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16. Abstract <p>The Falling Weight Deflectometer is commonly used in Texas for pavement evaluation and design purposes. Typically, measurements are made at a given date so that the data reflect the environmental conditions prevailing during the time of measurement. For pavement applications, the backcalculated asphalt concrete modulus needs to be adjusted or corrected to reference or standard conditions of temperature and loading frequency. The Modulus Temperature Correction Program (MTCP) incorporates procedures for adjusting backcalculated asphalt concrete (AC) moduli to user-prescribed reference pavement temperatures. In this way, seasonal variations in AC modulus may be predicted for pavement evaluation and design purposes. Instructions in using MTCP are given in this user's manual.</p>			
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**USER'S GUIDE FOR THE MODULUS TEMPERATURE
CORRECTION PROGRAM (MTCP)**

by

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Project Number 0-1863

Research Project Title: Evaluate the Use of FWD Data in Determining Seasonal Variations
in Pavement Structural Strength

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CHAPTER I

INTRODUCTION

BACKGROUND AND SCOPE OF REPORT

The Texas Department of Transportation uses the Falling Weight Deflectometer (FWD) for pavement evaluation. A common application is the backcalculation of pavement layer moduli by deflection basin fitting. In Texas, pavement engineers use the MODULUS program (Michalak and Scullion, 1995) to provide estimates of pavement layer moduli from measured FWD deflections. These estimates are subsequently used in other applications, such as the FPS-19 flexible pavement design procedure, the Program for Analyzing Loads Superheavy (Jooste and Fernando, 1995 and Fernando, 1997), and the Program for Load Zoning Analysis (PLZA) developed by Fernando and Liu (1999).

For pavement applications, the results obtained from the FWD need to be adjusted or corrected to reference or standard conditions of temperature, moisture, and loading frequency. The Modulus Temperature Correction Program (MTCP) described in this user's guide incorporates procedures for adjusting asphalt concrete moduli to user-prescribed reference pavement temperatures. To provide compatibility with the MODULUS program which is currently implemented within TxDOT, the output from MODULUS is used as an input to the modulus temperature correction program. This approach is expected to facilitate the implementation of MTCP within TxDOT.

To provide for implementation, researchers prepared this user's guide to explain how MTCP is used. The guide is organized into three chapters and an appendix:

1. Chapter I identifies the system requirements for running MTCP;
2. Chapter II provides instructions on using the program to estimate pavement temperatures, adjust backcalculated asphalt concrete (AC) moduli to a specified reference temperature, and predict the monthly variation of AC moduli at a given site;
3. Chapter III illustrates program output; and
4. the appendix provides a flow chart that may serve as a map of the analysis functions for practical applications.

Users of the program must have a working knowledge of MODULUS. The temperature corrections depend, to a considerable degree, on the layer moduli backcalculated from the FWD data. Thus, having a good working knowledge of MODULUS (and backcalculation, in general) will aid in understanding the results from the temperature corrections. In practice, it may be necessary to run MODULUS and MTCP a number of times to achieve realistic and reasonable results, particularly when the initial backcalculation indicates the need to divide the FWD data into two or more segments to better model the variations in pavement deflections, backcalculated moduli, or pavement layering.

SYSTEM REQUIREMENTS

MTCP requires a microcomputer with the Windows (9x, NT, 2000, ME) operating system and Microsoft Excel, version 97 or later. A Pentium microprocessor or its equivalent and a minimum of 32 Mb of memory are recommended. Users must have a good working knowledge of the Windows operating system and Microsoft Excel. To install the program, simply copy the files in the program disk onto a subdirectory of your computer's hard drive. For example, you may want to create a subdirectory called *C:\MTCP* and copy the program files into this subdirectory. Once you copy the files, you may run the program by first going into Excel and loading the spreadsheet called *MTCP.XLS* in the program subdirectory using Excel's *File/Open* command. You will then be asked if you want to disable or enable the macros that are in the MTCP spreadsheet. Click on the ***Enable Macros*** button of the dialog box to use the program for temperature correction of backcalculated AC moduli. The title screen in [Figure 1](#) is then displayed. If the MTCP title screen is bigger or smaller than your computer display, you may resize the screen using the zoom box at the top toolbar of the Excel spreadsheet. In the example shown in [Figure 1](#), the zoom box is currently set at 100%. Click the size you want in the zoom box or enter a number between 10 and 400 to resize the screen.

To start using MTCP, click anywhere on the MTCP title screen to get to the main program menu illustrated in [Figure 2](#). From this menu, you may access the available program functions. The available functions are described in the remainder of this user's guide.

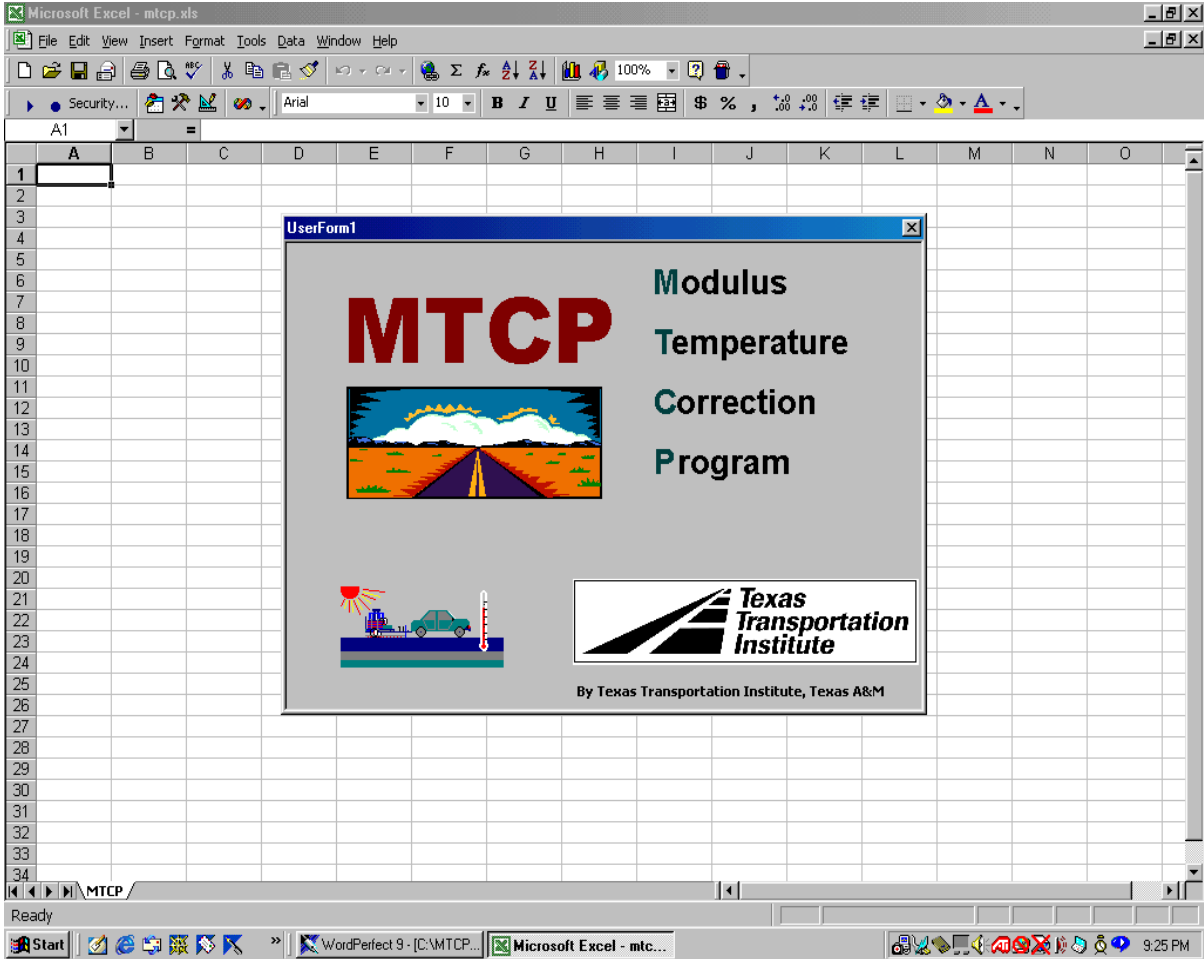


Figure 1. MTCP Title Screen.

