	0.404	8.47E+06	1.26E+05	1.48E-02	3.96E-01	1.70E+00
28	2.33	725	5.26E+03	298.66	0.412	7.83E+06	1.26E+05	1.61E-02	4.12E-01	1.71E+00
29	2.42	725	5.27E+03	302.85	0.417	7.41E+06	1.27E+05	1.71E-02	4.29E-01	1.71E+00
30	2.50	726	5.27E+03	304.08	0.419	7.30E+06	1.27E+05	1.74E-02	4.46E-01	1.72E+00
31	2.58	726	5.27E+03	302.03	0.416	7.50E+06	1.27E+05	1.70E-02	4.63E-01	1.72E+00
32	2.67	726	5.27E+03	297.90	0.410	7.93E+06	1.28E+05	1.61E-02	4.79E-01	1.73E+00
33	2.75	726	5.27E+03	294.32	0.405	8.33E+06	1.28E+05	1.54E-02	4.95E-01	1.73E+00
34	2.83	726	5.27E+03	289.71	0.399	8.88E+06	1.29E+05	1.45E-02	5.09E-01	1.74E+00
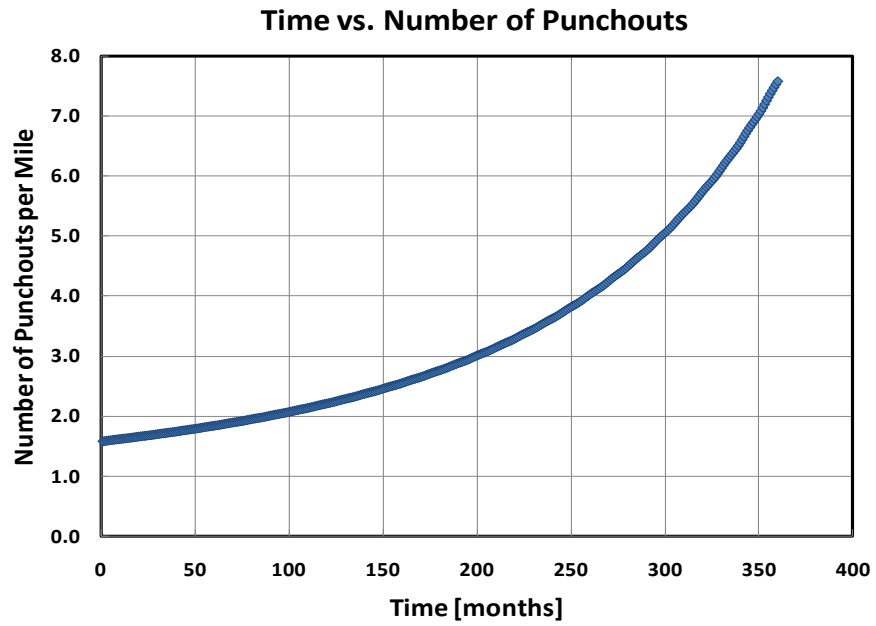
Figure 1.5 Number of punchouts over the design period

SECTION 2: Spalling Evaluation of CRCP

INTRODUCTION

This manual is a guide for the CRC-Spalling program which can be operated under Windows Vista or later versions of the Windows operating system. The 2003 or 2007 version of Microsoft Office Excel is used to input and analyze data relevant to the design of continuously reinforced concrete (CRC) pavement. In the spreadsheet, various factors are calibrated to accurately estimate the characteristics of spalling distress.

The CRC-Spalling program consists of three categories of modules: input, execution, and results. The program contains more than 30 modules, so only certain modules appear on the Excel tab bar for execution. The remaining modules are design variables such as cement type and are defaulted for efficiency purposes; selected variables that may be of interest for alteration are used to predict a spalling.

EXECUTION SYSTEM

To execute this software with Excel 2003, the Analysis ToolPak-VBA must be installed. This can be found under the Tools menu; click Add-Ins to find the Analysis ToolPak-VBA.
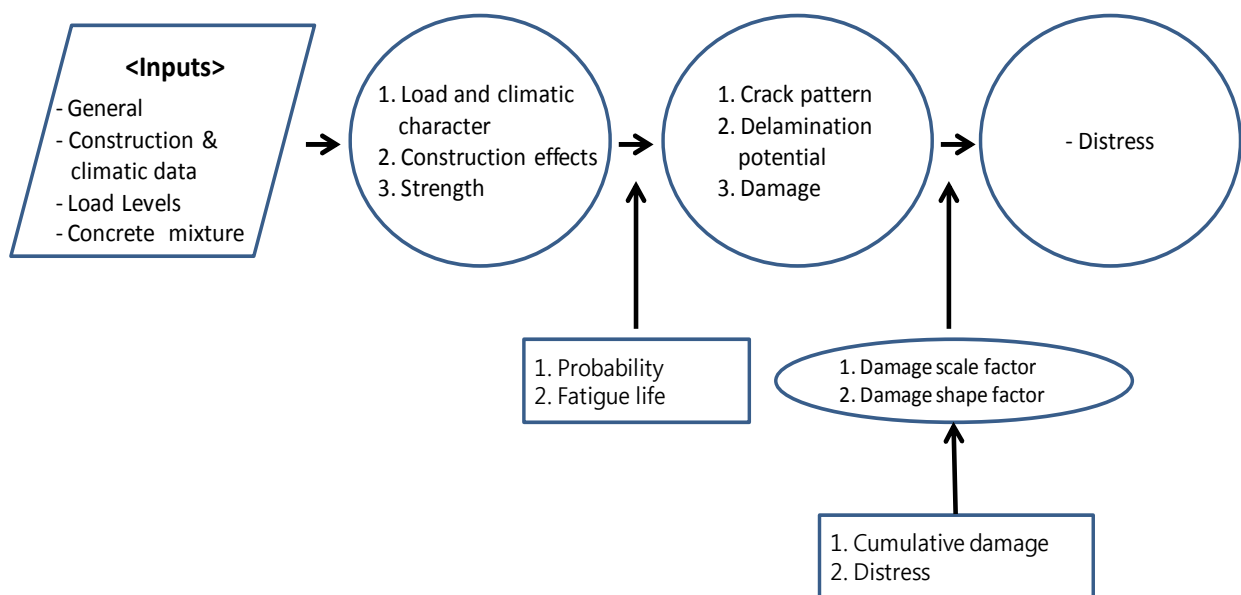
Figure 2.1 Framework of the TxCRCP-ME program for spalling

FRAMEWORK

The TxCRCP-ME design software for spalling is composed of four operational modules as illustrated in Figure 2.1.

I.   Design Inputs

Four input modules are provided to guide the user through the design input process. After completing all inputs, the program can be run. Figure 2.2 shows the input screen.
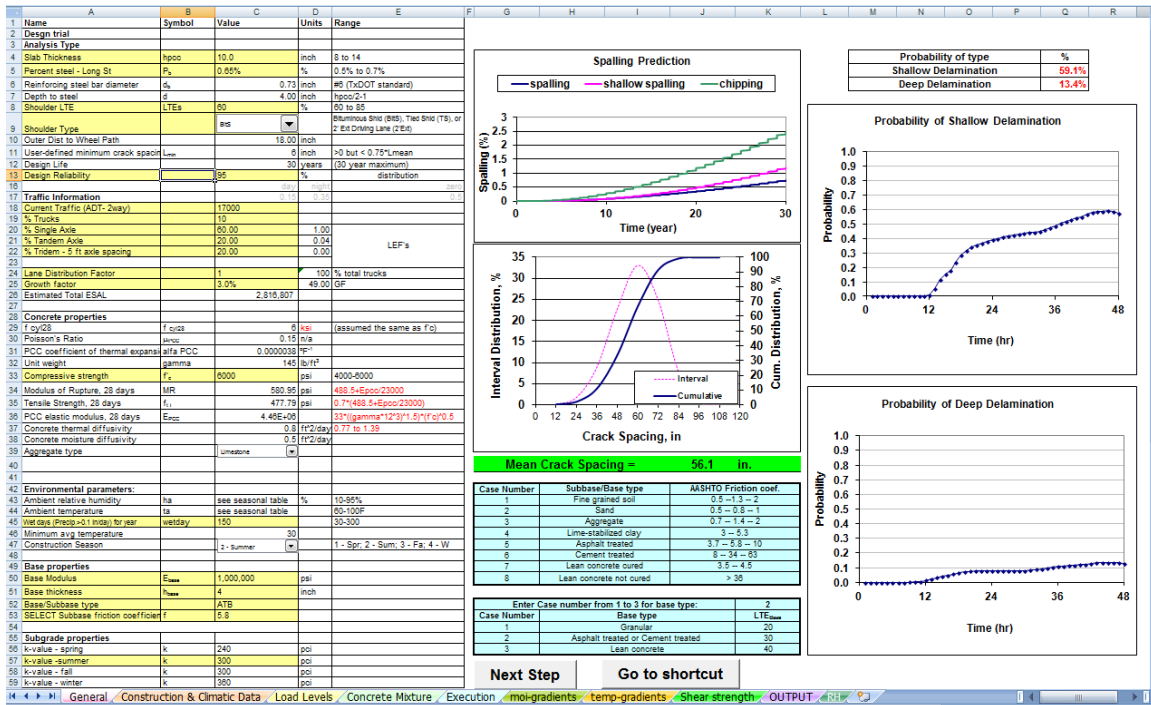
Figure 2.2 Input screen of TxCRCP-ME for spalling

The Input modules are:

A.   General

This module contains general input data pertaining to slab design, traffic data, concrete properties, environmental parameters, base and subgrade properties, etc. Selected parameters are easily changed or updated with new values. For example, slab design values (listed below) can be changed by clicking on the cell and inputting a new value. Slab thickness is limited to a range of eight to 14 inches. Steel percentages range from 0.05 to 0.071, and reinforcing steel bar size ranges from #5 to #7. Steel cover can also be selected by the user. Shoulder LTE along

the longitudinal joint ranges from 60% to 80%. The three types of shoulders given are bituminous, two feet extended driving lane, and tied shoulder. Outer distance to the wheel path is defaulted to 18 inches, but can be changed if needed. User-defined minimum crack spacing ranges from 0 to 24 inches. Maximum design life is used with 30 years and design reliability can be changed as needed.

General information input variables are:

- Slab Thickness
- Percent Long steel
- Reinforcing steel bar diameter
- Depth to steel
- Shoulder LTE
- Shoulder type
- Outer dist to wheel path
- User-defined minimum crack spacing
- Design life
- Design reliability

B. Traffic

B.1 Basic Inputs

These basic traffic inputs are used to compute total volume.

- Beginning year traffic
- Percent trucks
- Percent single- axle
- Percent tandem
- Percent tridem – 5-ft axle spacing
- Lane distribution factor
- Growth factor
- Total volume of traffic during service

Average daily traffic (ADT) is used based on current year traffic data. Percentage of trucks is the average percentage of truck among all categories of vehicles. The three classifications of truck axle groups considered in the traffic model are single, tandem, and tridem axle groups. The mix of trucks in the traffic volume is distributed by the user among three groups, and must total 100%. The user further distributes the traffic using a lane distribution factor (LDF). A growth factor is also assigned. The user can replace given values with other parameters in the traffic section of Input modules.

B.2 Load Limit Data

The load limit data specifies inputs relative to axle group (i.e. single, tandem, and tridem legal load limits.) Load limits shown in Table 2.1 are representative of typical axle load ranges. The user can change these values as needed.

Table 2.1 Load Limit for Axle Group

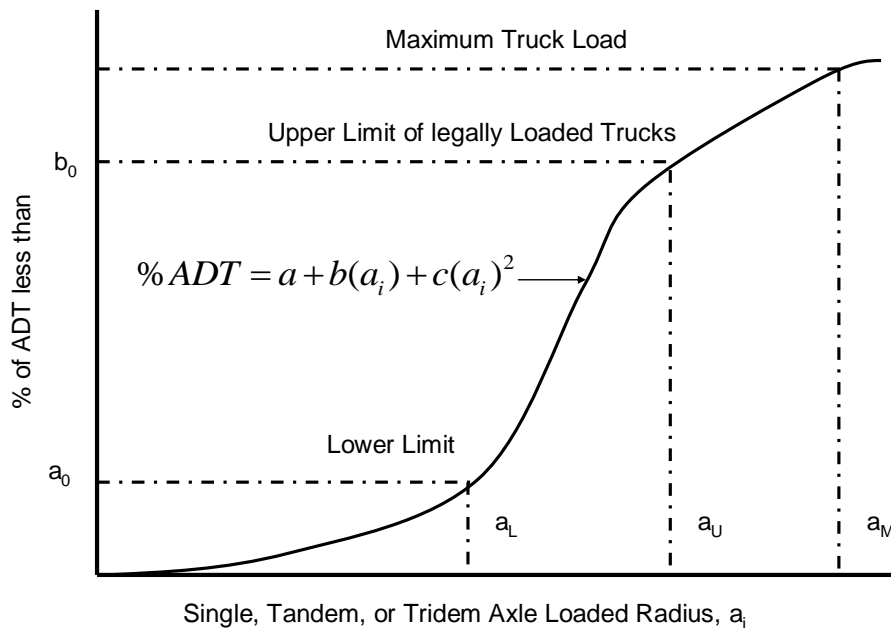|	Single Axle	Tandem Axle	Tridem Axle
Lower limit (kips)	9	25	40
Upper limit (kips)	21	36	54
Max limit (kips)	29	52	70

Figure 2.3 Traffic Model Used to Represent the Load Distribution for a Given Axle Type

Other factors considered are:

- Percentage of trucks within legal weight limits
- Percentage of lower load limit, percentage of upper load limit, and percentage of max load limit

Percentage of ADT is expressed in terms of which part is legal and which is not (i.e. exceeds legal weight limits.) Legal axle load group consist of vehicles which are both legal truck axles and passenger vehicles. On the other hand, illegal axles consist of overloaded trucks. The parameters (a_0 and b_0) represent the percentage of legal axles present in the traffic mix. Specifically, a_0 stands for the percentage of legal vehicle excluding trucks and b_0 includes all legal vehicles including those in the term, a_0. These terms (a_0 and b_0) are used to determine the coefficients of a, b, and c as shown in Figure 2.3 and the percentage of illegal axles. The load distribution (a_L, a_U and a_M) for a given axle type are related to a_0 and b_0. a_0 is the percentage of trucks with a loaded radius of a_L or less, and b_0 is the percentage of trucks with a loaded radius of a_L or less.

Accumulative traffic levels are determined in terms of an 18 kip single axle load for different distress types using Equation 1.5. This equation accounts for both legal and illegal axle loads. The first and second term $\left(\% \text{ of truck} \cdot \dfrac{ADT}{2} \right)$ expresses the one-way direction truck traffic volume. The next term, the lane distribution factor (LDF), ranges from 66% to 94 %, and is adjusted for the percentage of tracks in the design lane. The last term is expressed as percentage of axle group, configuration, and equivalent axle configuration.

$$ESAL_i = \% \text{ of truck} \cdot \frac{ADT}{2} \cdot LDF \cdot \sum_{j=1}^{3} \left[\left(\% ADT_{i+1} - \% ADT_{i,j} \right) A_j \cdot AEF \right]$$

(Eq 2.1)

where, i   = Load group

      j   = Axle configuration (Axle type)

      A_j = Load group (%)

      AEF   = Axle Equivalency Factor

      LDF   = Lane distribution Factor

$$ESAL_T = WEF \left(\sum ESAL_i \cdot LEF \right)$$

where, WEF   = Wander Equivalency Factor

      LEF   = Load Equivalency Factor

AEF and LEF can be determined from the equations listed in Table 2.2, which are dependent on distress types as listed in Table 2.3 and Table 2.4. The AEF of a single axle type is one, and that of the other types of axle are calculated using the listed expressions.

As noted previously, the equivalency depends on distress type. Since spalling and erosion distress modes are deflection–based, equivalency factors are determined from the load induced deflection caused by traffic. On the other hand, shallow spalling distress modes are fatigue damage based so the equivalency factors are stress-based.