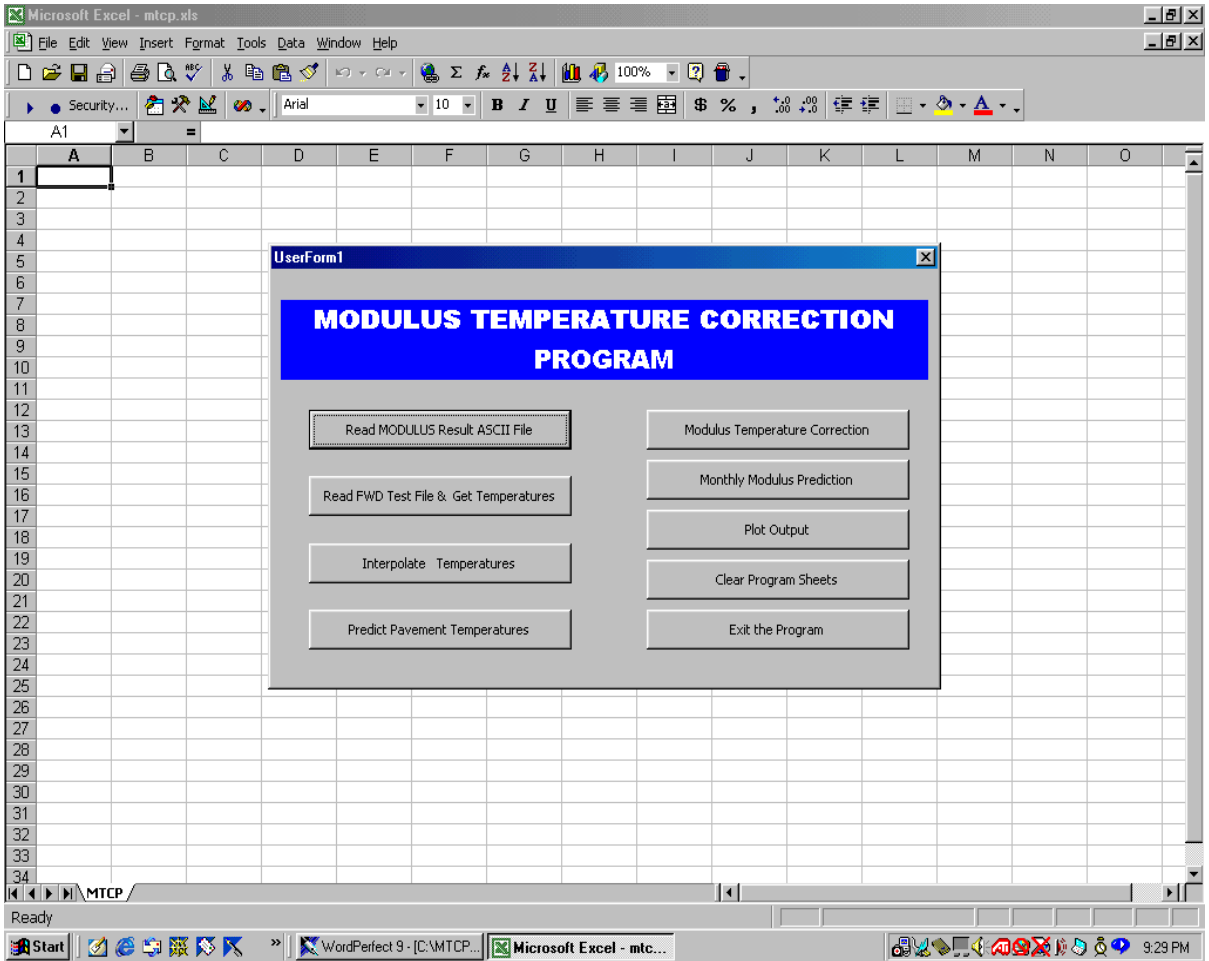


Figure 2. MTCP Main Menu.

CHAPTER II

USING THE MODULUS TEMPERATURE CORRECTION PROGRAM

The FWD is commonly used in Texas for pavement evaluation and design purposes. Typically, pavement engineers make measurements at a given date so that the data reflect the environmental conditions prevailing during the time of measurement. MTCP has been developed to give TxDOT pavement engineers a tool for adjusting backcalculated AC moduli to account for temperature effects. Through this program, seasonal variations in AC moduli may be predicted for pavement evaluation and design purposes. Instructions for using MTCP are given in this chapter.

SPECIFYING MTCP INPUT FILES

Within TxDOT, pavement engineers use MODULUS for backcalculating layer moduli from FWD measurements. Consequently, researchers developed MTCP to use the output from MODULUS directly. This is done by clicking on the ***Read MODULUS Result ASCII File*** button of the main menu given in [Figure 2](#). Specifying the MODULUS summary output file is the first step in using the program for temperature correction of backcalculated AC moduli. Clicking on ***Read MODULUS Result ASCII File*** brings up the dialog box shown in [Figure 3](#). From this menu, the user can specify the MODULUS summary output file to use in the analysis. Simply highlight the file by clicking on the file name in the dialog box. Then click on the ***Open*** button at the lower right corner of the dialog box to confirm your selection. From this menu, you may also search the different drives and subdirectories on your computer for the particular file you want to process.

The MODULUS output file is read, and the contents of the file are imported into the *output* worksheet shown in [Figure 4](#). To view the information, click on ***Exit the Program*** to close the main menu as illustrated in [Figure 5](#). You may go back to this menu at any time by pressing the *Ctrl*, *Shift*, and *M* keys in combination (*Ctrl+Shift+M*). The information displayed in [Figure 5](#) is the same as that given in the MODULUS summary output and consists of the:

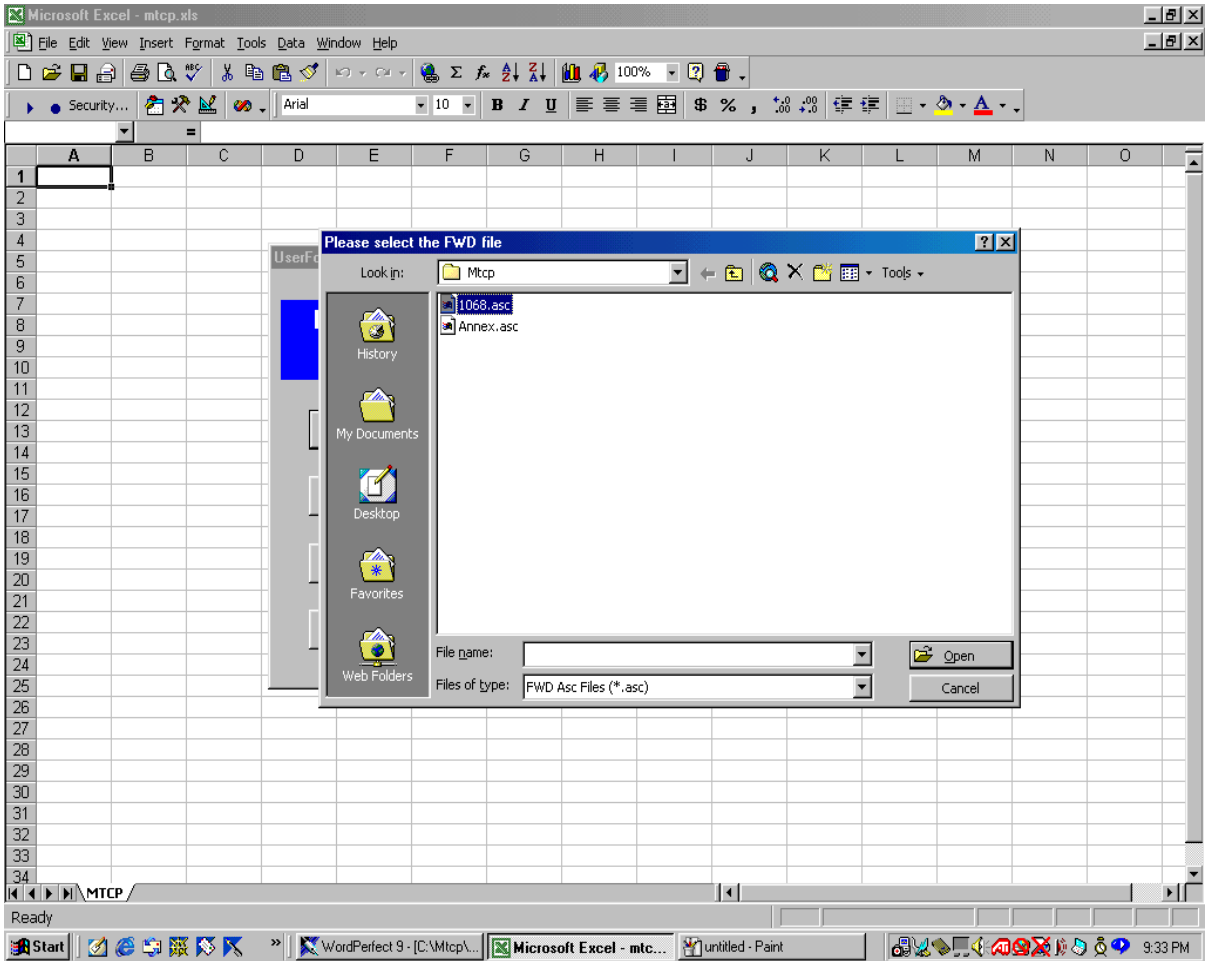


Figure 3. Dialog Box for Specifying MODULUS Output File to Analyze.

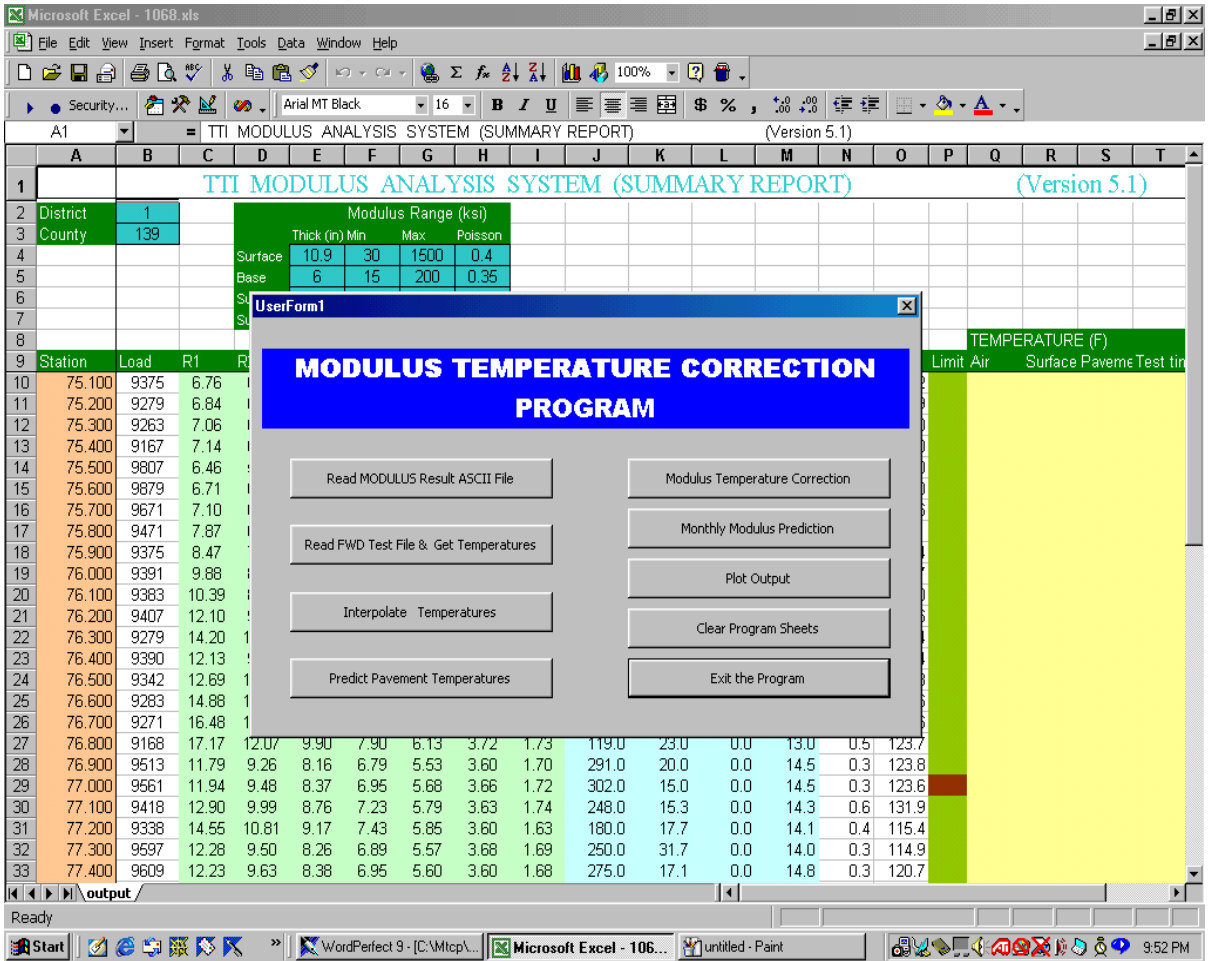


Figure 4. MODULUS Output File Imported into MTCP.

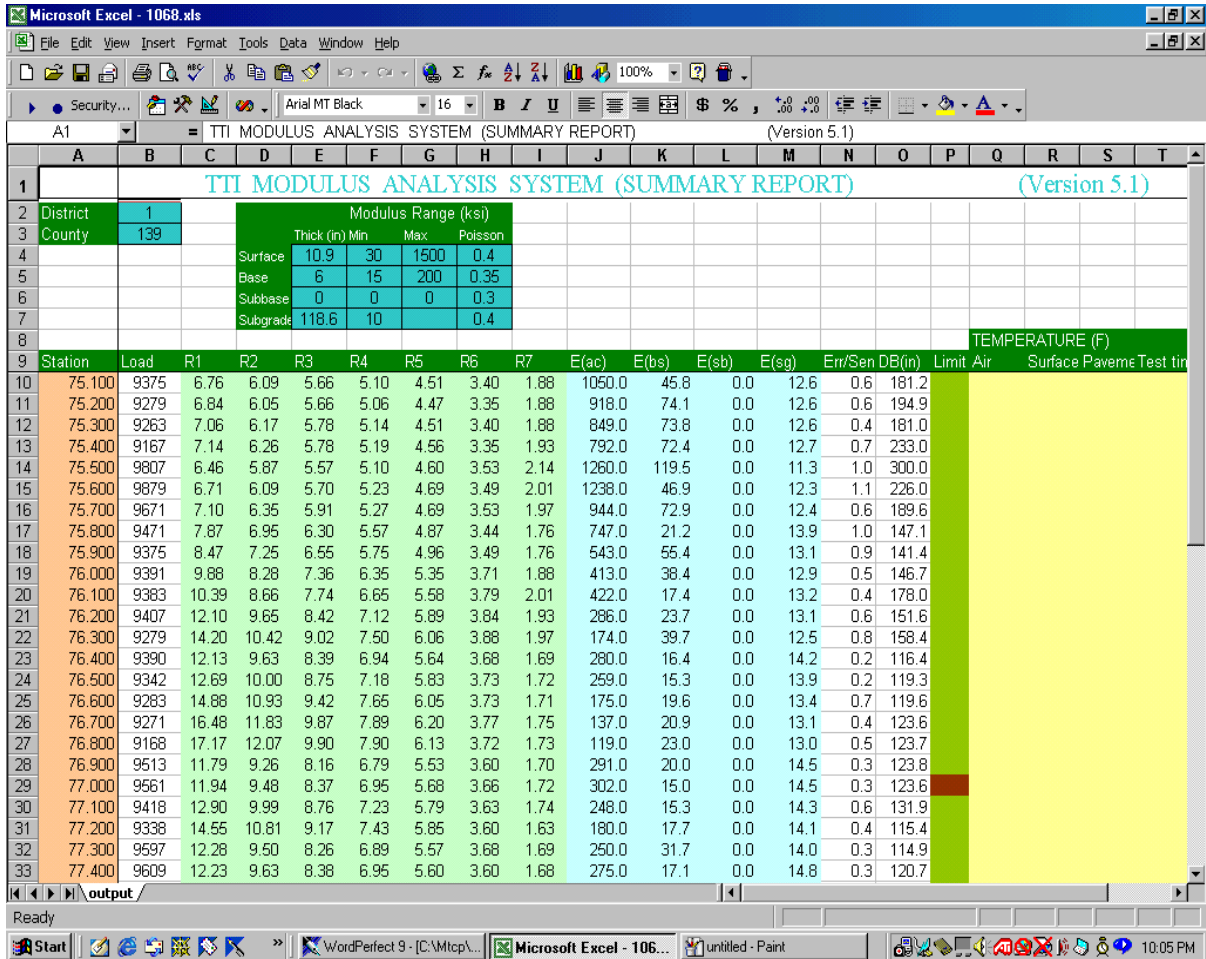


Figure 5. Viewing the MODULUS Summary Output File.

1. district and county where FWD measurements were taken;
2. pavement layer thicknesses;
3. allowable range of the backcalculated modulus for each layer;
4. FWD load, sensor deflections, and backcalculated layer moduli at each test location along with the absolute error per sensor between the predicted and measured deflections;
5. depth to bedrock estimated from the measured deflections at each station; and
6. computed means, standard deviations, and coefficients of variation for the measured deflections, backcalculated moduli, depths to bedrock, and absolute errors per sensor.

In addition, the column labeled *Limit* in the worksheet gives an indication of whether any of the backcalculated moduli reached the limits set by the user during the backcalculation. If moduli reach any limit, the program shades the cell for that particular station red under the *Limit* column. Otherwise, the cell is shaded green. To the right of the *Limit* column are blank cells where temperature data taken during FWD testing are entered. Air and surface temperatures are normally measured from sensors built into the FWD and are recorded at each test location. These measurements are written in the same data file where the deflections are saved. For the purpose of predicting pavement temperatures using the methods built into the program, surface temperatures taken with an infrared sensor are required. Consequently, researchers recommend that infrared sensors be installed in TxDOT's FWDs to implement the computer program developed from this project. In practice, attention must be given to maintaining the infrared sensor in good operating condition and checking the sensor calibration to ensure the validity of the temperature measurements.

In addition, the operator collects pavement temperatures at specific locations using a temperature probe. For this purpose, researchers recommend that temperatures be measured at half the depth of the surface layer if the thickness is known at the time of FWD testing, or at a depth of 1.6 inches (4 cm) from the surface if the thickness is not known. These recommendations are based on the findings from this study ([Fernando and Liu, 2001](#)).

Since layer thicknesses are needed to analyze the FWD deflections using MODULUS, users may obtain this information beforehand and use it in planning the FWD testing. For this purpose, researchers strongly suggest a Ground Penetrating Radar (GPR) survey on the route to establish the variations in layer thicknesses from the profiles obtained. Specifically, the GPR survey should be conducted to:

1. detect changes in pavement layer thicknesses and divide the project into analysis segments,
2. establish the locations of FWD measurements consistent with pavement thickness variations identified from the radar data, and
3. establish the need for cores or Dynamic Cone Penetrometer (DCP) data to supplement the radar survey and identify locations where coring and DCP measurements should be made.