Table 2.2 AEF and LEF for Axle Type

% Axle Type (A_j)	AEF_j	LEF_i
% of Single Axle (SA)	1	$10^{k_2(r_{18kips}-r_i)}$
% Tandem Axle (TA)	$10^{k_2(r_{SA}-r_{TA})}$	$10^{k_2(r_{36kips}-r_i)}$
% Tridem Axle (TR)	$10^{k_2(r_{SA}-r_{TR})}$	$10^{k_2(r_{54kips}-r_i)}$

$(k_2 = -17.61)$

Table 2.3 Equivalency Factors Based on Fatigue Stress

LEF						AEF			EDR
Axle load (Kips)	Single Axle	Axle load (Kips)	Tandem Axle	Axle load (Kips)	Tridem Axle	Single	Tandem	Tridem	
8	0.21	24	0.29	44	0.55				
10	0.28	26	0.35	46	0.62				
12	0.39	28	0.44	48	0.7				
14	0.53	30	0.54	50	0.79				
16	0.73	32	0.66	52	0.89	1	0.041	0.002	0.66
18	1	34	0.81	54	1				
20	1.37	36	1	56	1.13				
22	1.87	38	1.23	58	1.27				
24	2.57	40	1.51	60	1.44				
26	3.51	42	1.86	62	1.62				

Table 2.4 Equivalency Factors Based on Deflection Induced by Traffic

LEF						AEF			EDR
Axle load (Kips)	Single Axle	Axle load (Kips)	Tandem Axle	Axle load (Kips)	Tridem Axle	Single	Tandem	Tridem	
8	0.977	24	0.986	44	0.992				
10	0.981	26	0.988	46	0.994				
12	0.986	28	0.991	48	0.995				
14	0.991	30	0.993	50	0.997				
16	0.995	32	0.995	52	0.998	1	0.998	0.995	0.64
18	1	34	0.998	54	1				
20	1.005	36	1	56	1.002				
22	1.009	38	1.002	58	1.003				
24	1.014	40	1.005	60	1.005				
26	1.018	42	1.007	62	1.006				

C. Concrete Properties

The following are concrete properties used in this software package, relative to typical concrete properties. These can be changed by the user as needed.

- Poisson's Ratio
- PCC coefficient of thermal expansion
- Unit weight
- Compressive strength
- Modulus of Rupture, 28 days
- Tensile Strength, 28 days
- PCC elastic modulus, 28 days
- Concrete thermal diffusivity
- Concrete moisture diffusivity
- Coarse aggregate factor (CAF)
- Percent air required
- Water cement ratio
- Cementitious content
- Aggregate properties (AC, SG, UW, and Moisture contents)

Aggregate properties include unit weight, fineness modulus, absorption capacity, and total moisture content. Types of aggregate are classified as coarse, intermediate, and fine aggregate. Cement and fly ash type can also be specified, but if not classified are defaulted to Type I and Class C, respectively.

D. Environmental Condition

The following are inputs for environmental design factors.

- Relative humidity
- Temperature
- Annual wet days
- (Precipitation.>0.5 in/day) for year
- Avg. Annual Min temperature
- Season of construction

Seasonal relative humidity and temperature data is entered according to seasonal trends. The annual wet days are an important performance factor affecting erosion potential; this data is also available from the Long Term Performance Pavement (LTPP) database.

E. Base and Subgrade Materials

The inputs types for base and subgrade layer materials are:

- Base modulus
- Base thickness
- Base/Subbase type
- SELECT Subbase friction coefficient
- k-value

Modulus, thickness, material type, and friction coefficient are required inputs; the friction coefficient is determined according to material type (see Table 2.5). Subgrade k-value is also an important input value for structural analysis, but must be representative of the subgrade layer and not the top of the base.

Table 2.5 Friction Coefficients

Case Number	Subbase/Base Type	AASHTO Friction Coefficients.
1	Fine grained soil	*0.5 --1.3 -- 2*
2	Sand	*0.5 -- 0.8 -- 1*
3	Aggregate	*0.7 -- 1.4 -- 2*
4	Lime-stabilized clay	*3 -- 5.3*
5	ATB	*3.7 -- 5.8 -- 10*
6	CTB	*8 -- 34 -- 63*
7	LCB cured	*3.5 -- 4.5*
8	LCB not cured	*> 36*

Four input modules		#	Sheet name
		1	General
		2	Construction & Climatic Data
		3	Load Levels
		4	Concrete Mixture

Executing sheet — **Generating Climatic Profile, Gradients**

Main Result

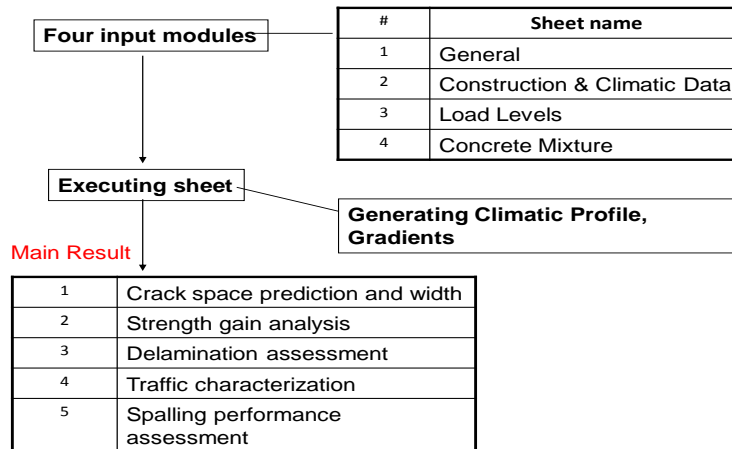| 1	Crack space prediction and width
2	Strength gain analysis
3	Delamination assessment
4	Traffic characterization
5	Spalling performance assessment

Figure 2.4 Overview of CRC-Spalling Program

II. Program Execution

An overview of the design program is shown in Figure 2.4. After the user completes all inputs, the design program can be executed to generate various output files needed to carry out the design assessment. The design involves clicking two buttons:
- Generate Climatic Data
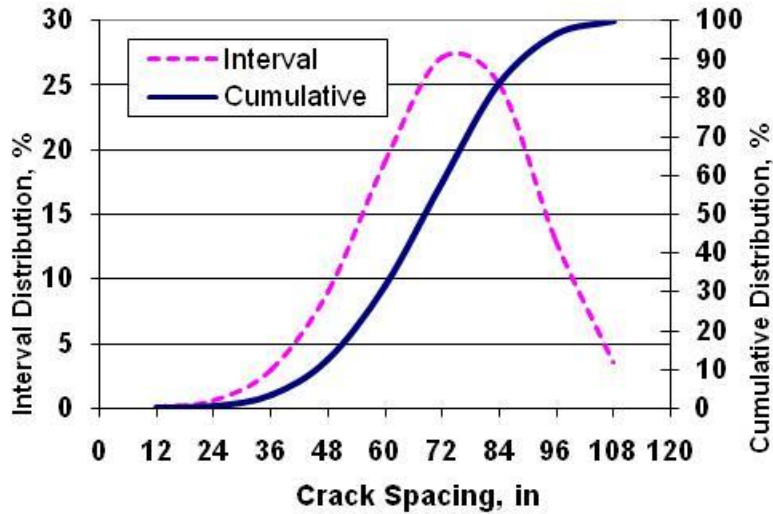- Generate Performance Assessment

Figure 2.5 Accumulative Crack Spacing vs Distribution %

III. Output Results

The objective of the design process is to assess the potential of spalling for a given pavement section and traffic level. Crack spacing, delamination assessment, strength gain, and traffic equivalencies are used to determine the potential for spalling models. The user must not jump to spalling assessment without generating the necessary supporting data.

A. Cracking spacing

Crack spacing prediction includes an estimate of the average crack spacing and standard deviation for a single layer of steel. The crack width is also computed based on the average crack spacing. The effect of the reinforcing steel is reflected through the amount and the age. The cracking pattern is assumed to conform to a Weibull distribution. Figure 2.5 shows the result of relationship between crack spacing and crack distribution.

B. Strength Gain

Shear strength is determined from the relationship between strength and the degree of hydration, which can be expressed as shown in Equation 2.2. Specifically, α_{hyd} can be assessed by the use of the maturity method which is a function of a temperature of the concrete, which is predicted at a given position by the design program. α and β are based on laboratory strength results. Shear strength at one inch below the surface is predicted from 0 to 48 hours as shown in Figure 2.6.

$$\frac{\tau}{\tau_u} = \alpha_{hyd} = e^{-\left(\frac{\beta}{t_e}\right)^{\alpha}}$$

(Eq 2.2)

where, τ = shear strength at age t_e (*psi*)

τ_u = ultimate shear strength (*psi*)

α_{hyd} = degree of hydration

α = shape constant

β = time constant

t_e = equivalent age (*h*) $\left(t_e = \sum_0^t \exp\left[\frac{E}{R}\left(\frac{1}{273+T_r} - \frac{1}{273+T_c} \right) \right] \cdot \Delta t \right)$

E = activation energy (J/mol)

R = universal gas constant (8.3144 J/mpl/K)

T_r = reference temperature ($^\circ C$)

T_c = average concrete temperature during time interval ($^\circ C$)

Δt = chronological time interval between temperature measurements (*h*)
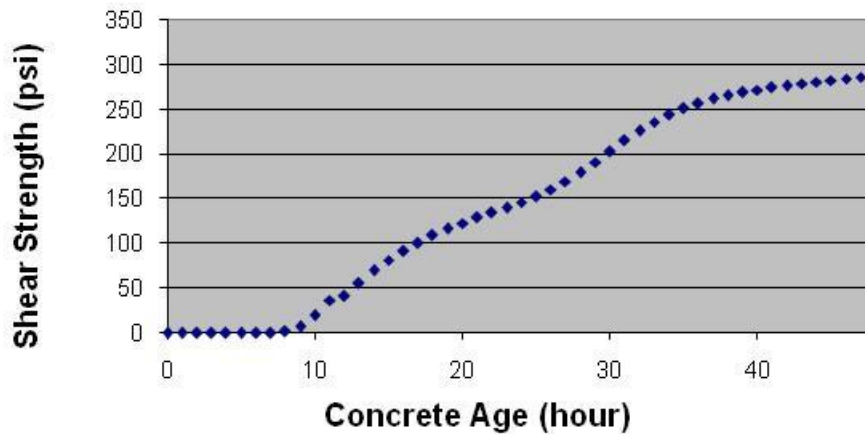

Figure 2.6 Shear Strength vs. Time

C. Delamination Assessment

Analysis of spalling potential is based on the potential for shallow and deep delamination. Shallow and deep delaminations are both dependent upon the shear stress at a certain depth below the pavement surface. Shear stress for shallow delamination is based on medium-thick plated theory and shear stress for deep delamination is created based on both plate theory and beam theory. Conditions necessary for formation of shallow delamination include low shear

strength (that typically occurs at the face between the aggregate and mortar) and sufficient evaporation of pore water from the hydrating concrete, resulting in differential drying shrinkage near the pavement surface. Shear stress (or delamination stress) can be determined based on slab curling and warping behavior under the effect of drying shrinkage and temperature change. Medium-thick plate theory provides the basis for several boundary conditions that were considered in the development of the coefficient equations. Curling and warping curvature within the horizontal *x-y* plane was modeled by deriving the curling and warping deformation model with respect to *x* and *y*. The coefficients substituted into the curling and warping curvature model can be used to determine the twisting moment and the shear or delamination stress derived from plate theory as:

$$M_{xy} = -D(1-v)w_{,xy}$$

(Eq 2.3)

$$\tau_{xy} = \frac{E_c z}{1+v} w_{,xy}$$

(Eq 2.4)

where, M_{xy} = twisting moment of the slab

D = flexural rigidity of the slab = $\dfrac{Eh^3}{12(1-v^2)}$

v = poisson's ratio

$w_{,xy}$ = curling and warping deformation

τ_{xy} = shallow delamination stress

E_c = concrete modulus of elasticity

z = distance from the middle depth of the slab to delamination depth

Shear stress due to curling and warping behavior is also a key to horizontal cracking at a greater depth coincidental with the plane of the reinforcing steel. The presence of the steel increases the stress levels due to modulus differences between the steel and the concrete. Deep delamination stress can be calculated using beam theory as shown in Equation 2.5.

$$\tau_{deep-dela} = \frac{\partial M_x}{\partial x}\frac{Q}{Dt} = \frac{\partial M_x}{\partial x}\frac{d_c}{D}\frac{(h-d_c)}{2} = -\frac{2\sigma_0}{\sqrt{2}\ell}\frac{d_c}{D}\frac{(h-d_c)}{2} = -\frac{E\varepsilon}{\sqrt{2}\ell}\frac{d_c}{D}\frac{(h-d_c)}{2}$$

(Eq 2.5)

where, $\tau_{deep-dela}$ = deep delamination stress

$\dfrac{\partial M_x}{\partial x}$ = horizontal shear at the level of steel

$$= \frac{\partial \sigma_x}{\partial x} \frac{h^2}{6} = -\frac{\sigma_0}{\ell} e^{-\frac{x}{\sqrt{2}\ell}} \left[\cos\left(\frac{x}{\sqrt{2}\ell} + \frac{\pi}{4} \right) + \sin\left(\frac{x}{\sqrt{2}\ell} + \frac{\pi}{4} \right) \right]$$

$$= -\frac{\sigma_0}{\ell} \left[\cos\left(\frac{\pi}{4} \right) + \sin\left(\frac{\pi}{4} \right) \right] = -\frac{2}{\sqrt{2}} \frac{\sigma_0}{\ell}$$

σ_0 $= \dfrac{E\varepsilon}{2}$ (FL^{-2})

ε $= \alpha \Delta T_{eq} + \varepsilon_\infty \Delta (1 - RH^3)_{eq}$

Q $=$ first moment of the area $= \displaystyle\int y dA = A^* y_c$

A^* $= d_c t$

d_c $=$ depth of cover (L)

y_c $= \dfrac{h - d_c}{2}$ (L)

t $=$ unit thickness perpendicular to the shear (L)

D $=$ moment of inertia of the slab cross section area (L^4/L)

The degree to which the concrete shear stress surpasses the concrete shear strength governs the degree or probability that delamination will occur. The probability that concrete shear stress exceeds in shear strength is expressed as (see Figure 2.7):

$$\mathrm{Prob}(\tau_{xy} - \tau_0 > 0) \quad \text{or} \quad \mathrm{Prob}(\tau_{deep-dela} - \tau_0 > 0)$$

(Eq 2.6)

where, τ_0 $=$ shear strength ($\tau_0 \sim \dfrac{f_t}{2} \sim \dfrac{1}{4} \cdot MoR \sim \dfrac{1}{20} f_c$)

f_t $=$ tensile strength,

MoR $=$ modulus of rupture
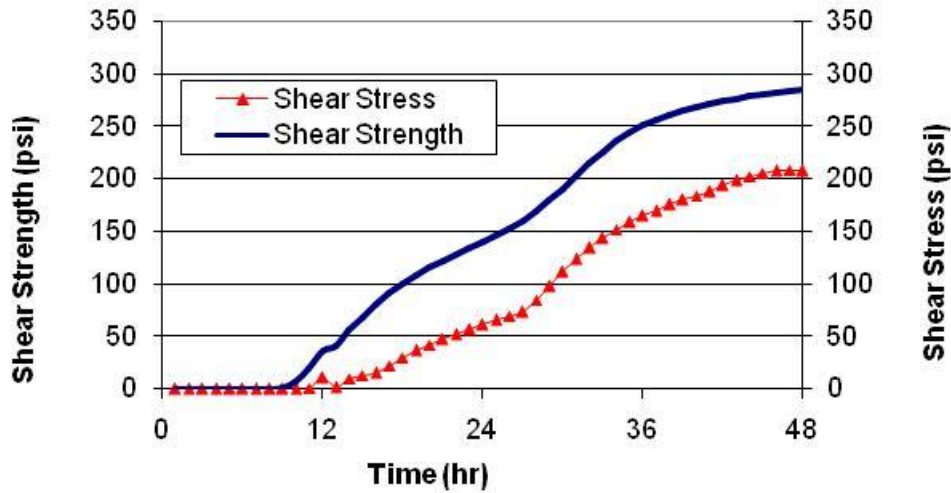
f_c $=$ compressive strength