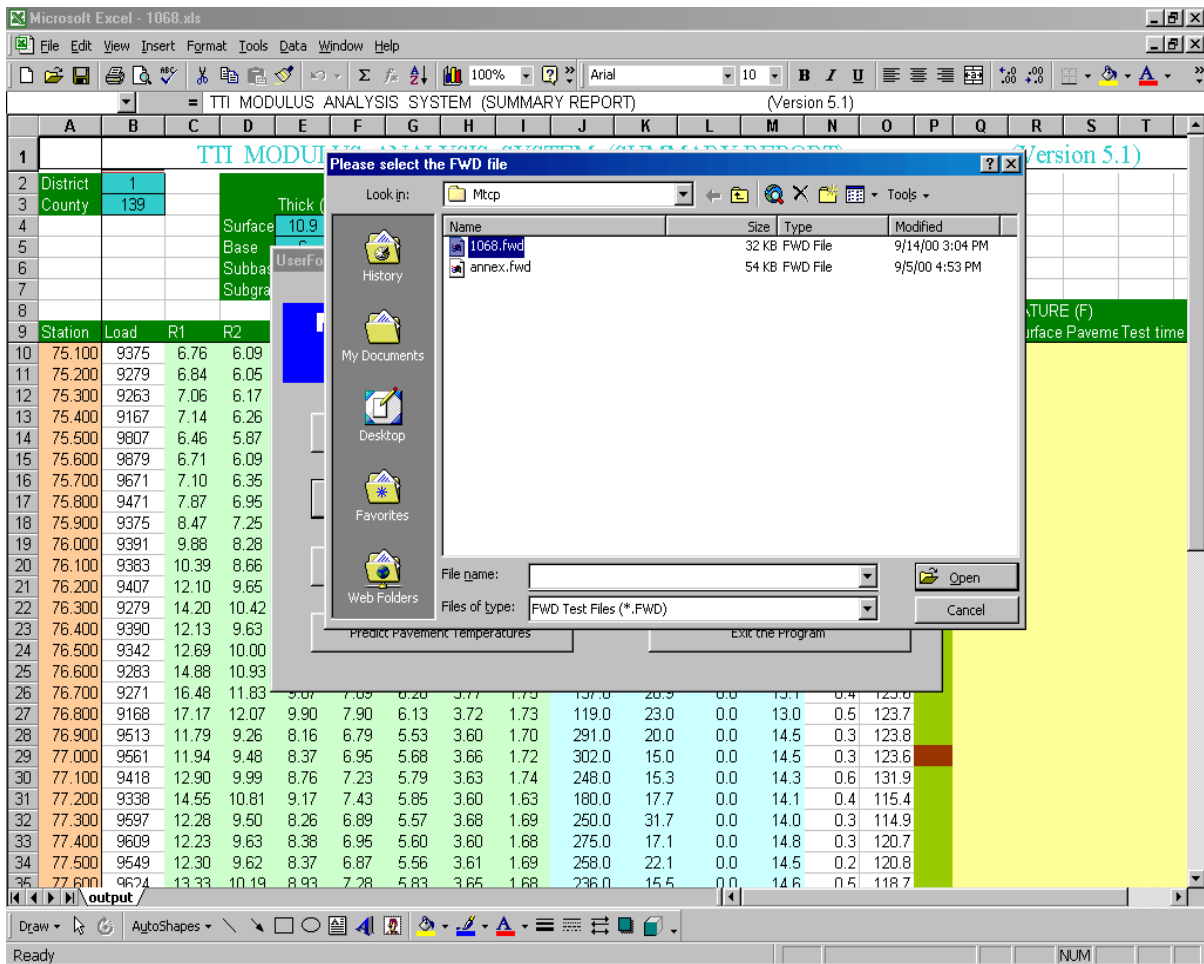


Figure 6. Dialog Box for Specifying the FWD Data File.

Pavement temperatures measured during the FWD survey should be properly recorded into the data file consistent with the FWD operator’s manual (TxDOT, 1996). In this way, all temperature data may be read from the file and imported directly into the MTCP spreadsheet without having to manually key in the pavement temperatures. The air, surface, and pavement temperatures taken during the survey may be imported into the spreadsheet by clicking on the *Read FWD Test File & Get Temperatures* button of the main menu given in Figure 2. The dialog box in Figure 6 is then displayed for you to specify the name of the FWD data file. After selecting the FWD file, click on the *Open* button of the dialog box to import the temperature data into the spreadsheet as illustrated in Figure 7.

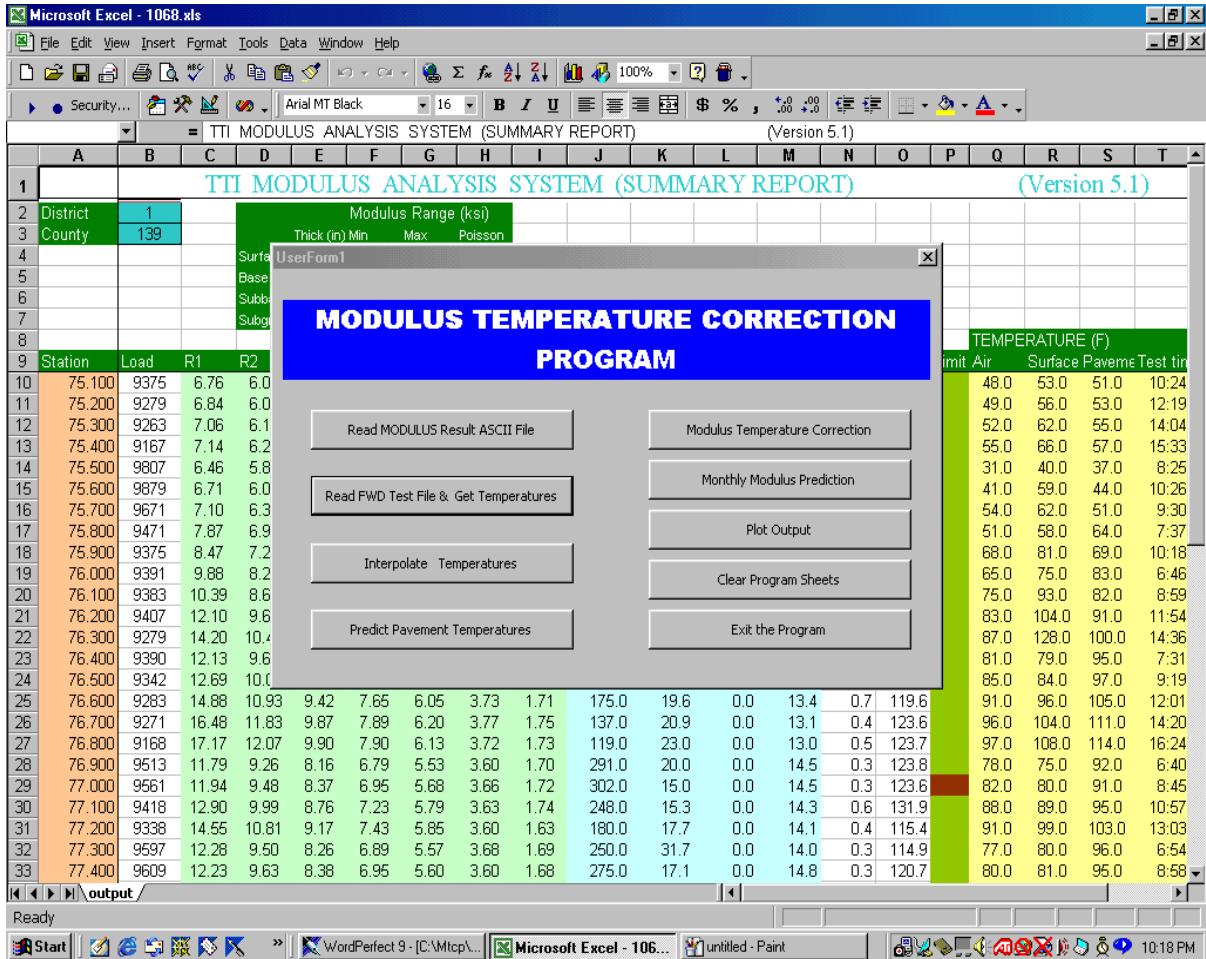


Figure 7. Temperature Data Imported from the FWD Data File.

PERFORMING THE TEMPERATURE CORRECTION

Before corrections to a reference temperature may be made, the pavement temperatures you are correcting from must first be established. These pavement temperatures are referred to herein as the base temperatures for the modulus correction and refer to the pavement temperatures at which the FWD deflections were taken. There are two functions available in MTCP to establish the base temperatures. One allows you to estimate the pavement temperature at a given FWD station by interpolating between pavement temperatures measured at two neighboring stations that bound it.

In practice, pavement temperatures will not normally be measured at each test location. By clicking on the *Interpolate Temperatures* button in the main menu, you can fill in the missing information by interpolation from the available pavement temperature measurements. As a minimum, pavement temperatures should be measured at the beginning

and end of the FWD survey for a given project. The program uses a linear interpolation based on the time of the FWD measurement. This is given in the *Test Time* column of the spreadsheet illustrated in [Figure 7](#). No extrapolation is done for locations that are outside the range of stations where pavement temperatures were measured. Stations preceding the first temperature measurement are assigned that pavement temperature while stations following the last measurement are assigned the last value.

If you did not enter the pavement temperatures at the time of the FWD survey, you may manually key in the data along the *Pavement* column of the spreadsheet inside the cells corresponding to stations where pavement temperatures were taken. After manually entering the data, you may then click on ***Interpolate Temperatures*** to fill in the rest of the cells along the *Pavement* column with interpolated pavement temperatures.

Alternatively, if pavement temperatures were not measured during the survey, the base temperatures for the correction may be established using one of three options available within MTCR for predicting pavement temperature. All three options require the infrared surface temperatures taken with the FWD and the average of the previous day's minimum and maximum air temperatures at the vicinity of the project. The first two options are the BELLS2 and BELLS3 equations which were developed using data from Seasonal Monitoring Program (SMP) sites located in North America. The development of these equations are documented in a report by [Lukanen, Stubstad, and Briggs \(1998\)](#) and in a paper by [Stubstad et al. \(1998\)](#). BELLS2 is the equation for the FWD testing protocol used in the Long-Term Pavement Performance (LTPP) program. On the other hand, BELLS3 is intended for routine testing and was developed from efforts made to consider the effects of shading on the infrared surface temperatures measured on the SMP sites. The functional form of the BELLS2 and BELLS3 equations is given by:

$$T_d = \beta_0 + \beta_1 IR + [\log_{10}(d) - 1.25] [\beta_2 IR + \beta_3 T_{(1\text{-day})} + \beta_4 \sin(\text{hr}_{18} - 15.5)] + \beta_5 IR \sin(\text{hr}_{18} - 13.5) \quad (1)$$

where,

T_d = pavement temperature at depth, d, within the asphalt layer, °C

IR = surface temperature measured with the FWD infrared temperature gauge, °C

d = depth at which the temperature is to be predicted, mm

Table 1. Coefficients of the BELLS2 and BELLS3 Equations.

Coefficient	BELLS2	BELLS3
β_0	+2.780	+0.950
β_1	+0.912	+0.892
β_2	-0.428	-0.448
β_3	+0.553	+0.621
β_4	+2.630	+1.830
β_5	+0.027	+0.042
R^2	0.977	0.975
SEE	1.8 °C	1.9 °C
N_{obs}	10,304	10,304

$T_{(1\text{-day})}$ = the average of the previous day's high and low air temperatures, °C

hr_{18} = time of day in the 24-hour system but calculated using an 18-hour asphalt temperature rise and fall time as explained by [Stubstad et al. \(1998\)](#)

The coefficients of [Eq.\(1\)](#) are given in [Table 1](#) for both the BELLS2 and BELLS3 equations. Also shown are the R^2 , standard error of the estimate (SEE) and the number of observations (N_{obs}) used to develop each equation. Note that the average of the previous day's high and low air temperatures is the only variable not collected during routine FWD testing that the user needs to provide to predict pavement temperatures with BELLS2 or BELLS3.

Researchers recommend that pavement temperatures be predicted at half the depth of the surface layer.

The third option available within MTCP to predict pavement temperature uses the same variables as BELLS2 and BELLS3 but has the functional form given by [Eq.\(2\)](#) below:

$$T_d = \beta_0 + \beta_1 (IR + 2)^{1.5} + \log_{10}(d) * \{ \beta_2 (IR + 2)^{1.5} + \beta_3 \sin^2(hr_{18} - 15.5) + \beta_4 \sin^2(hr_{18} - 13.5) + \beta_5 [T_{(1\text{-day})} + 6]^{1.5} \} + \beta_6 \sin^2(hr_{18} - 15.5) \sin^2(hr_{18} - 13.5) \quad (2)$$

where the terms are as defined previously and the coefficients are:

$$\begin{array}{llll} \beta_0 = 6.460 & \beta_1 = 0.199 & \beta_2 = -0.083 & \beta_3 = -0.692 \\ \beta_4 = 1.874 & \beta_5 = 0.059 & \beta_6 = -6.783 & \end{array}$$

Equation (2) has an R^2 of 0.931 and a standard error of the estimate of 3.1 °C with 1575 observations. It was developed using data collected from SMP sites in Texas, New Mexico, and Oklahoma and from two flexible pavement sections located at the Texas A&M Riverside Campus. If the pavement temperatures at these sites are predicted using the original BELLS2 and BELLS3 equations, standard errors of the estimate of 4.1 °C and 4.9 °C are obtained, respectively (Fernando and Liu, 2001). To improve the predictive accuracy, researchers undertook to calibrate the BELLS2 and BELLS3 equations using data that are representative of conditions within Texas. These efforts led to the development of **Eq.(2)** which is referred to as the Texas-LTPP equation.

You may access the available options for predicting pavement temperature by clicking on the ***Predict Pavement Temperatures*** button of the main menu. This will display the dialog box illustrated in **Figure 8** where you will specify:

1. the depth, in inches, at which the temperature is to be predicted;
2. the average of the previous day's high and low air temperatures in °F; and
3. the method for predicting pavement temperature, i.e., BELLS2, BELLS3, or the Texas-LTPP equation given by **Eq.(2)**.

You may select the equation to use by clicking on the down arrow in the *Select Equation* field of the dialog box to display the list of available options (see **Figure 9**). Select the equation by clicking on it. Note that the surface thickness from the MODULUS output file is displayed in the dialog box for your reference when you specify the depth at which pavement temperatures are to be predicted. It is also important that you specify the depth in inches and the average of the previous day's high and low air temperatures in °F as noted in the dialog box. The program automatically converts these inputs to the corresponding metric units used in the equations.

After entering the required data in **Figure 8**, click on the **OK** button of the dialog box to proceed with the temperature prediction. The results are written into the spreadsheet immediately to the right of the *Test time* column as shown in **Figure 10**. This column is labeled *Predicted Temperature*. If you bring the pointer inside the cell for this label, a comment box is displayed (**Figure 10**) which gives information on the equation selected for predicting pavement temperatures, the depth at which the temperatures were predicted, and

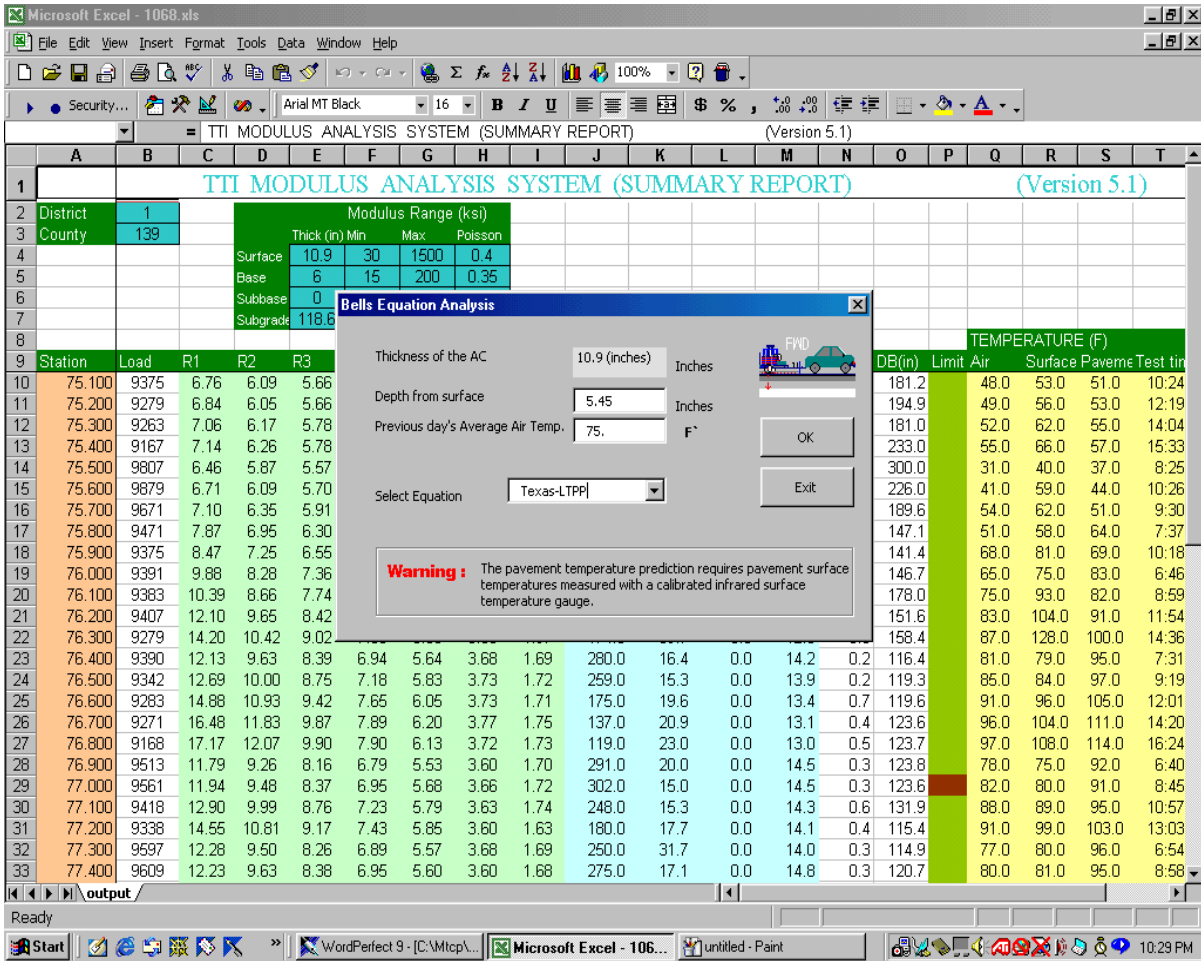


Figure 8. Dialog Box to Specify Input Data for Pavement Temperature Prediction.

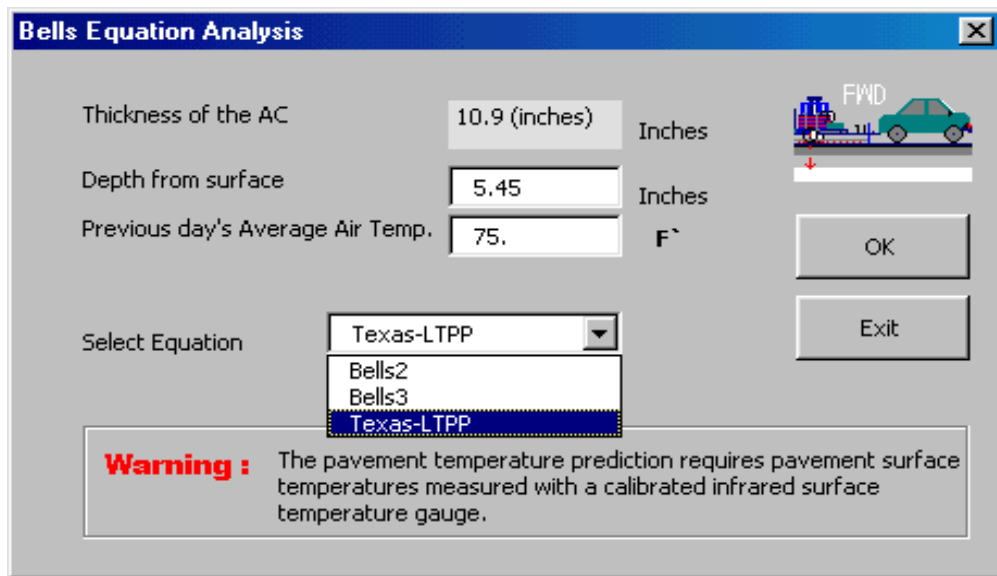


Figure 9. Equations Available for Predicting Pavement Temperatures.