Figure 2.7 Comparison of Early Age Strength and Stress for Delamination Possibility
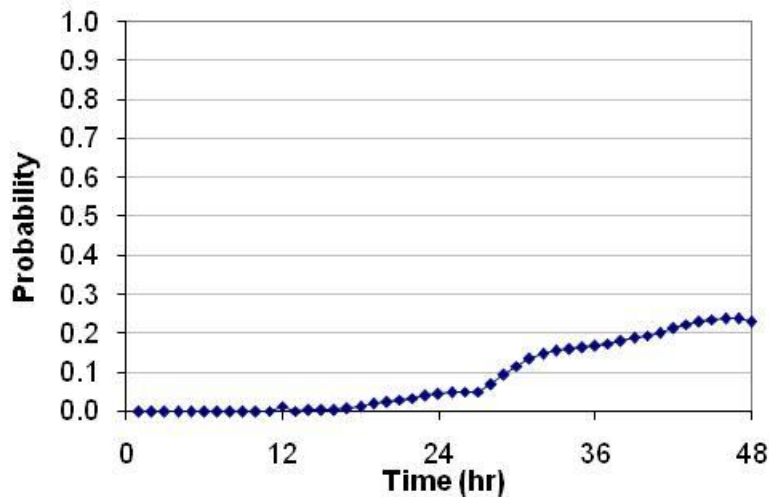

Figure 2.8 Probability of Delamination during the Early Age of Concrete

D. <u>Spalling Potential</u>

Spalling is not expected to occur without the presence of delamination; therefore, the probability of delamination should be determined to assess the possible number of spalled cracks that may occur based on the relation between concrete shear stress and strength under a specific set of site conditions. Specifically, the degree that concrete shear stress surpasses the concrete shear strength govern the degree that delamination can initiate. Thus, the probability is based on the difference of means of two populations of shear strength and stress which have a standard deviation made up from the variances of the two populations (see Figure 2.8). A spalling distress model, is suggested for calibration and for spalling prediction due to accumulated fatigue damage calibrated to field performance data. The spall performance

model with its attendant calibration parameters are expressed in Equation 2.7. The spalling model is designed with the exponential growth of spalling distress (S) with either traffic or fatigue damage (D). Relative to damage accumulation, the Weibull distribution α and β parameters control the shape and the rate of spall development predicted by the spall model, while the S_0 term represents the maximum amount of spalled cracks. A unique feature of the shape parameter is its relationship to the variability of performance, where its determination being based on field data not only establishes a calibrated mean value but also calibrates the performance reliability. The α and β parameters are therefore derived from performance data. The β can be determined from a minimum of two data points which are required for each site to determine the site coefficients with respect to percent of spalled cracking (S / S_0) and damage. The α can be expressed with exponential grow with surveyed condition and damage shape factor.

$$\% S = S_0 e^{-\left(\frac{D}{\alpha}\right)^{\beta}}$$

(Eq 2.7)

where S = number of spalls per 100 ft of pavement

S_0 = ultimate number of spalls per 100 ft of pavement

D = accumulated damage

α = damage scale factor of Weibull function, and

$= e^{\left(\frac{\beta x_2 - y_2}{\beta}\right)}$

β = damage shape factor of Weibull function

$= \beta = \dfrac{\ln[-\ln(y_2)] - \ln[-\ln(y_1)]}{\ln(x_2) - \ln(x_1)}$

y_1 = % of spalled cracking at initial condition

y_2 = % of spalled cracking at surveyed condition

x_1 = % of damage at initial condition

x_2 = % of damage at surveyed condition
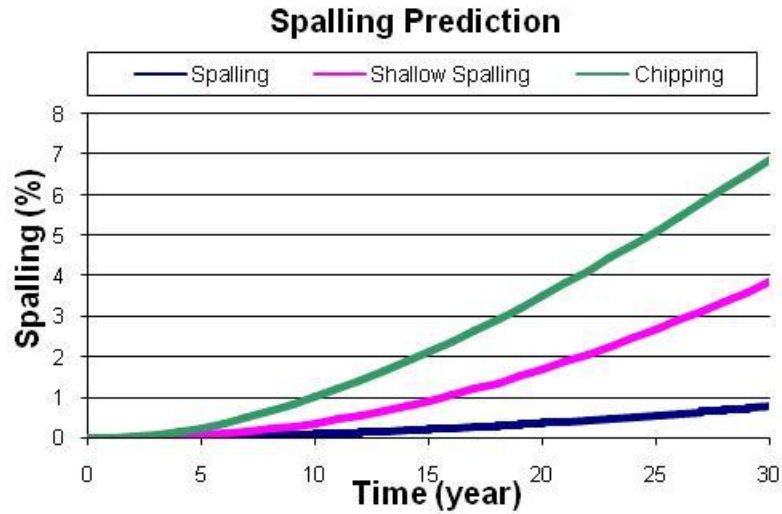
Spalling Prediction

Figure 2.9 Spalling vs Time

E. LTE vs Increment of Season

Load transfer efficiency is used to represent the transfer of load or distribution across joints or cracks (AASHTO, 1993). When a wheel load is applied at a joint or crack, both the loaded slab and adjacent unloaded slab can deflect. Thus, the degree of the deflection from unloaded slab can be considered as joint performance. LTE can be briefly expressed as:

$$LTE = \frac{\delta_L}{\delta_U} \times 100$$

(Eq 2.8)

where, δ_L = deflection of loaded slab

δ_U = deflection of unloaded slab

The LTE on the transverse crack for each time increment can be also calculated using Equation 2.9:

$$LTE = \frac{100}{1 + \log^{-1}\left[\dfrac{0.214 - 0.183\dfrac{a}{l} - \log(J_c)}{1.18}\right]}$$

(Eq 2.9)

where, LTE = Load transfer efficiency on the transverse crack due to aggregate interlock for the time increment (i), %

l = radius of relative stiffness, in

J_c = Transverse crack stiffness for the time increment (i)

a = loaded radius, in = 6 inch (This is a typical radius for a loaded area)

J_c can be calculated using coefficients and Equation 2.10. Coefficients of joint stiffness are listed in Table 2.6.

Table 2.6 Coefficients of Joint Stiffness for Faulting

Coefficient	a	b	c	d	e	f	g
Value	-4	-11.26	7.56	-28.85	0.35	0.382	56.25

$$Log(J_{cki}) = ae^{-e^{-\left(\frac{J_s-b}{c}\right)}} + de^{-e^{-\left(\frac{s_0-e}{f}\right)}} + ge^{-e^{-\left(\frac{J_s-b}{c}\right)}} \cdot e^{-e^{-\left(\frac{s_0-e}{f}\right)}}$$

(Eq 2.10)

And, s_0 is a function of the transverse crack width and PCC slab' thickness

$$s_0 = ae^{-0.039cw} = 0.0312h_{pcc}^{1.4578}e^{-0.039cw}$$

(Eq 2.11)

where, s_0 = Dimensionless shear capacity (the range is 0 to 0.9)

a = Ranges from 0.55 to 1.3 as a function of slab thickness $(=0.0312h_{pcc}^{1.4578})$

The shear stress (τ) on vertical crack face can be expressed as

$$\tau = Agg\frac{\delta_L(1-LTE_\delta)}{h} = Agg\frac{\delta_{fe}(1-LTE_\delta)}{h}$$

(Eq 2.12)

where Agg = Aggregate interlock factor (AIF)

h = Slab thickness

δ_L = Loaded slab deflection

δ_{fe} = Free edge slab deflection

LTE_δ = Deflection loaded transfer efficiency

AIF is commonly used in finite element representations of load transfer systems at joints and cracks. The shear stress (τ) on the crack face can be related to wear that occurs under the effect of load transfer across the joint. Furthermore, reference shear stress based on PCA test results can be expressed as

$$\tau_{ref} = 111.1 S_{pca} = 111.1(a + b(\ln(J_c))^2 + c(\ln(J_c)) + de^{-J_c})$$

(Eq 2.13)

where, τ_{ref} = Reference shear stress derived from the PCA test results

S_{pca} = Dimensionless shear stress

J_c = Joint stiffness

a = 0.0848

b = -3.64×10^{-4}

c = 1.88×10^{-2}

d = -6.357×10^{-3}

Loss in shear capacity (Δs) of a crack or joint occurs as a result of wheel loads passing over the joint; the amount of loss is a function of the width of the transverse crack. This condition was derived from the analysis of load transfer test data developed by PCA and is important for accounting for the effect of aggregate wear. If the ratio of crack width over slab thickness is less than 3.1, the crack is not sufficiently wide for deterioration in LTE to take place and $\Delta s_i = 0.0$. Otherwise:

$$\Delta s = \sum_j (0.069 - 1.5317e^{-cw/h}) \left(\frac{n_j}{10^6} \right) \left(\frac{\tau}{\tau_{ref}} \right)$$

(Eq 2.14)

where, Δs = loss in shear capacity accumulated over shear capacity loss due to load applications in each weight/ axle type group (*j*)

n_j = number of axle load application for current load level (*j*)

The level of shear capacity is adjusted to

$$s_{new} = s_i - \Delta s$$

(Eq 2.15)

where, s_{new}　　= Adjusted shear capacity

s_i　　= Previous value (*i*) of the dimensionless shear

In common, several factors affects LTE, which are temperature, number and magnitude of load application, crack spacing, and aggregate interlock, etc. The trends of LTE are plotted vs the increment of season effect as shown in Figure 2.10.
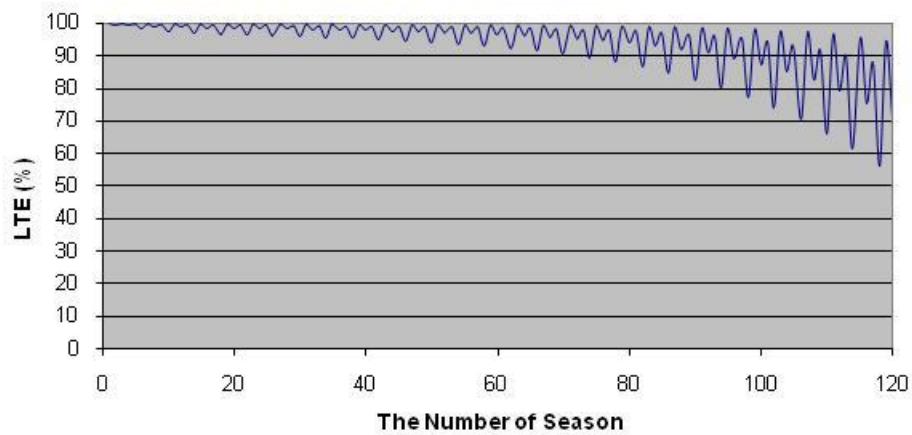

Figure 2.10 ⏐ LTE vs Seasonal Increment

REFERENCE

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User's Guide for TxCRCP-ME Design Software

<u>Ver. 0.1</u>

Volume II

Software Architecture

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SECTION 2: Spalling Evaluation of CRCP

APPENDIX A-C

SECTION 1: Structural Design of CRCP

INTRODUCTION

This document describes the architecture of the mechanistic-empirical CRCP design program, TxCRCP-ME developed under TxDOT Research Project 0-5832. As described in Volume I, the User's Guide, the software was developed in the MS Office Excel 2007, following the conceptual algorithm shown below. The role of each executable module can be found in Chapter 4 of research report 0-5832-1.

Figure 1.1 illustrates the overall design flow diagram. With input values provided by the user, critical concrete stress is evaluated at each month during the design period. The critical stress is used to estimate damages in the concrete slab using a fatigue equation and wheel loading applications. Damages are accumulated each month and the number of punchouts is estimated by a transfer function. The total number of punchouts per mile estimated at the end of the design life is compared with the limiting design criteria provided by the user and the acceptability of the design is determined. In this version of the software, v0.1, the user is required to provide a trial slab thickness as an input and the number of punchouts at the end of the design life is estimated. Accordingly, this version of the software is not a design program. Effort is underway to make this program a true design program, where the program automatically determines the minimum slab thickness that meets the given design criteria.
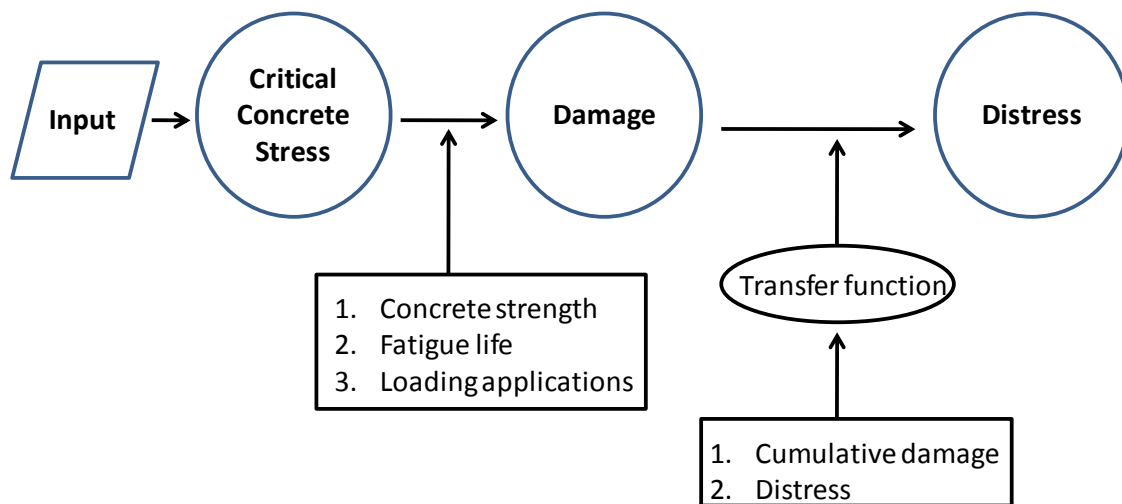
Figure 1.1 Overall design flow of mechanistic-empirical CRCP design program

ARCHITECTURE OF THE DESIGN SOFTWARE

Programming in MS Office Excel is quite simple and straightforward. The most complicated task in the development of this software was the estimation of critical concrete stresses. In this program, concrete stresses were evaluated using three-dimensional finite element analysis. The detailed description of the concrete stress analysis is described in Chapter 3 of the research report 0-5832-1. To facilitate computations and increase the efficiency of the software, critical concrete stresses were tabulated and imported to Excel.

Figure 1.2 illustrates the architecture of the design software. Red circled numbers indicate a specific variable, and will be used throughout this document to describe how that variable is used in the program. It shows that the program can be divided into three subsections. Subsection #1 determines critical concrete stresses. The input variables under the left "Inputs" column are used to estimate critical concrete stresses.
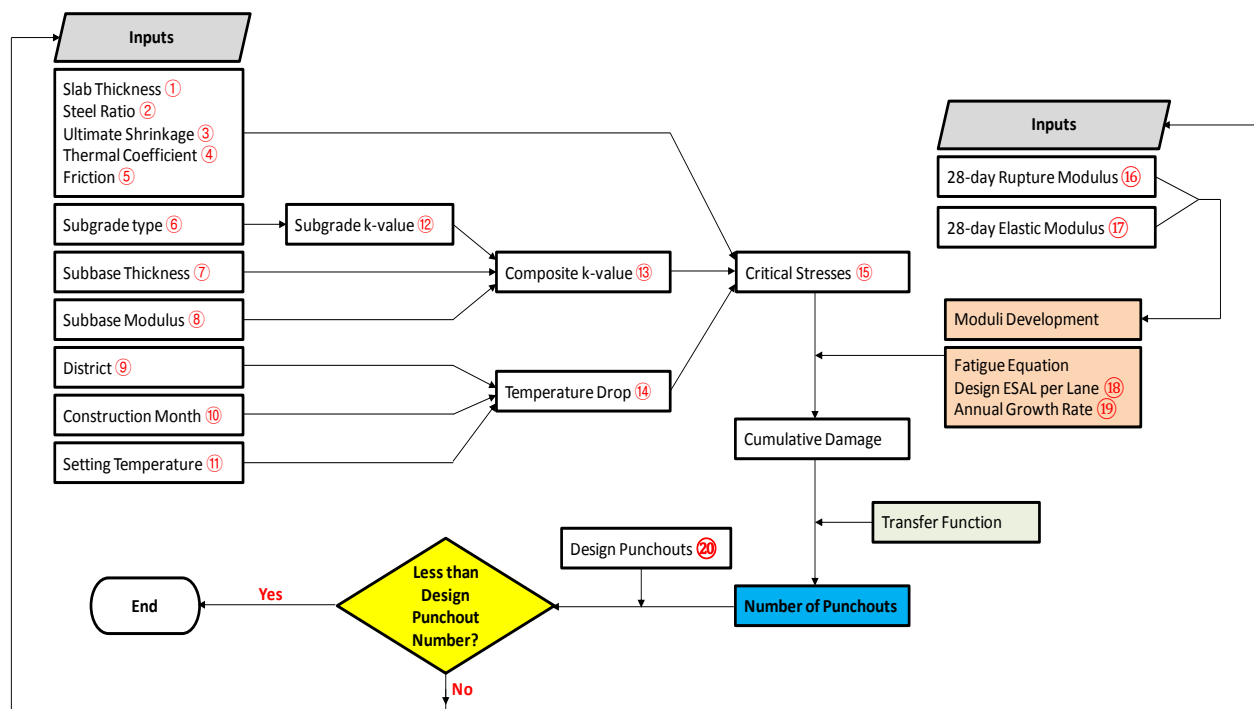
Figure 1.2 Architecture of TxCRCP-ME software

Subsection #2 computes cumulative damage in the pavement. The input variables under the right "Inputs" column are used to estimate cumulative damage in the pavement slab. Subsection #3 calculates the number of punchouts per mile, using the information on cumulative fatigue damage and a transfer function.

The program consists of 16 sheets in Excel. The names of the 16 sheets are:

1. Inputs
2. Stress
3. Temperature
4. DT=-55F
5. DT=-25F
6. DT=5F
7. DT=35F
8. DT=65F
9. DT=95F
10. k-Table
11. Composite k
12. Analysis Results
13. Time vs. Punchouts
14. Summary
15. Time vs. Cumulative Damage
16. Cumulative Damage vs. Punchouts

Of the 16 sheets, the last three sheets are for information only and are hidden. Only 13 sheets are visible. If the user wants to see the information on the last three sheets, the user must right-click and select the "unhide" option. A small "Unhide" window appears with the list of hidden sheets. The user needs to select the sheet and click "Ok."

I.   General Inputs

The user provides inputs in the "Inputs" sheet, the first sheet. Once the "Inputs" sheet is selected, the input screen as shown in Figure 1.3 appears. In the input screen, all the required fields are provided by the user. There are seven categories of inputs as follows:

1) Project information

2) Design parameters (design life and criteria on punchouts per mile)

3) Design traffic (design ESALs and annual growth rate)

4) Steel design (longitudinal steel amount and bar diameter)

5) Construction information (concrete placement month)

6) Concrete materials/layer information

   a. Slab thickness

   b. Coarse aggregate type

  c. Concrete setting temperature

  d. Coefficient of thermal expansion

  e. Ultimate drying shrinkage

  f. 28-day compressive or flexural strength

  g. 28-day modulus of elasticity

7) Subbase layer information

  a. Subbase type

  b. Subbase thickness

  c. Modulus of subbase layer

  d. Subbase friction

  e. Subgrade layer information (Type of subgrade soil is provided per AASHTO or Unified Classification System.)
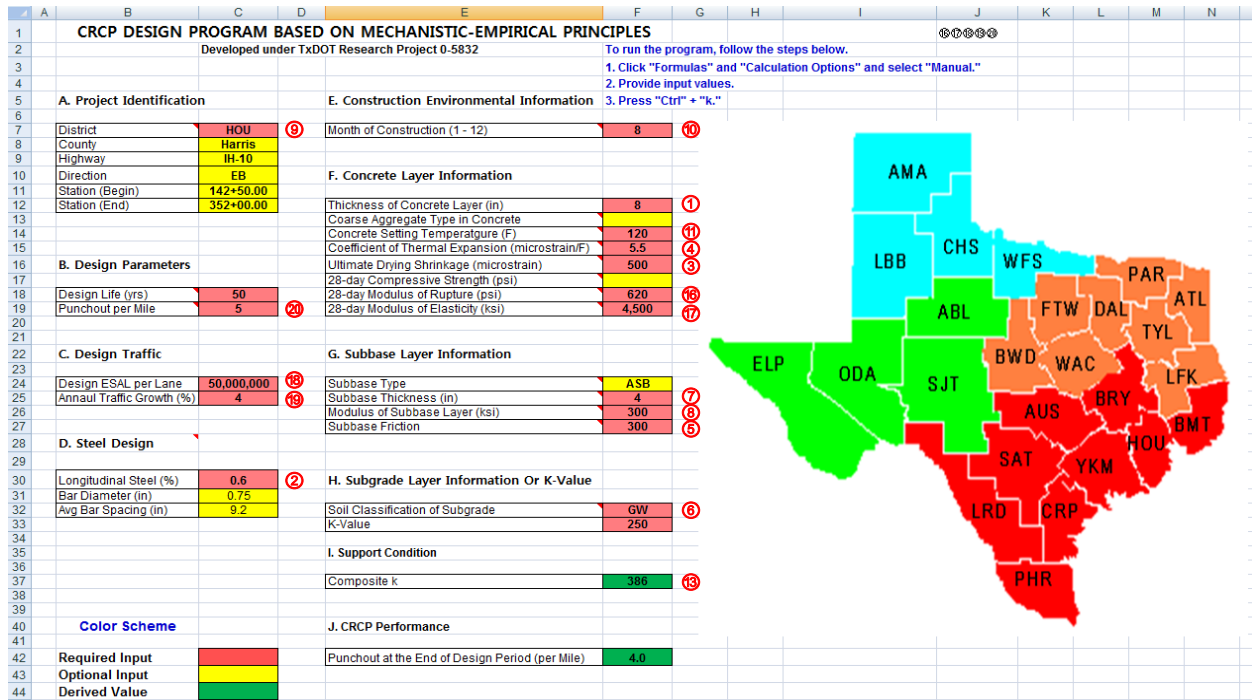
Figure 1.3 Input screen with typical input values

The details of these input variables are described in companion Volume I "User's Guide" and are not repeated here. Once the input values are provided by the user, the values are automatically shared with other sheets in the program and CRCP structural responses are computed.

As shown in Figure 1.2, critical concrete stresses are determined from given input values. Figure 1.4 shows the algorithm to compute critical concrete stresses. It illustrates that for the determination of concrete critical stresses, the composite k value and temperature drops (delta T) need to be estimated first. Values for other variables are direct inputs.
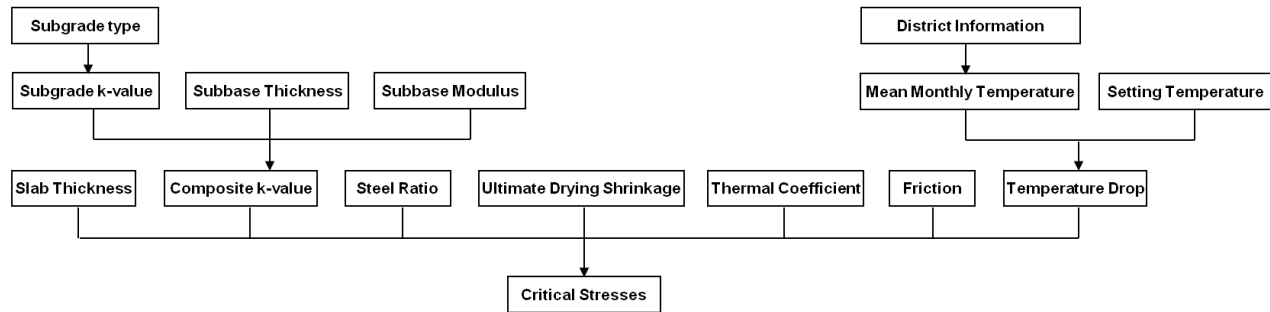
Figure 1.4 Overall algorithm of critical stress estimation

II.   Composite k

The composite k is based on the modulus of subgrade reaction of the subgrade soil and resilient modulus of the subbase material as shown in the top left of the algorithm in Figure 1.4. The derivation of composite k is described in the Appendix A of research report 0-5832-1. The results of the analysis for composite k are tabulated in the "k-Table" sheet.

To estimate the composite k-value, three parameters are required: subgrade k-value, subbase thickness, and subbase modulus. The subgrade k-value is obtained based on the subgrade type the user selected. The k-value for each soil type is embedded in the "Composite k" sheet. For example, if the user selects "GW" for subgrade type, the subgrade k-value is estimated as 300 psi/in. On the other hand, the values for subbase thickness and subbase modulus are directly defined by the user. Once a certain combination of the subgrade type and subbase information is provided, the program automatically recalls the composite k-value in the "k-Table" sheet, using the "DSUM" function included in MS Office Excel. Figure 1.5 shows an example of how the DSUM function operates in Excel. The upper table in Figure 1.5 represents the example combination of variables provided by the user from the "Composite k" sheet. The role of the DSUM function is to find the same variable combination in the "k-Table" sheet as shown in the lower table in Figure 1.5. Once the identical combination of values for three variables – subbase thickness, subgrade k and subbase modulus – is found, the DSUM function selects the value in the fourth column of the table, i.e. composite k-value, as output and the value is shared in cell

A5 in the "Composite k" sheet. This process of estimating composite k can be summarized as shown in Figure 1.6.

Subgrade Type	Subgrade k (psi/in.)	Subbase Thickness (in.)	Subbase Modulus (ksi)
GW	300	3	400

Input variables

Subbase Thickness (in.)	Subgrade k (psi/in.)	Subbase Modulus (ksi)	Composite k-value (psi/in)
3	250	1800	536
3	250	1900	548
3	250	2000	560
3			336
3			339
3	300	70	342
3	300	80	346
3	300	90	349
3	300	100	352
3	300	150	361
3	300	200	371
3	300	250	380
3	300	300	389
3	300	350	397
3	300	400	405
3	300	450	
3	300	500	
3	300	550	427
3	300	600	434
3	300	650	441
3	300	700	448
3	300	750	455
3	300	800	461
3	300	850	468
3	300	900	475
3	300	950	482
3	300	1000	489
3	300	1100	501

Find same combination in database

Output

Figure 1.5 Example of DSUM function
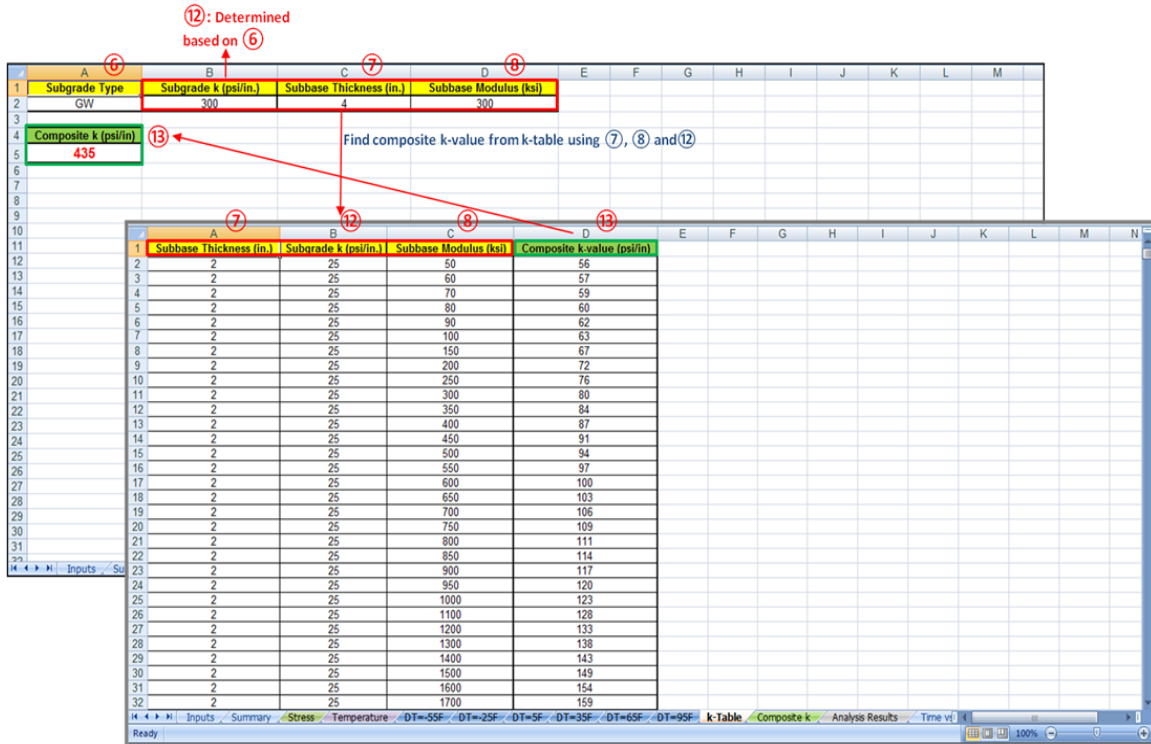
Figure 1.6 Estimation of composite k value

III. Temperature Drop (delta T)

As described in Volume I: User's Guide for TxCRCP-ME, this software considers environmental loading (temperature variations) and wheel loading for critical concrete stresses. Ambient and concrete temperatures vary constantly, and stress computations due to temperature variations could be quite intensive if the computations are carried out on an hourly basis or even on a daily basis. Since the concrete material is assumed to be linear elastic in this program, the use of the mean monthly temperature will be valid and the computations greatly simplified. Based on historical weather records, the monthly mean temperature (MMT) at each district in the state of Texas were determined and tabulated in the sheet "Temperature," shown in Figure 1.7. Once the user determines the district and construction month information, the MMT for the next 12 months is indicated in the fifth column of the table, as seen in Figure 1.7. It is assumed that this mean monthly temperature will repeat for the design period.
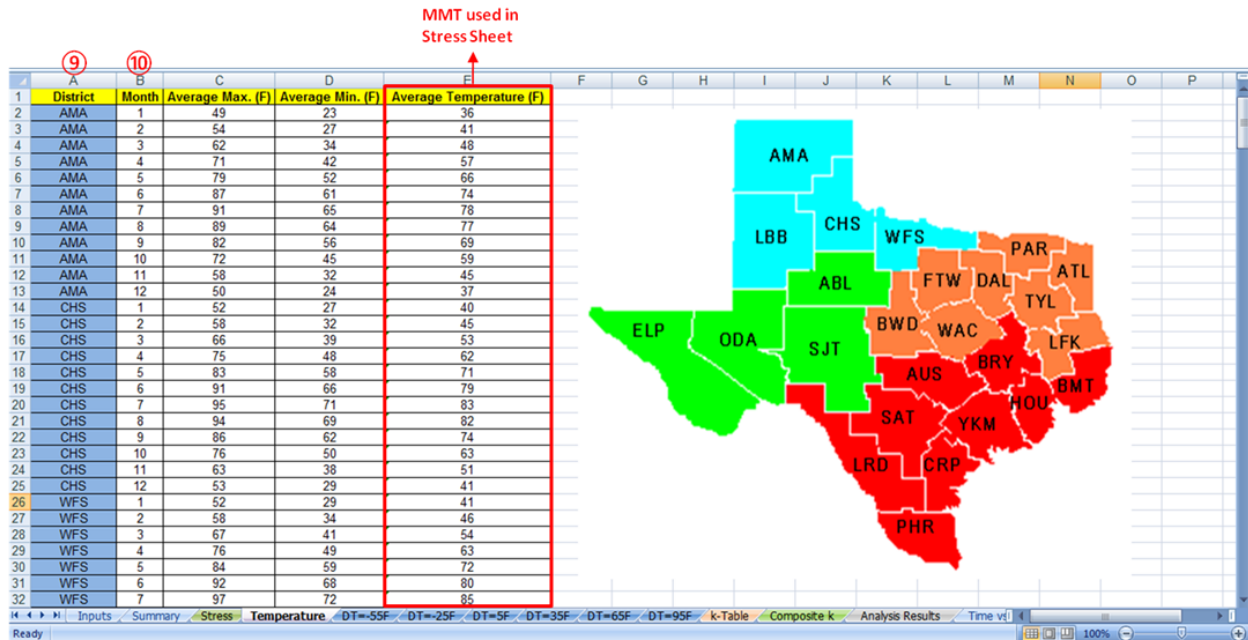
Figure 1.7 Mean monthly temperature for each district

Figure 1.2 shows that once composite k and delta T are determined, the next step is to compute critical concrete stresses.