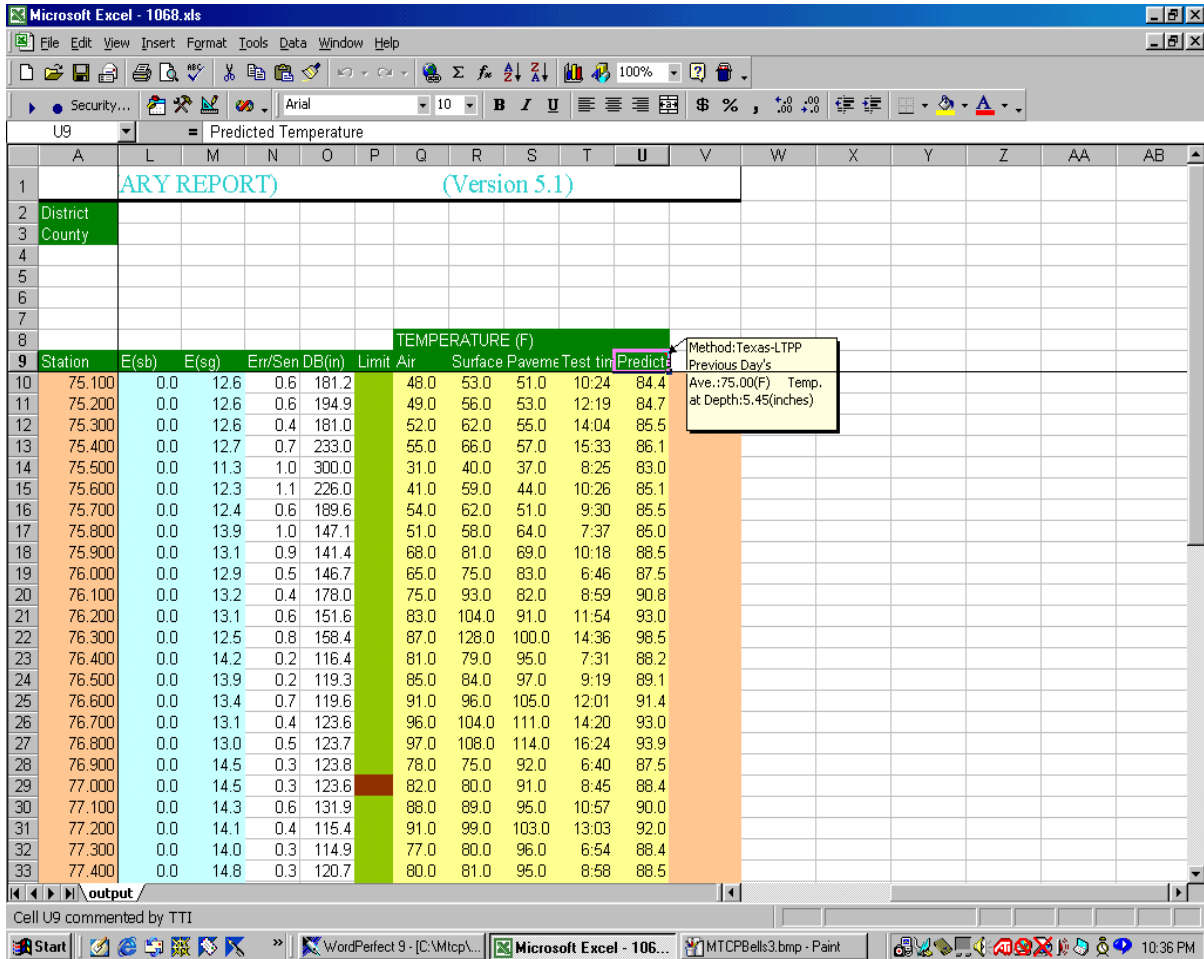


Figure 10. Predicted Pavement Temperatures from MTCP.

the average of the previous day's high and low air temperatures. A red triangular spot at the upper right corner identifies cells with comment boxes. Sometimes there may be more information than can be displayed inside the comment box. In this case, you may resize the box by right clicking on the cell and selecting the *Edit Comment* function (Figure 11) to view all of the information inside the box.

After the base temperatures are established, you can proceed with the modulus correction by clicking on the *Modulus Temperature Correction* button of the main menu illustrated in Figure 2. This will display the dialog box shown in Figure 12 which provides the following three options for temperature correction of backcalculated AC moduli:

1. the existing **TxDOT equation** used in the Flexible Pavement System (FPS) and load zoning analysis programs,
2. the **Chen equation** (Chen at al., 2000), and
3. Witczak's dynamic modulus equation.

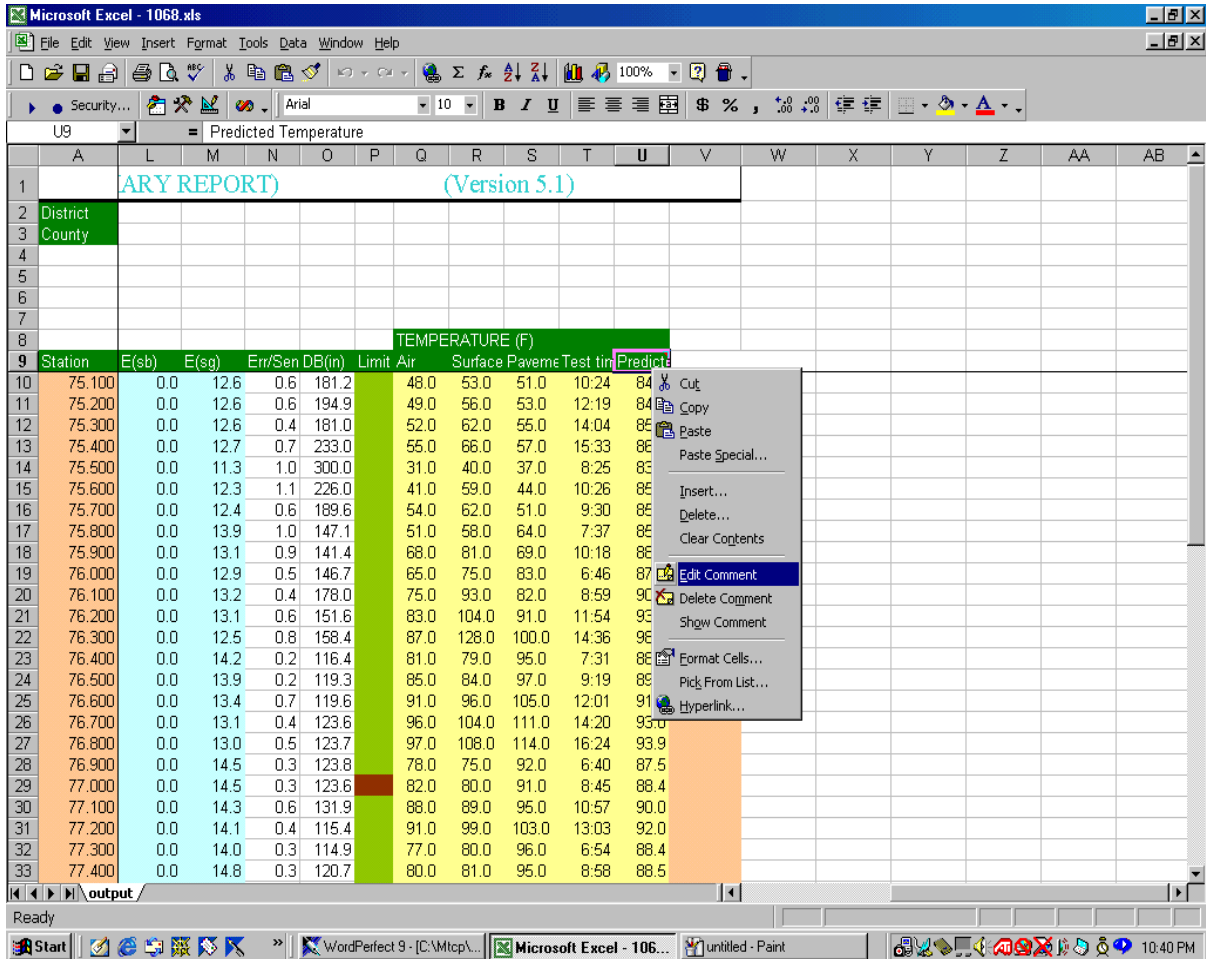


Figure 11. Resizing the Comment Box Using the *Edit Comment* Function in Excel.

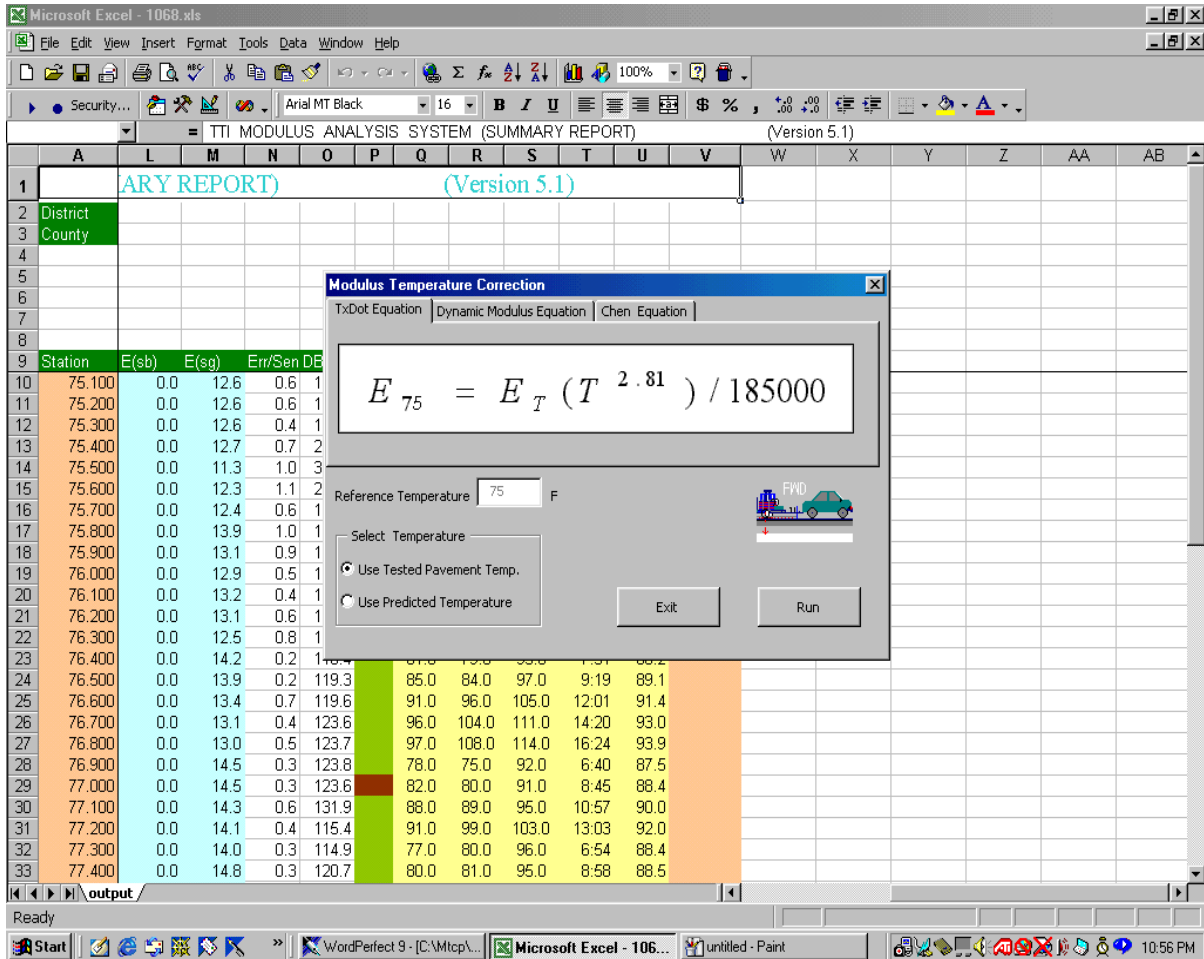


Figure 12. Dialog Box Showing TxDOT’s Equation for Modulus Temperature Correction.