IV. Critical Concrete Stress

As described in Chapter 3 in the report 0-5832-1, critical stresses were evaluated using the three-dimensional FEM analysis for a total of 5,708,430 combinations: 17 levels of slab thickness, 41 levels of composite k-value, five levels of steel ratio, seven levels of ultimate drying shrinkage, 13 levels of thermal coefficient of concrete, three levels of friction, and six levels of temperature drop. As discussed in Chapter 3 of research report 0-5832-1, critical stresses due to environmental loading were evaluated at six different levels of temperature drop (delta T), i.e. -55 to 95 °F in 30 °F increments. Figure 1.8 illustrates the stress values for a delta T of - 55 ºF at various pavement conditions (different pavement structures, composite k values, steel percentages, shrinkage values, coefficients of thermal expansion and friction values). There are six sheets in the program, each of them for a specific delta T. Each sheet has 951,405 rows.

Slab Thickness (in.)	Modulus of Subgrade Reaction (pci)	Steel Ratio (%)	Ultimate Drying Shrinkage (microstrain)	Coefficient of Thermal Expansion (microstrain/F)	Friction (psi/in.)	Stress (T) (psi)	Stress (E) (psi)
6	100	0.5	300	4	100	438.19	-199.88
6	100	0.5	300	4	300	438.19	-199.88
6	100	0.5	300	4	500	438.19	-199.88
6	100	0.5	300	4.25	100	438.19	-199.97
6	100	0.5	300	4.25	300	438.19	-199.97
6	100	0.5	300	4.25	500	438.19	-199.97
6	100	0.5	300	4.5	100	438.19	-200.06
6	100	0.5	300	4.5	300	438.19	-200.06
6	100	0.5	300	4.5	500	438.19	-200.06
6	100	0.5	300	4.75	100	438.19	-200.14
6	100	0.5	300	4.75	300	438.19	-200.14
6	100	0.5	300	4.75	500	438.19	-200.14
6	100	0.5	300	5	100	438.19	-200.23
6	100	0.5	300	5	300	438.19	-200.23
6	100	0.5	300	5	500	438.19	-200.23
6	100	0.5	300	5.25	100	438.19	-200.32
6	100	0.5	300	5.25	300	438.19	-200.32
6	100	0.5	300	5.25	500	438.19	-200.32
6	100	0.5	300	5.5	100	438.19	-200.41
6	100	0.5	300	5.5	300	438.19	-200.41
6	100	0.5	300	5.5	500	438.19	-200.41
6	100	0.5	300	5.75	100	438.19	-198.33
6	100	0.5	300	5.75	300	438.19	-198.33
6	100	0.5	300	5.75	500	438.19	-198.33
6	100	0.5	300	6	100	438.19	-196.26
6	100	0.5	300	6	300	438.19	-196.26
6	100	0.5	300	6	500	438.19	-196.26
6	100	0.5	300	6.25	100	438.19	-194.18
6	100	0.5	300	6.25	300	438.19	-194.18
6	100	0.5	300	6.25	500	438.19	-194.18
6	100	0.5	300	6.5	100	438.19	-192.1

Inputs / Summary / Stress / Temperature / DT=-55F / DT=-25F / DT=5F / DT=35F / DT=65F / DT=95F / k-Table / Composite k / Analysis Results / Time vs

Figure 1.8 Critical concrete stresses at various conditions with delta T of –55 ºF

Critical concrete stresses are calculated in the sheet "Stress." First, delta T is computed as shown in Figure 1.9. In Figure 1.9, MMT for each month is imported from the "Temperature" sheet using the DSUM function for District and Month. This example shows the Houston District, where the concrete will be placed in August with a setting temperature of 95 ºF. In column E, delta T is computed for each month (Setting temperature – Column C).

	District	Month	MMT (F)	Setting Temp.	dT (F)	Stress (T) (psi)	Stress (E) (psi)
2	HOU	8	84	95	11	174.92	142.15
3	HOU	9	81		15	174.92	143.93
4	HOU	10	72		23	174.92	148.24
5	HOU	11	63		32	174.92	152.82
6	HOU	12	56		39	174.92	155.98
7	HOU	1	54		41	174.92	156.80
8	HOU	2	58		38	174.92	155.36
9	HOU	3	65		31	174.92	152.05
10	HOU	4	70		25	174.92	149.26
11	HOU	5	77		18	174.92	145.70
12	HOU	6	83		13	174.92	142.91
13	HOU	7	85		11	174.92	141.89

Figure 1.9 Delta T computation & critical concrete stress in "Stress" sheet

This delta T information is used to compute critical concrete stresses in each month. Since stress tables were developed only for six delta T values, concrete stress values at a delta T between the pre-determined delta T values are computed using a linear interpolation method as shown in Figure 1.10. Stress (T) and Stress (E) in the table indicate the derived stresses due to traffic and environmental loadings, respectively. It shows that critical concrete stress due to wheel loading stays constant throughout the year. Only environmental stresses vary month to

month. In this program, it is assumed that concrete is a linear elastic material, and the superposition principle applies. Once the critical concrete stresses due to environmental and wheel loadings are determined, these stresses are imported into the sheet "Analysis Results," for fatigue and damage estimations.
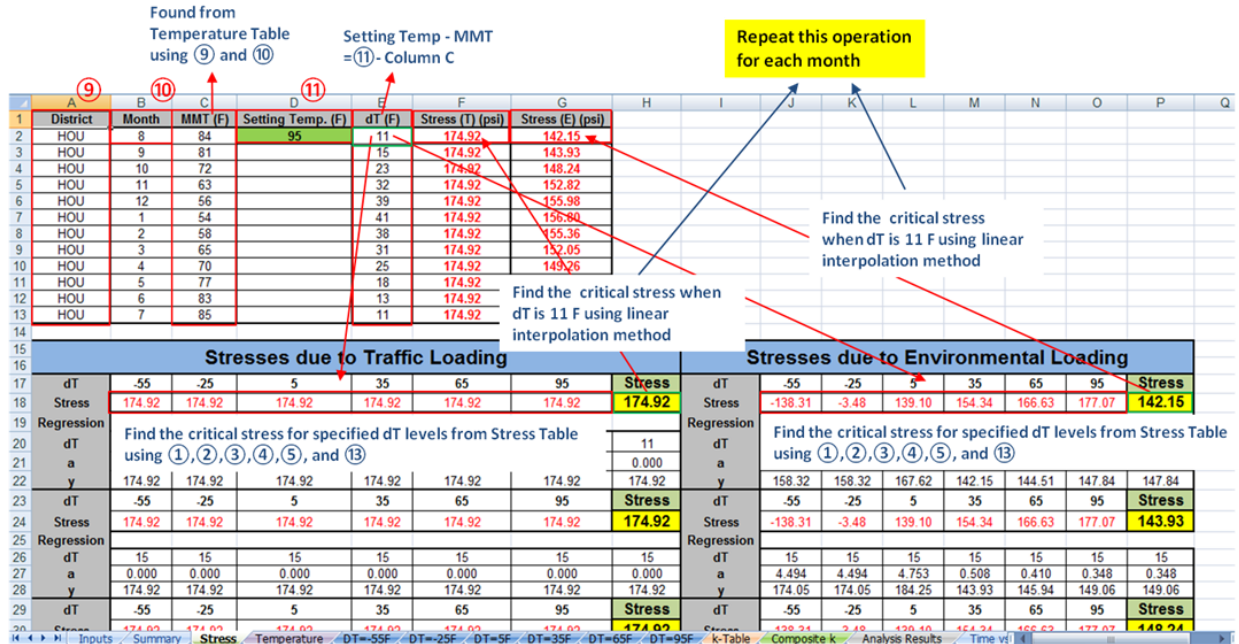
Figure 1.10 Determination of critical concrete stresses due to traffic and environmental loading

V.   Fatigue Life of Concrete Slab & Damage Estimation

Figure 1.11 shows the Analysis Results sheet. Columns A and B illustrate months and years after the construction, respectively. Columns C and D show concrete modulus of rupture and modulus of elasticity, respectively. Variations of concrete modulus of rupture over time were assumed to follow the same rate as for compressive strength gain in the ACI equation, as shown in Eq 1.1.

$$f'_{c(t)} = f'_{c(28)} \left(\frac{t}{4+0.85t} \right)$$ (Eq 1.1)

where, $f'_{c(t)}$ is the compressive strength at age t (psi);
   $f'_{c(28)}$ is the compressive strength at 28-day (psi); and
   t is the age in days.

Since modulus of elasticity of concrete is proportional to the square root of compressive strength, the gain in modulus of elasticity over time was assumed to be proportional to the square root of compressive strength.

2-10

Critical concrete stresses determined in the "Stress" sheet are imported into Columns E and F of the "Analysis Results" sheet for environmental and traffic loading, respectively, for each month for the duration of the design life. Column G is for the combined critical concrete stress, which is the sum of stresses in Columns E and F (environmental and traffic loadings). In the program, the two columns E and F are hidden to make room for other variables so that most of the columns in this sheet are viewed in one screen.

Pavement Age Month	Year	Concrete Modulus of Rupture (psi)	Concrete Modulus of Elasticity (ksi)	Concrete Stress (psi)	Maximum Stress Ratio (psi/psi)	Number of Load Repetitions to Failure	Number of Load Repetitions	Pavement Damage	Cumulative Damage	Number of Punchouts per Mile
1	0.08	620	4.50E+03	302.85	0.488	3.95E+06	5.76E+04	1.46E-02	1.46E-02	1.58E+00
2	0.17	676	4.70E+03	310.21	0.459	5.08E+06	5.78E+04	1.14E-02	2.60E-02	1.59E+00
3	0.25	693	4.76E+03	315.99	0.456	5.21E+06	5.80E+04	1.11E-02	3.71E-02	1.59E+00
4	0.33	702	4.79E+03	321.26	0.458	5.13E+06	5.82E+04	1.14E-02	4.84E-02	1.59E+00
5	0.42	707	4.81E+03	324.85	0.459	5.05E+06	5.84E+04	1.16E-02	6.00E-02	1.60E+00
6	0.50	711	4.82E+03	326.02	0.459	5.08E+06	5.86E+04	1.15E-02	7.15E-02	1.60E+00
7	0.58	713	4.83E+03	324.91	0.455	5.23E+06	5.88E+04	1.12E-02	8.28E-02	1.60E+00
8	0.67	715	4.83E+03	321.92	0.450	5.49E+06	5.90E+04	1.08E-02	9.35E-02	1.61E+00
9	0.75	717	4.84E+03	319.37	0.445	5.71E+06	5.92E+04	1.04E-02	1.04E-01	1.61E+00
10	0.83	718	4.84E+03	316.05	0.440	6.00E+06	5.94E+04	9.90E-03	1.14E-01	1.61E+00
11	0.92	719	4.85E+03	313.44	0.436	6.24E+06	5.96E+04	9.56E-03	1.23E-01	1.62E+00
12	1.00	720	4.85E+03	312.54	0.434	6.34E+06	5.98E+04	9.43E-03	1.33E-01	1.62E+00
13	1.08	721	4.85E+03	312.85	0.434	6.34E+06	6.00E+04	9.47E-03	1.42E-01	1.62E+00
14	1.17	721	4.85E+03	314.64	0.436	6.22E+06	6.02E+04	9.68E-03	1.52E-01	1.63E+00
15	1.25	722	4.86E+03	318.88	0.442	5.91E+06	6.04E+04	1.02E-02	1.62E-01	1.63E+00
16	1.33	722	4.86E+03	323.37	0.448	5.60E+06	6.06E+04	1.08E-02	1.73E-01	1.63E+00
17	1.42	723	4.86E+03	326.49	0.452	5.40E+06	6.08E+04	1.12E-02	1.84E-01	1.64E+00
18	1.50	723	4.86E+03	327.32	0.453	5.36E+06	6.10E+04	1.14E-02	1.96E-01	1.64E+00
19	1.58	723	4.86E+03	325.96	0.451	5.46E+06	6.12E+04	1.12E-02	2.07E-01	1.64E+00
20	1.67	724	4.86E+03	322.77	0.446	5.69E+06	6.14E+04	1.08E-02	2.18E-01	1.65E+00
21	1.75	724	4.86E+03	320.08	0.442	5.89E+06	6.16E+04	1.05E-02	2.28E-01	1.65E+00
22	1.83	724	4.86E+03	316.65	0.437	6.16E+06	6.18E+04	1.00E-02	2.38E-01	1.65E+00
23	1.92	724	4.86E+03	313.95	0.433	6.38E+06	6.20E+04	9.72E-03	2.48E-01	1.65E+00
24	2.00	725	4.87E+03	312.98	0.432	6.47E+06	6.22E+04	9.62E-03	2.57E-01	1.66E+00
25	2.08	725	4.87E+03	313.25	0.432	6.45E+06	6.24E+04	9.68E-03	2.67E-01	1.66E+00
26	2.17	725	4.87E+03	315.00	0.434	6.32E+06	6.26E+04	9.92E-03	2.77E-01	1.66E+00
27	2.25	725	4.87E+03	319.22	0.440	5.99E+06	6.28E+04	1.05E-02	2.88E-01	1.67E+00
28	2.33	725	4.87E+03	323.68	0.446	5.67E+06	6.31E+04	1.11E-02	2.99E-01	1.67E+00
29	2.42	725	4.87E+03	326.77	0.450	5.47E+06	6.33E+04	1.16E-02	3.10E-01	1.67E+00
30	2.50	726	4.87E+03	327.59	0.451	5.42E+06	6.35E+04	1.17E-02	3.22E-01	1.68E+00

Figure 1.11 Analysis Results sheet showing the final results

The combined critical concrete stress is shown in Column G. Each month, critical concrete stress is estimated and the ratio of this critical concrete stress (Column G) to concrete strength (Column C) is computed. This ratio is used to compute fatigue life of the slab each month. Allowable fatigue life is estimated by the equation developed by Vesic, as shown in Eq 1.2.

$$N_i = 225{,}000 \left(\frac{\sigma}{MR}\right)^4 \qquad \text{(Eq 1.2)}$$

where, N_i is the fatigue number;
MR is the modulus of rupture (psi); and
σ is the tensile concrete stress (psi).

For concrete stress, the value in the vicinity of longitudinal steel reinforcement at a transverse crack derived from 3-dimensional analysis was used for Equation 1.2. This equation was developed assuming a modulus of rupture for plain concrete. The fatigue behavior of concrete near longitudinal steel might be slightly different. There are no equations available for the fatigue behavior of concrete near reinforcement due to static and dynamic loading. However, as long as there is no large difference in the shape of the fatigue equations, errors due to not using the exact fatigue equation will be minimized by the selection of a proper transfer function.

Once the allowable fatigue life and modulus development of the concrete slab are determined, damage caused by wheel load applications and environmental loading is computed by dividing the monthly traffic (Column J) by the allowable fatigue number (Column I). Damages thus estimated are shown in Column K. Damage computed at the end of each month is accumulated through the design period and shown in Column L.

VI.   Estimation of Number of Punchouts per Mile

A transfer function provides the conversion of cumulative damage in concrete to the frequency of punchouts. The development of a punchout is quite complicated, and it's almost impossible to develop a purely mechanistic punchout development model. A relational function that correlates concrete damage to punchout development is required. In mechanistic-empirical based pavement design procedures, the development of an accurate transfer function is quite critical. The detailed discussions of the development of a transfer function for this program are presented in Chapter 4 of research report 0-5832-1 and are not repeated here. The transfer function incorporated in the current version of the program is as follows:

$$y = 1.5801 \cdot e^{0.1871x} \hspace{4cm} \text{(Eq 1.3)}$$

where, y is the number of punchouts per mile; and
x is the accumulated damage over the period.

The number of punchouts per mile estimated using the Eq 1.3 with the cumulative damage in Column L is shown in Column M.

The development of punchouts for the design period is presented in a graphical form in the "Time vs. Punchout" sheet as shown in Figure 1.12.
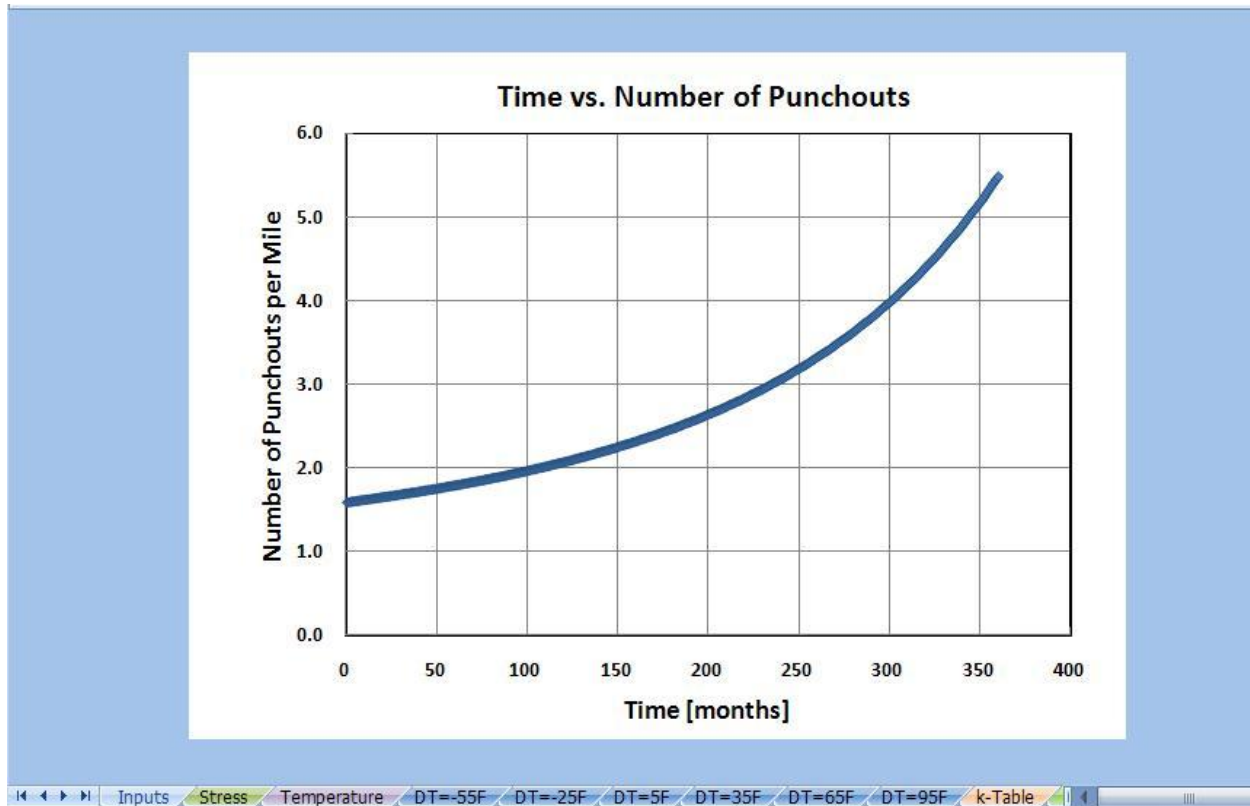
Figure 1.12 Analysis results in a graphical form

SUMMARY

The TxCRCP-ME software was developed in MS Office Excel 2007. There are a total of 13 sheets that perform various functions. Programming in MS Office Excel is quite simple and straight forward. The most complicated task in the development of this software was the estimation of critical concrete stresses. To facilitate computations and increase the efficiency of the software, critical concrete stresses were tabulated and imported to Excel. Due to its setup, the program file size is quite big, more than 197 MB. It may take a while to load the software. However, full execution of the program takes less than two minutes even for quite complicated designs.

SECTION 2: Spalling Evaluation of CRCP

INTRODUCTION

This manual is a guide for the CRC-Spalling program which can be operated under the Vista or later versions of the Windows operating system. The 2003 or 2007 version of Microsoft Office Excel is used to input and analyze data relevant to the design of continuously reinforced concrete (CRC) pavement. In the spread sheet, various factors are calibrated in order to accurately estimate the characteristics of spalling distress.

<Inputs>
- General
- Construction & climatic data
- Load Levels
- Concrete mixture

1. Load and climatic character
2. Construction effects
3. Strength

1. Crack pattern
2. Delamination potential
3. Damage

- Distress

1. Probability
2. Fatigue life

1. Damage scale factor
2. Damage shape factor

1. Cumulative damage
2. Distress
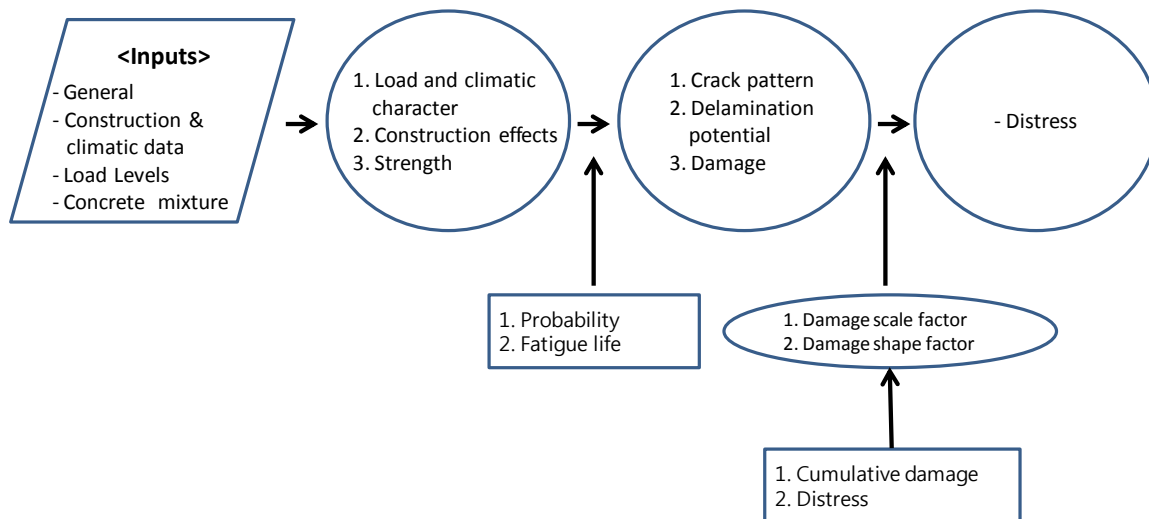
Figure 2.1 Framework of the TxCRCP-ME program for spalling

ARCHITECTURE OF THE DESIGN SOFTWARE

The TxCRCP-ME design software for spalling is composed of four operational modules as illustrated in Figure 2.1. The CRC-Spalling program consists of three categories of modules: input, executing, and results modules. Moreover, other modules that are invisible to the user are also contained in the program but are only briefly described. Basic input modules are:

- General
- Construction & Climatic Data
- Load Levels
- Concrete Mixture

The General module addresses design-related aspects such as traffic, concrete properties, base and subgrade parameters. Along with these inputs, the prediction of spalling distresses over

time, shallow and deep delamination stress, and the expected crack spacing distribution are shown for the convenience of the user in the form of charts and graphs. The Construction and Climatic data module includes short term and seasonal temperature and relative humidity related parameters. The data entered into this module is key for the prediction of shallow and deep delamination. The user specifies axle load levels for each axle groups under the Load Levels module. Lower, upper, and maximum load limits are entered according to actual traffic information. The Concrete Mixture module allows user input regarding detailed concrete mixture proportions.

A Shortcut module is provided to execute all parameters in order to analyze and predict the effect of major features on performance. Major features of the CRC-Spalling program are:

- Crack pattern prediction characteristics
- Load and climatic characteristics
- Construction effects characteristics
- Strength gain characteristics
- Delamination potential (Deep and Shallow)
- Distress prediction

Crack pattern characteristics such as interval distribution and crack width are determined to calculate shear capacity for spalling distress prediction. This information is useful as it affects the value of load transfer efficiency (LTE). Traffic volume with respect to equivalent single axle tracks is calculated using load equivalency factors based on both fatigue and deflection-induced damage with respect to distress type.

Construction factors such as the method of curing affect temperature and humidity profiles formed in the pavement concrete, which affects strength gain since it is based on degree of hydration. The potential of shallow and deep delamination is determined based on strength and stress profiles that develop in the slab at a specific depth below the surface. The potential of shallow and deep delamination affects the prediction of spalling models.

The program encompasses several support functions to facilitate design computation relevant to the prediction of spalling distress:

- Early age temperature and humidity profiles from which temperature and moisture gradients are derived for curling and warping stress in hardening concrete
- Seasonal temperature and moisture gradients for hardened concrete
- Calculation for prediction of strength
- Reliability of spalling distress prediction

Spalling performance predictions are generated in the Mechanistic module (hidden). Early age temperature and humidity profile are used to calculate the early age shear stress, which is compared to the shear strength to calculate the potential for delamination. Seasonal temperature and moisture gradients are used to calculate seasonal curling and warping stresses. The user can easily see moisture and temperature profile plots in these modules. Based on the moisture-temperature profile data and user inputs, the relationship between time and strength can be found in the Shear Strength module.

To execute this software with Excel 2003, the Analysis ToolPak-VBA must be installed. This can be found under the Tools menu; click Add-Ins to find the Analysis ToolPak-VBA.

The CRC-Spalling program contains more than 30 modules, so only certain modules appear on the Excel tab bar for execution; the remaining design variables such as cement type are defaulted to maximize efficiency. Selected variables the user may be interested in altering are listed in APPENDIX B. Possible alterations are discussed further in APPENDIX B.

I.   **Design Input Modules**

Four input modules are provided to guide the user through the design input process. As noted above, not all design parameters need to be input, as many are defaulted to expedite the input and execution process. But after completing all inputs, the program can be run. The Input modules are subsequently described in detail with respect to name, function, and typical values.

A. General

This module contains general input data pertaining to slab design, traffic data, concrete properties, environmental parameters, base and subgrade properties, etc.

Selected parameters are easily changed or updated with new values. For example, slab design values (listed below) can be simply changed by clicking on the cell and inputting a new value. Slab thickness is limited to a range from 8 to 14 inches. Steel percentages range from 0.05 to 0.071 and reinforcing steel bar size ranges from #5 to #7. Steel cover can also be selected by the user.   Shoulder LTE along the longitudinal joint ranges from 60 to 80 percent. The three types of shoulders given are bituminous, two-feet extended driving lane, and tied shoulder. Outer distance to the wheel path is defaulted to 18 inches, but can be changed if needed. User-defined minimum crack spacing ranges from 0 to 24 inches. Maximum design life used is 30 years and design reliability can be changed as needed.

- Slab Thickness
- Percent Long steel
- Reinforcing steel bar diameter
- Depth to steel
- Shoulder LTE
- Shoulder type
- Outer distance to wheel path
- User-defined minimum crack spacing
- Design life
- Design reliability

Figure 2.2 shows the input screen.
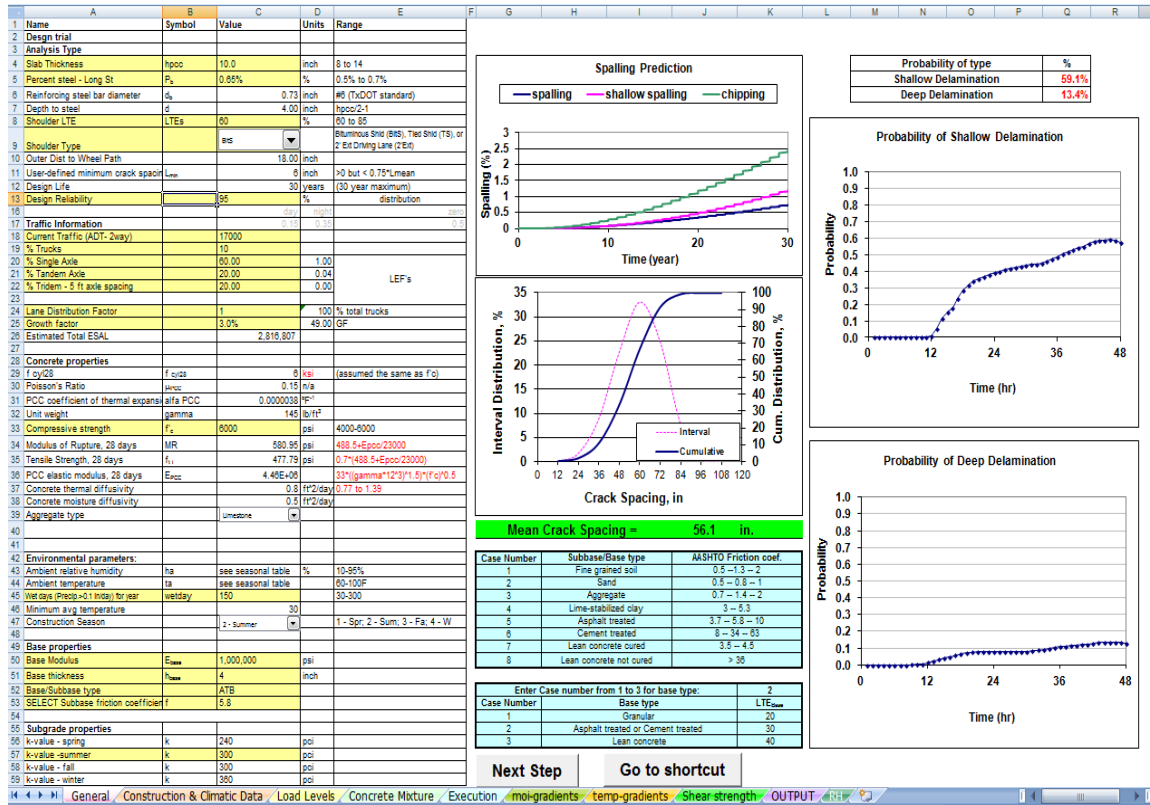
Figure 2.2 Input screen of TxCRCP-ME for spalling

B. <u>Traffic</u>

A summary of the traffic inputs are shown in Table 2.1. Traffic-related values are used to compute total volume. Average daily traffic (ADT) is used based on current year traffic data. Percentage of trucks is the average percentage of trucks among all categories of vehicles. Three classifications of truck axle groups are considered in the traffic model: single, tandem,

and tridem axle groups. The mix of trucks in the traffic volume is distributed by the user among three groups and must total 100%. The user farther distributes the traffic using a lane distribution factor (LDF). A growth factor is also assigned. User can replace given values with other parameters in traffic section of Input modules.

The Load limit data specifies inputs relative to axle group (i.e. single, tandem, and tridem legal load limits). Load limits shown in **Error! Reference source not found.** are representative of typical xle load ranges. The user can change these values as needed.

Table 2.1 Example Input Values for Traffic

Name	Unit
Beginning year traffic	/
% Trucks	%
% SA	%
% Tandem	%
% Tridem - 5 ft axle spacing	%
Lane Distribution Factor	/
Growth factor	%
Total volume of traffic during service	ESAL

Table 2.2 Load Limit for Axle Group

	Single Axle	Tandem Axle	Tridem Axle
Lower limit (kips)	9	25	40
Upper limit (kips)	21	36	54
Max limit (kips)	29	52	70

Accumulative traffic levels are determined in terms of an 18-kip single axle load for different distress types using the expression below. This equation accounts for both legal and illegal axle loads. The first and second term $\left(\%\text{ of truck}\cdot\dfrac{ADT}{2}\right)$ expresses the one-way direction truck traffic volume. The next term, the lane distribution factor (LDF), ranges from 66 to 94%, and is adjusted for the percentage of tracks in the design lane. The last term is expressed as percentage of axle group, configuration, and equivalent axle configures.

$$ESAL_i = \%\text{ of truck}\cdot\frac{ADT}{2}\cdot LDF\cdot\sum_{j=1}^{3}\left[\left(\%ADT_{i+1}-\%ADT_{i,j}\right)A_j\cdot AEF\right]$$

(Eq 2.1)

where, i   = Load group

j   = Axle configuration (axle type)

A_j = Load group (%)

AEF   = Axle Equivalency Factor

LDF   = Lane distribution Factor

$$ESAL_T = WEF\left(\sum ESAL_i\cdot LEF\right)$$

where, WEF   = Wander Equivalency Factor

LEF   = Load Equivalency Factor

AEF and LEF can be determined from the equations listed in **Error! Reference source not ound.**, which are dependent on distress types as listed in **Error! Reference source not found.** and **Error! Reference source not found.**. The AEF of a single axle type is 1, and AEF of the ther types of axle are calculated using the listed expressions.