You can select the equation to use for temperature correction by clicking on the appropriate folder tab of the dialog box in Figure 12, where TxDOT’s equation for modulus temperature correction is shown. This equation is based on a reference temperature of 75 °F. The independent variables of the equation are the FWD test temperature T in °F and the backcalculated asphalt concrete modulus E_T that is read from the MODULUS summary output file. The FWD test temperatures correspond to the base pavement temperatures established in the previous step. As shown in Figure 12, you have two options for specifying the base pavement temperatures. If pavement temperatures were measured during the FWD survey, you can use the measured temperatures at specific stations and the interpolated values at the other stations by clicking on the *Use Tested Pavement Temp.* option in the dialog box. If no pavement temperatures were measured during the survey, you can use the predicted temperatures from BELLS2, BELLS3, or the Texas-LTPP equation presented previously.

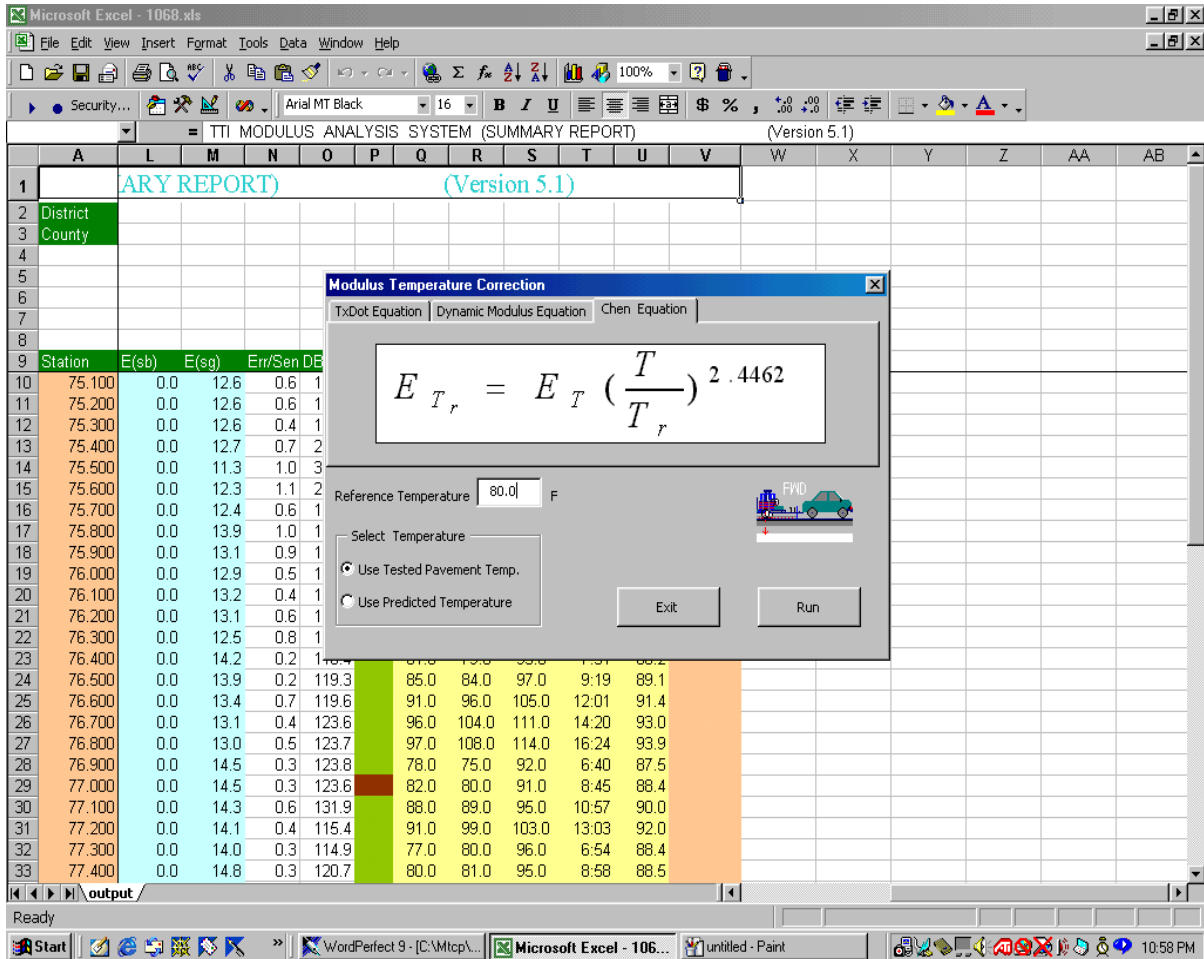


Figure 13. Chen Equation for Modulus Temperature Correction.

You may then perform the modulus temperature correction by clicking the **Run** button of the dialog box. Alternatively, you may click the **Exit** button to go back to the main menu without performing the temperature corrections.

Figure 13 shows the Chen equation. This equation was developed using FWD and pavement temperature data taken from three test sections established as part of TxDOT’s Mobile Load Simulator (MLS) project (Chen et al., 2000). The equation is therefore applicable for pavements that are similar to the sections tested. Nevertheless, modulus temperature correction factors from this equation were found to agree reasonably well with corresponding factors from TxDOT’s equation even though the two were developed from different studies.

The Chen equation permits the correction to be made for any user-specified reference temperature T_r . The reference temperature (in °F) is specified in the dialog box of Figure 13. Note that both the Chen and existing TxDOT equations do not require AC mixture properties

for modulus temperature correction and are thus easy to use in practice. These equations were developed for the typical mixtures used in the state. However, there may be occasions where the user may want to evaluate the temperature dependency for the specific asphalt mix used in a given project. Consequently, a third option (Figure 14) was incorporated into MTCP that is based on the prediction equation for dynamic modulus developed by Witzczak and Fonseca (1996). This option requires data on the aggregate gradation and the binder viscosity-temperature relationship for the asphalt concrete mixture. The equation for modulus temperature correction is given by:

$$\log_{10} E_R = \log_{10} E_T + A \left[\frac{1}{1 + e^{-(B_R + 0.7425 \log_{10} \eta_R)}} - \frac{1}{1 + e^{-(B_T + 0.7425 \log_{10} \eta_T)}} \right] \quad (3)$$

$$R^2 = 0.93 \quad \text{SEE} = 0.12 \quad (\text{log scale})$$

where,

$$A = 1.87 + 0.003 p_4 + 0.00004 p_{3/8} - 0.00018 (p_{3/8})^2 + 0.0164 p_{3/4} \quad (4)$$

$$B_R = 0.716 \log_{10} f_R \quad (5)$$

$$B_T = 0.716 \log_{10} f_T \quad (6)$$

E_R = AC modulus corrected for the selected reference temperature, 10^5 psi

E_T = backcalculated asphalt concrete modulus, 10^5 psi

η_R = binder viscosity corresponding to the reference temperature, 10^6 Poises

η_T = binder viscosity corresponding to the FWD test temperature, 10^6 Poises

p_4 = cumulative percent retained on #4 sieve by total aggregate weight

$p_{3/8}$ = cumulative percent retained on 3/8-inch sieve by total aggregate weight

$p_{3/4}$ = cumulative percent retained on 3/4-inch sieve by total aggregate weight

f_R = reference loading frequency, Hz

f_T = test frequency, Hz

For the impulse loading of the FWD, the test frequency may be approximated from the following relationship proposed by Lytton et al. (1990):