As noted previously, the equivalency depends on distress type. Since spalling and erosion distress modes are deflection-based, equivalency factors are determined from the load-induced deflection caused by traffic. On the other hands, shallow spalling distress modes are fatigue damage based such that the equivalency factors are stress-based.

Table 2.3 AEF and LEF for Axle Type

% Axle Type (A_j)	AEF_j	LEF_i
% Single Axle (SA)	1	$10^{k_2\left(r_{18kips}-r_i\right)}$
% Tandem Axle (TA)	$10^{k_2\left(r_{SA}-r_{TA}\right)}$	$10^{k_2\left(r_{36kips}-r_i\right)}$
% Tridem Axle (TR)	$10^{k_2\left(r_{SA}-r_{TR}\right)}$	$10^{k_2\left(r_{54kips}-r_i\right)}$

$(k_2 = -17.61)$

Table 2.4 Equivalency Factors Based on Fatigue Stress

LEF						AEF			EDR
Axle load (Kips)	Single Axle	Axle load (Kips)	Tandem Axle	Axle load (Kips)	Tridem Axle	Single	Tandem	Tridem	
8	0.21	24	0.29	44	0.55				
10	0.28	26	0.35	46	0.62				
12	0.39	28	0.44	48	0.7				
14	0.53	30	0.54	50	0.79				
16	0.73	32	0.66	52	0.89	1	0.041	0.002	0.66
18	1	34	0.81	54	1				
20	1.37	36	1	56	1.13				
22	1.87	38	1.23	58	1.27				
24	2.57	40	1.51	60	1.44				
26	3.51	42	1.86	62	1.62				

Table 2.5 Equivalency Factors Based on Deflection Induced by Traffic

LEF						AEF			EDR
Axle load (Kips)	Single Axle	Axle load (Kips)	Tandem Axle	Axle load (Kips)	Tridem Axle	Single	Tandem	Tridem	
8	0.977	24	0.986	44	0.992				
10	0.981	26	0.988	46	0.994				
12	0.986	28	0.991	48	0.995				
14	0.991	30	0.993	50	0.997				
16	0.995	32	0.995	52	0.998	1	0.998	0.995	0.64
18	1	34	0.998	54	1				
20	1.005	36	1	56	1.002				
22	1.009	38	1.002	58	1.003				
24	1.014	40	1.005	60	1.005				
26	1.018	42	1.007	62	1.006				

Table 2.6 Default Values for Concrete Properties

Name	Value	Unit
Poisson's Ratio	0.15	ratio
PCC coefficient of thermal expansion	4×10^{-6}	$^{\circ}F^{-1}$
Unit weight	0.0839	lb/in^3
Compressive strength	6000	psi
Modulus of Rupture, 28 days	580	psi
Tensile Strength, 28 days	4776	psi
PCC elastic modulus, 28 days	4.82×10^6	/
Concrete thermal diffusivity	1.39	ft^2/day
Concrete moisture diffusivity	0.5	ft^2/day

C. Concrete properties

Error! Reference source not found. lists default values used in this software package, relative to ypical concrete properties. These can be changed by the user as needed.

Other concrete properties are listed below. These inputs relate to the properties of the paving concrete. Main parameters considered are:

- Coarse aggregate factor (CAF)
- Percent air required
- Water cement ratio
- Cementitious content
- Aggregate properties (AC, SG, UW, and Moisture contents)

Aggregate properties include unit weight, fineness modulus, absorption capacity, and total moisture content. Type of aggregate are classified as coarse, intermediate, and fine aggregate. Cement and fly ash type can also be specified but are defaulted to Type I and Class C, respectively. APPENDIX B contains instructions to change defaulted input values.

D. Environmental design parameters

Error! Reference source not found. lists inputs for environmental design factors. Seasonal relative umidity and temperature data is entered according to seasonal trends. The annual wet days are an important performance factor affecting erosion potential; this data is also available from the Long-Term Performance Pavement (LTPP) database.

Table 2.7 Environmental Design Parameters

Name	Value	Units	Range
Relative humidity	/	%	10-95%
Temperature	/	^oF	60-100F
Annual Wet days (Precipitation.>0.5 in/day) for year	120		30-300
Avg. Annual Min temperature	30	^oF	/
Season of construction	1		1- Spring; 2 - Summer; 3 - Fall; 4 - Winter

Table 2.8 Base Properties

Name	Value	Units
Base Modulus	500,000	psi
Base thickness	4	inch
Base/Subbase type	ATB	/
SELECT Subbase friction coefficient	4	/
k-value	300	pci

Table 2.9 Friction Coefficients

Case Number	Subbase/Base Type	AASHTO Friction Coefficients.
1	Fine grained soil	*0.5 --1.3 -- 2*
2	Sand	*0.5 -- 0.8 -- 1*
3	Aggregate	*0.7 -- 1.4 -- 2*
4	Lime-stabilized clay	*3 -- 5.3*
5	ATB	*3.7 -- 5.8 -- 10*
6	CTB	*8 -- 34 -- 63*
7	LCB cured	*3.5 -- 4.5*
8	LCB not cured	*> 36*

E. Properties of base and subgrade layer materials

Error! Reference source not found. lists the inputs types for base and subgrade layer materials. odulus, thickness, material type, and friction coefficient are required inputs; the friction coefficient is determined according to material type (see **Error! Reference source not found.**). ubgrade k-value is also an important input value for structural analysis but it must be representative of the subgrade layer and not the top of the base.

II. Program Execution

An overview of the design program is shown in **Error! Reference source not found.**. After the user ompletes all inputs, the Design program can be executed to generate various output files needed to carry out the design assessment. The design involves clicking these two buttons:

- Generate Climatic Data
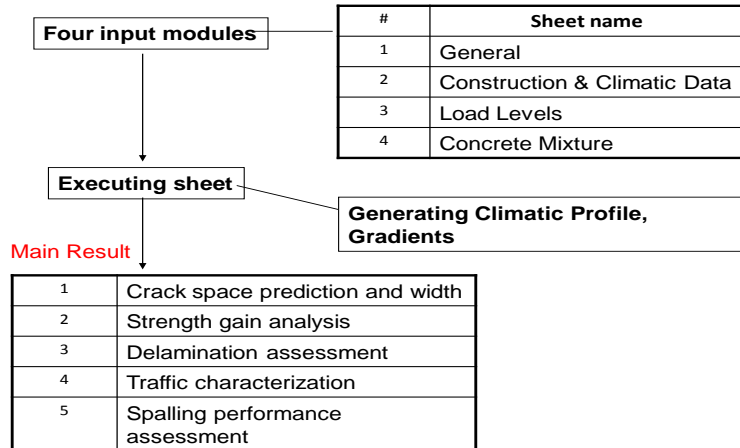- Generate Performance Assessment

#	Sheet name
1	General
2	Construction & Climatic Data
3	Load Levels
4	Concrete Mixture

Four input modules

Executing sheet — **Generating Climatic Profile, Gradients**

Main Result

1	Crack space prediction and width
2	Strength gain analysis
3	Delamination assessment
4	Traffic characterization
5	Spalling performance assessment

Figure 2.3 Overview of CRC-Spalling Program

III.   Output Results

The objective of the design process is to assess to the potential of spalling for a given pavement section and traffic level. Crack spacing, delamination assessment, strength gain, and traffic equivalencies are used to determine the potential for spalling models. The user must not jump to spalling assessment without generating the necessary supporting data.

A. Cracking spacing

Crack spacing prediction includes an estimate of the average crack spacing and standard deviation for a single layer of steel. The crack width is also computed based on the average crack spacing. The effect of the reinforcing steel is reflected through the amount and the age. The cracking pattern is assumed to conform to a Weibull distribution. **Error! Reference source ot found.** shows the relationship between crack spacing and crack distribution.
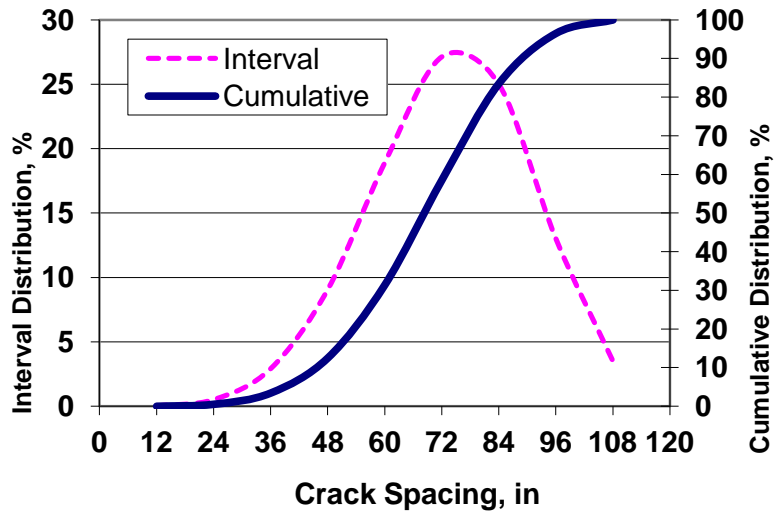
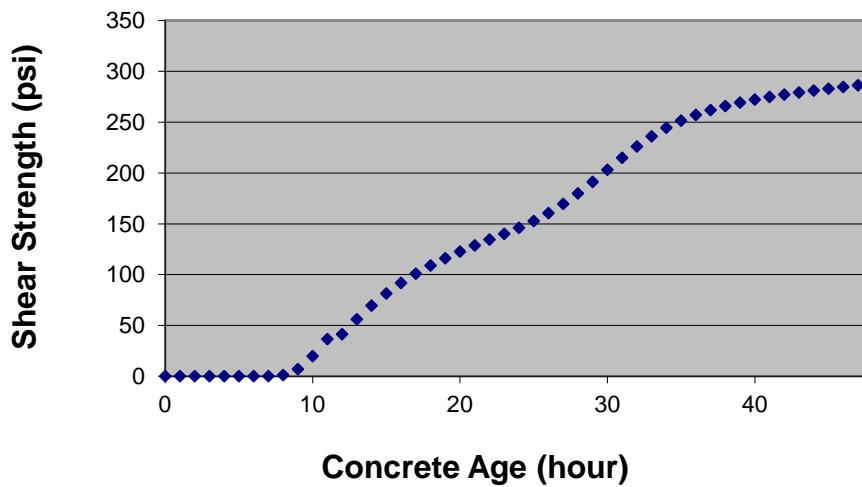**Figure 2.4 Accumulative Crack Spacing vs Distribution %**

Figure 2.5 Shear Strength vs. Time

B. <u>Strength Gain</u>

Shear strength is determined from the relationship between strength and the degree of hydration. Specifically, shear strength can be calculated by the use of the maturity method which is a function of a temperature of the concrete, which is predicted at a given position by the design program. Shear strength at one inch below the surface is predicted from 0 to 48 hours as shown in **Error! Reference source not found.**.

The degree that the concrete shear stress surpasses the concrete shear strength governs the degree or probability that delamination can occur. The probability that concrete shear stress exceeds shear strength is illustrated in Figure 2.7.
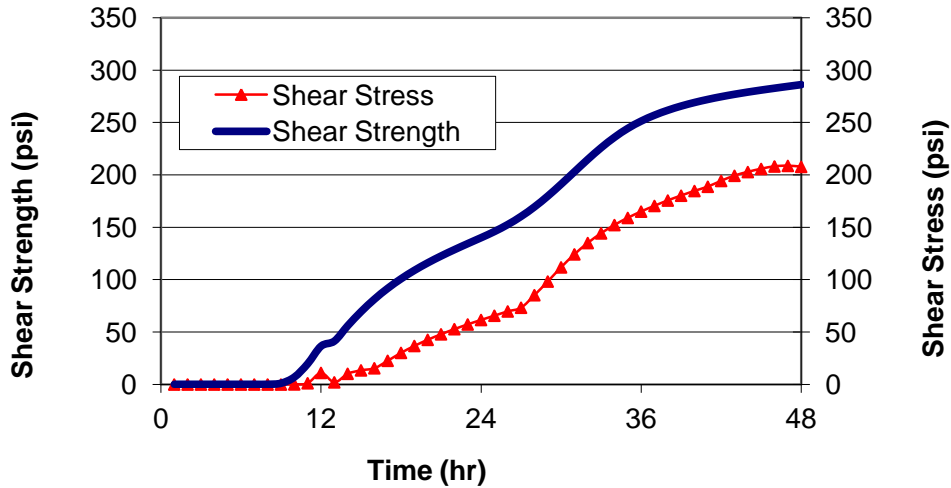

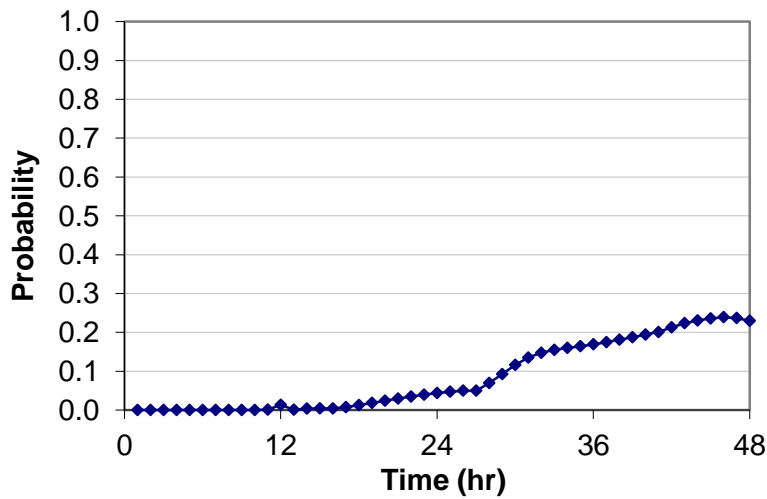**Figure 2.6 Comparison of Early Age Strength and Stress for Delamination Possibility**

Figure 2.7 Probability of Delamination during the Early Age of Concrete

C. Spalling Potential

Spalling is not expected to occur without the presence of delamination, so the probability of delamination should be determined to assess the possible number of spalled cracks that may

occur based on the relation between concrete shear stress and strength under a specific set of site conditions. Specifically, the degree to which concrete shear stress surpasses the concrete shear strength governs the degree that delamination can initiate. Thus, the probability is based on the difference of means of two populations of shear strength and stress, which have a standard deviation made up from the variances of the two populations.

A spalling distress model is suggested for calibration and for spalling prediction due to accumulated fatigue damage calibrated to field performance data. Spalling model is designed with the exponential growth of spalling distress (S) with either traffic or fatigue damage (D). Relative to damage accumulation, the Weibull distribution α and β parameters control the shape and the rate of spall development predicted by the spall model, while the S_0 term represents the maximum amount of spalled cracks. A unique feature of the shape parameters is its relationship to the variability of performance, where its determination being based on field data not only establishes a calibrated mean value but also calibrates the performance reliability. The α and β parameters are therefore derived from performance data. The β can be determined from a minimum of two data points which are required for each site to determine the site coefficients with respect to percent of spalled cracking (S/S_0) and damage. The α can be expressed with exponential grow with surveyed condition and damage shape factor.

$$\%S = S_0 e^{-\left(\frac{D}{\alpha}\right)^{\beta}}$$

(Eq 2.2)

where, S = number of spalls per 100 ft of pavement

S_0 = ultimate number of spalls per 100 ft of pavement

D = accumulated damage

α = damage scale factor of Weibull function, and

$$= e^{\left(\frac{\beta x_2 - y_2}{\beta}\right)}$$

β = damage shape factor of Weibull function

$$= \beta = \frac{\ln[-\ln(y_2)] - \ln[-\ln(y_1)]}{\ln(x_2) - \ln(x_1)}$$

y_1 = % of spalled cracking at initial condition

y_2 = % of spalled cracking at surveyed condition

x_1 = % of damage at initial condition

x_2 = % of damage at surveyed condition
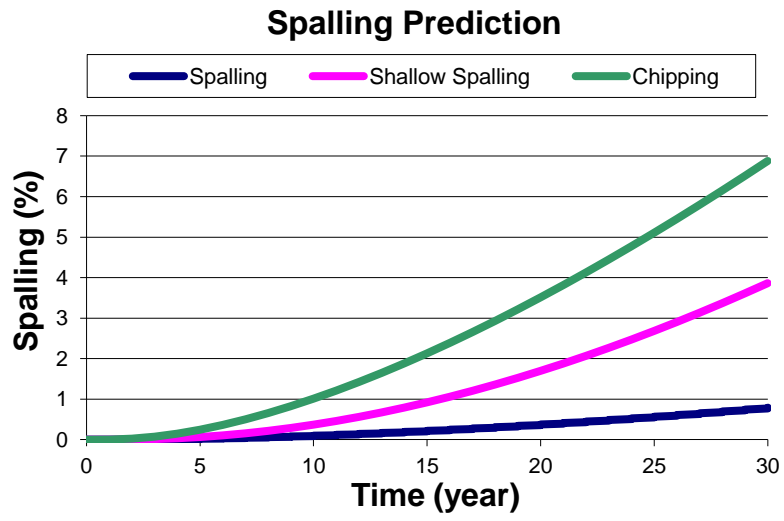
Spalling Prediction

Figure 2.8 Spalling vs Time

Appendix A- Design Example for Spalling

A sample design is produced to illustrated use of the spreadsheet and how selected parameters affect performance input parameters such as slab thickness, traffic volume, percentage of trucks, and compressive strength.

 shows the default values. Figures A1 through A4 show how the selected values affect the final results for spalling distress.

Table A.1 Values Used for Examples.

| Concrete slab general information		Traffic and load data	
Slab Thickness (inch)	12.00	Current year traffic	25000
Percent steel - Long St (fraction)	0.0045	% Trucks	15
Reinforcing steel bar diameter (Inch)	0.63	% SA	60.00
Depth to steel (inch)	5.00	% Tandem	20.00
Shoulder LTE	80.00	% Tridem - 5 ft axle spacing	20.00
Shoulder Type	TS		
Outer Dist to Wheel Path (inch)	18.00	Lane Distribution Factor	0.7
User-defined minimum crack spacing (inch)	6	Growth factor (%)	3.00
Design Life (year)	30	Design Reliability (%)	95
Concrete Slab General Information			
Total aggregate/cement ratio		4.2	
Coarse aggregate/cement ratio		3.6	
Fine aggregate/cement ratio		1.8	
water/cement ratio		0.45	
f cyl28		2	
Poisson's Ratio		0.15	
PCC coefficient of thermal expansion ($^\circ F^{-1}$)		4×10^{-6}	
Unit weight		0.0839	
Compressive strength (psi)		6000	
Modulus of Rupture, 28 days		580	
Tensile Strength, 28 days		477	
PCC elastic modulus, 28 days		2,576,801	
Environmental, Subgrade, and Subbase Properties			
Wet-day (precipitation>0.01 inch/day) for year		120	
k-value		300	
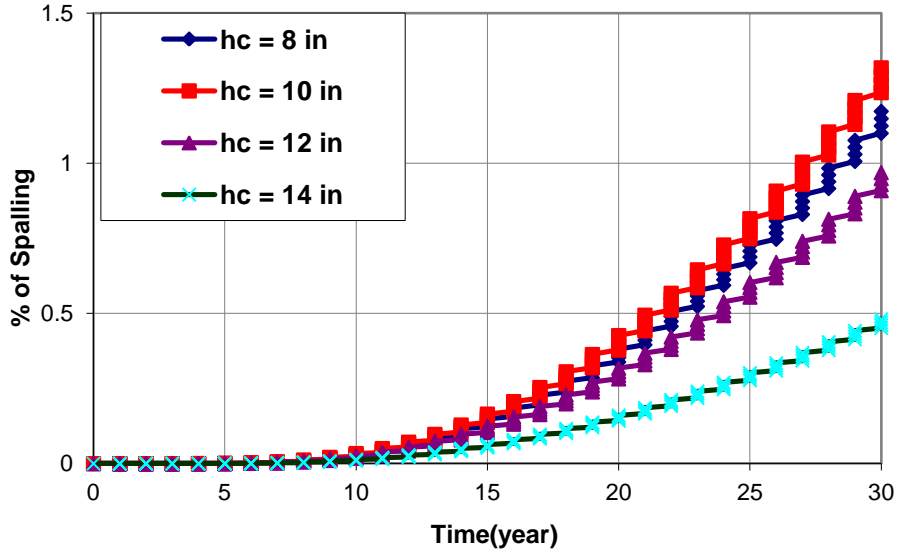
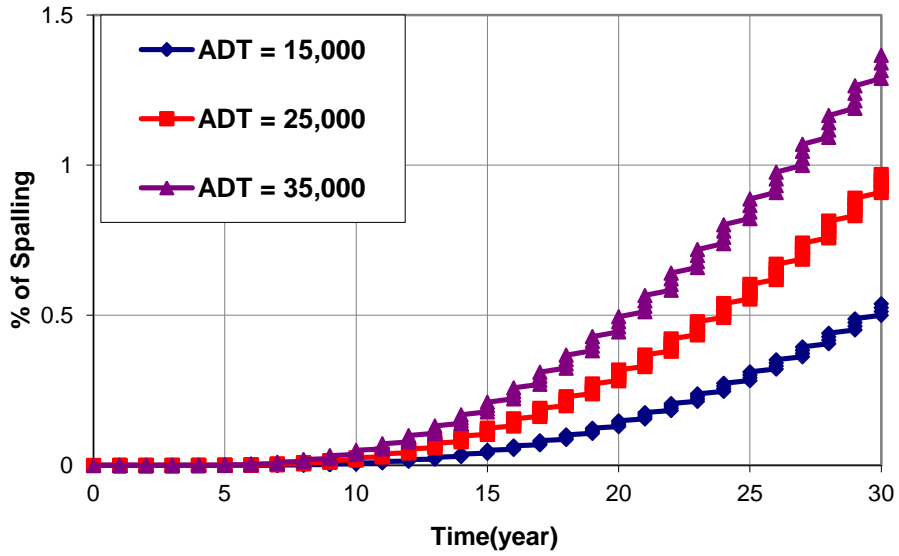**Figure A.1 % Spalling vs Year with respect to Slab Thickness.**

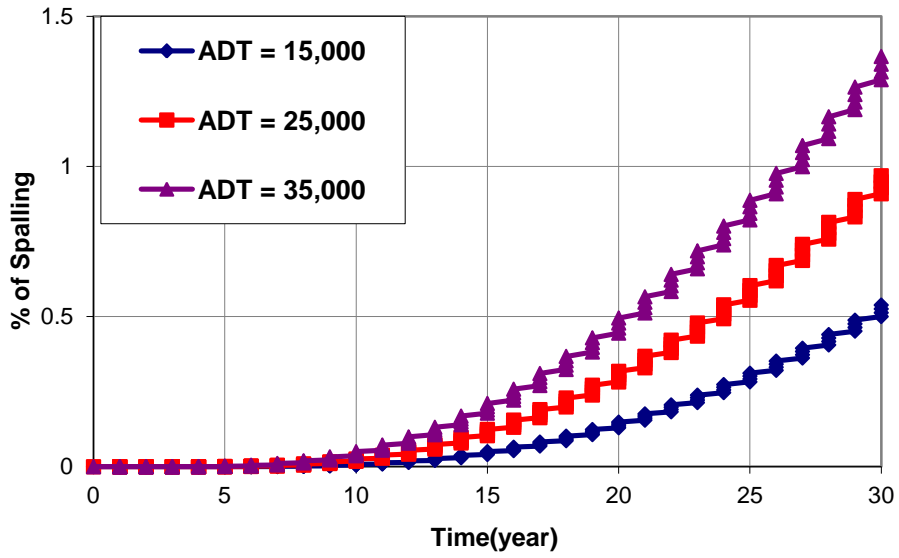**Figure A.2 % Spalling vs Year with respect to Average Daily Traffic.**

Figure A.3 % Spalling vs Year with respect to % of Truck.
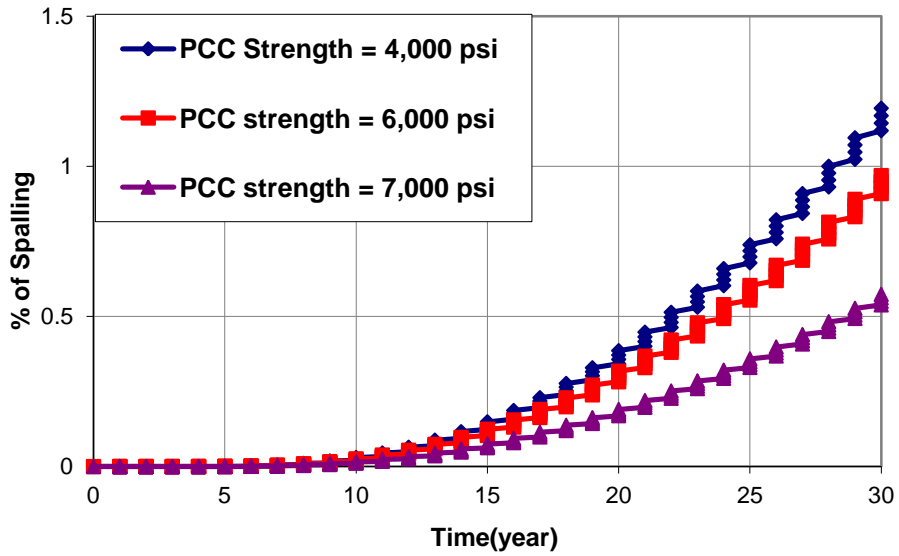

Figure A.4 % Spalling vs Year with respect to Compressive Strength.

Appendix B- Intermediate Functions and Defaulted Parameters and Outputs

The design analysis consists of several intermediate functions that are hidden to the user, but consist of defaulted parameters to simplify the input process. Many of the defaulted values can be modified for advanced analysis purpose. The outputs of the functions are also described.

Table B.1 Intermediate Functions Used in the Software Package.

Function	Purpose & Defaulted Parameters
Mixture proportion	Input_Mixdesign
Moisture and Heat transportation	Input_Materials&properties
CRC pavement design by 98 AASHTO Method	1998 AASHTO Method 98 seasonal k
Faulting	Faulting
Cracking information	Crack spacing factors Cracking
Climatic conditions	Cyclic_Seasonal_Input
Temperature and Relative humidity Profile	Output
Moisture and Temperature gradients	moi-gradients, temp-gradients
Parameters for Mechanisitc module	VAR PO, VAR sigma, dDdx, VAR LTE
Parameters for 98 AASHTO Method	Single CS, Single CS-suppliment Tandem CS, Tandem 8ft CS Tridem 8ft CS, Tridem 12ft CS
Static Temperature and RH figures	STATIC
Dynamic Temperature and RH figures	DYN
Reliability of spalling	Reliability

Mixture proportion
The software computes the concrete mixture proportions based on used inputs of cement contents, CAF, w/cm. The following functions are carried out:
- Weight
- Volume
- Proportions

Moisture and Temperature Transportation
Coding under the Input_Materials & Properties tab addresses the transfer of temperature and moisture in the paving concrete. **Error! Reference source not found.** lists the heat transport arameters and their defaulted values.

Table B.2 Heat Transport Parameters

Parameters	Default value
Total heat	*436.1 J/g*
Activation energy	*39184 J/mol*
Shape parameters	$\alpha_u = 0.743, \tau = 18.95, \beta = 0.785$
Specific heat	*1.048 J/g °C*

CRC pavement Design by 98 AASHTO Method

A modified version of the 1998 AASHTO Method is calculated to correct the computed wheel load stress for CRC load behavior.

Defaulted input parameters are listed in **Error! Reference source not found.**. Some parameters ome from Input modules and user should input the rest of parameters in **Error! Reference source not found.**. Then, road test constants and loss of serviceability can be calculated through the 1998 AASHTO Method.

Table B.3 Values Used in 98 AASHTO Method

Parameter	Defaulted Value	Unit
Initial serviceability	*4.5*	*/*
Terminal serviceability	*3.0*	*/*
Joint spacing	*0*	*ft*
Edge support adjustment factor	*0.94*	*/*
Mean annual temperature	*75.6875*	*°F*
Mean annual precipitation	*31*	*in*
Mean annual wind speed	*10*	*mph*

As a result, the following parameters can be determined from this spreadsheet.

Faulting
Some of faulting parameters are introduced in this module, which are mainly used to predict shallow spalling and chipping behavior. For example, joint stiffness and aggregate interlock are determined from this faulting module so that these values are transported into the spalling analysis. To calculate delamination width, it is necessary to know joint stiffness, whether the stiffness is due to aggregate interlock and dowels if they are present in the joint. This is the main purpose of the Faulting module.

Cracking Pattern

This module is related to the generation of the cracking pattern such as the average crack spacing, crack distribution and crack width. The cracking spacing factors module provides the user with crack spacing.

Climatic Condition

This function calculates temperature and relative humidity gradients based on cyclic temperature and moisture user inputs. The gradients can be used to calculate the equivalent total strain difference between the pavement surface and bottom for each cyclic season. Furthermore, determined gradients are used to determine effective positive temperature differential in the AASHTO Method.

Temperature and Relative Humidity Profile

This function generates temperature and RH profiles with respect to depth and time based on defaulted values. Specifically, the temperature and RH are used to calculate deep and shallow shear strength and stress.

Reliability of Spalling

Reliability of spalling is designed based on the factors shown in **Error! Reference source not ound.**. Initial reliability level in this program is 95 % and the user can change reliability level, values, and coefficient of variation.

Table B.4 Reliability Design Values

Name	Value	Coefficient of Variation
k1	17.61	0.4
k2	-17.61	0.4
Tensile strength of concrete, ft (inch)	488.6	0.15
Length of spall, $l*$ (inch)	3	0.5
Depth of spall ,t (inch)	1.5	0.5
Slab thickness, h (inch)	12	0.1
Load transfer efficiency,LTE	99.9	0.3
Angle of spall fracture , θ (degree)	60	0.1
Shear stress from tire loading, τ_p (psi)	25	0.1

Static figures-STATIC Module
This program generates figures showing relative humidity vs. time, RH vs. slab thickness, temperature vs. slab thickness, and temperature vs. time.

Dynamic figures in terms of thickness of slab-DYN Module
This generates a temperature and RH profile history in the Dynamic spread sheet.

Appendix C-Defaulted Values

Error! Reference source not found. shows a list of input parameters used in the software.

Table C.1 General Default Values

Parameter	Defaulted Value	Unit
Percent steel - Long St	0.0045	ratio
Reinforcing steel bar diameter	0.63	inch
Shoulder LTE	80.00	%
Shoulder Type	TS	/
Outer Dist to Wheel Path	18.00	inch
User-defined minimum crack spacing	6	inch
Design reliability	95	%
Lane distribution factor	0.7	ratio
Growth factor	3.00	%
Poisson's Ratio	0.15	ratio
PCC coefficient of thermal expansion	4×10^{-6}	$°F^{-1}$
Unit weight	0.0839	lb/in^3
Compressive strength	6000	psi
Modulus of Rupture, 28 days	580	psi
Tensile Strength, 28 days	4776	psi
PCC elastic modulus, 28 days	4.82×10^6	/
Concrete thermal diffusivity	1.39	ft^2/day
Concrete moisture diffusivity	0.5	ft^2/day
Total aggregate/cement ratio	4.2	ratio
Coarse aggregate/cement ratio	3.6	ratio
Fine aggregate/cement ratio	1.8	ratio
water/cement ratio	0.45	ratio
Total heat	436.1	J/g
Activation energy	39184	J/mol
Shape parameters	$\alpha_u = 0.743, \tau = 18.95, \beta = 0.785$	/
Specific heat	1.048	$J/g \; °C$
Curing type	Mat curing	/
Cement type	Type I	/
Cementitious material	Class C fly ash	$°F$

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