$$f_T = \frac{1}{2t} \quad (7)$$

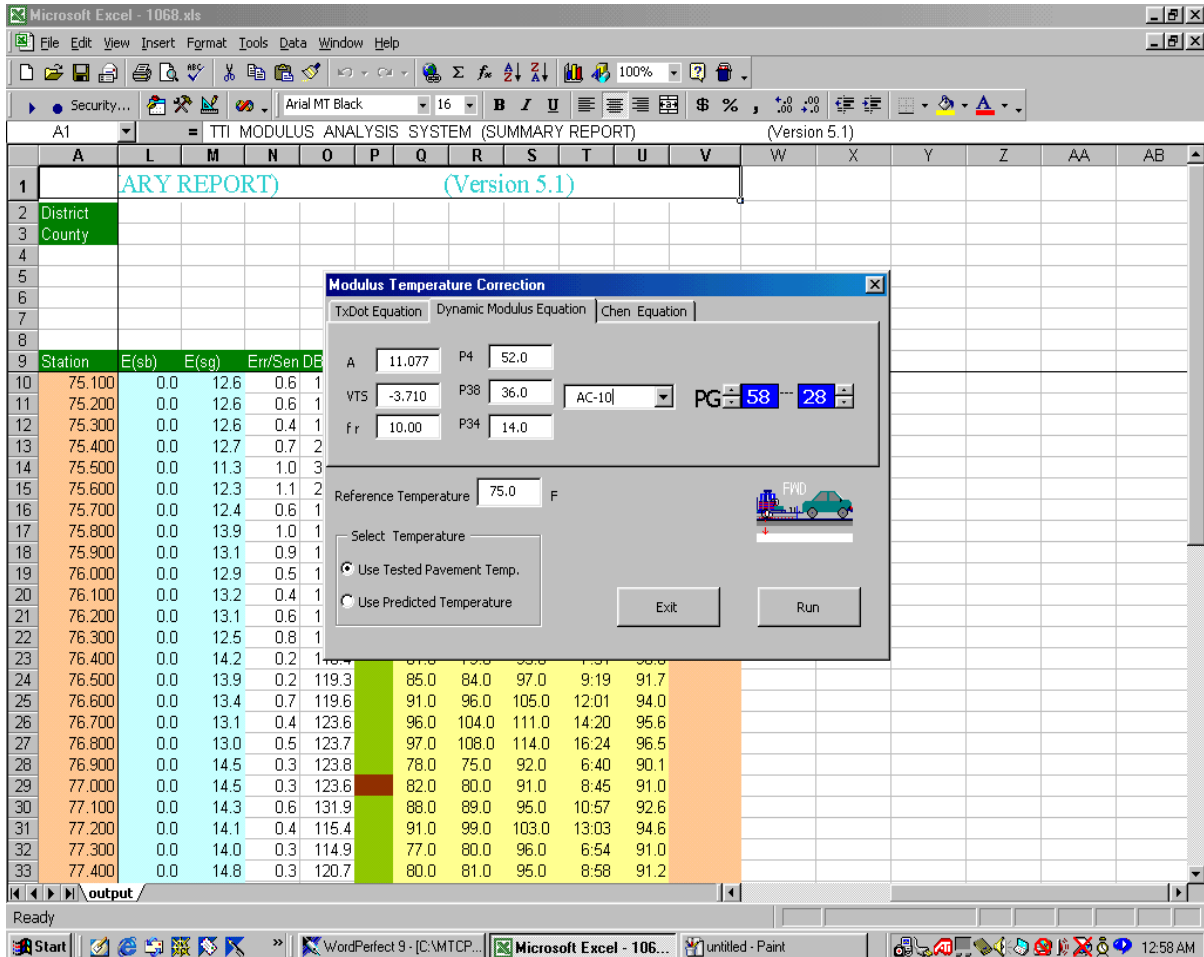


Figure 14. Dialog Box for Temperature Correction Based on Witczak’s Dynamic Modulus Equation.

where t is the duration of the impulse load in seconds. The duration of the impulse load for the FWD is about 30 msecs which gives a test frequency of about 16.7 Hz, the value used in MTCP for modulus correction. On the other hand, f_R should correspond to the frequency of loading used in pavement design. This typically ranges from 8 to 10 Hz for the standard 18-kip single axle load traveling at typical highway speeds. The reference frequency is entered in the f_r field of the dialog box shown in Figure 14. Note that if you enter a value equal to the FWD load frequency (16.7 Hz), no correction for the effect of load duration on the AC modulus will be made.

The gradation information for the mix is entered in the fields labeled P_4 , P_{38} , and P_{34} corresponding, respectively, to p_4 , $p_{3/8}$, and $p_{3/4}$. The binder viscosity corresponding to the reference and base pavement temperatures are determined using the ASTM D-2493 viscosity-temperature relationship given by:

$$\log_{10} \log_{10} \eta = A + VTS \log_{10} T_{\circ_R} \quad (8)$$

where η is the binder viscosity, T_{\circ_R} is the temperature in degrees Rankine, and A and VTS are model coefficients determined from testing. In practice, A and VTS may be determined by conducting dynamic shear rheometer (DSR) tests at a range of temperatures on the binder extracted from a core taken at the project site. This extraction will also provide the gradation data needed to use the dynamic modulus equation for temperature correction.

DSR tests may be conducted at an angular frequency of 10 rad/sec and for a temperature range of 40 to 130 °F. From the binder complex shear modulus G^* and phase angle δ determined at a given temperature, the corresponding binder viscosity may be estimated from the **equation**:

$$\eta = \frac{G^*}{10} \left(\frac{1}{\sin \delta} \right)^{4.8628} \quad (9)$$

The binder viscosities determined at the different test temperatures may be used in a regression analysis to get the A and VTS coefficients of **Eq.(8)**. These coefficients are then entered in the corresponding fields of the dialog box given in **Figure 14**.

In the absence of actual test data to determine the coefficients, researchers have incorporated default values into MTCP to permit you to conduct an approximate analysis. The default coefficients are based on the asphalt grade and are applicable for unmodified binders. **Table 2** shows the coefficients for AC-graded binders while **Table 3** shows the coefficients for performance-graded (PG) asphalts. The coefficients in **Table 2** are based on research conducted by **Mirza (1993)** and are representative of asphalts that have undergone field aging. Those in **Table 3** are from unpublished data taken from the AASHTO 2002 development work. The predicted binder viscosities from these coefficients are representative of mix/laydown conditions.

If the binder on the project is AC-graded, you may specify the asphalt type by clicking on the down arrow in **Figure 14** to display the list of asphalt grades for which default coefficients are available (see **Figure 15**). From this list, you may click on the applicable binder type to select it. The coefficients corresponding to this binder are then displayed in the A and VTS fields of the dialog box.

Table 2. Default *A* and *VTS* Coefficients for AC-Graded Asphalts¹.

Viscosity Grade (Original Conditions)	Viscosity Range at 140 °F (Poises)	<i>A</i>	<i>VTS</i>
AC - 2.5	100 - 350	11.8408	-3.9974
AC - 5	350 - 700	11.4711	-3.8557
AC - 10	700 - 1400	11.0770	-3.7097
AC - 20	1400 - 2800	10.9168	-3.6469
AC - 40	2800 - 5200	10.6528	-3.5477

¹ Representative of asphalts that have undergone field aging.

Table 3. Default A and VTS Coefficients for PG-Graded Asphalts¹.

High Temp. Grade	Low Temperature Grade													
	-10		-16		-22		-28		-34		-40		-46	
	A	VTS	A	VTS	A	VTS	A	VTS	A	VTS	A	VTS	A	VTS
46									11.504	-3.901	10.101	-3.393	8.755	-2.905
52	13.38 6	-4.570	13.305	-4.541	12.755	-4.342	11.840	-4.012	10.707	-3.602	9.496	-3.164	8.310	-2.736
58	12.31 6	-4.172	12.248	-4.147	11.787	-3.981	11.010	-3.701	10.035	-3.350	8.976	-2.968		
64	11.43 2	-3.842	11.375	-3.822	10.980	-3.680	10.312	-3.440	9.461	-3.134	8.524	-2.798		
70	10.69 0	-3.566	10.641	-3.548	10.299	-3.426	9.715	-3.217	8.965	-2.948	8.129	-2.648		
76	10.05 9	-3.331	10.015	-3.315	9.715	-3.208	9.200	-3.024	8.532	-2.785				
82	9.514	-3.128	9.475	-3.114	9.209	-3.019	8.750	-2.856	8.151	-2.642				

¹ Coefficients representative of mix/laydown conditions (unpublished data from AASHTO 2002 development work).

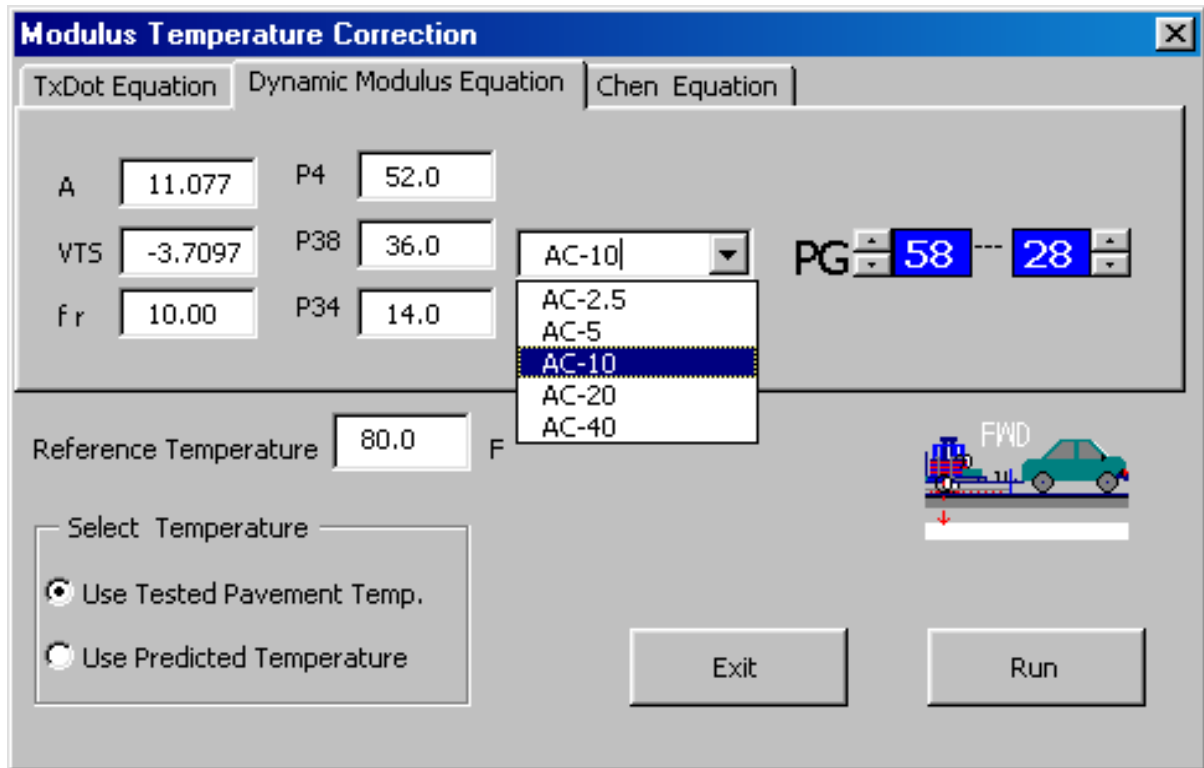


Figure 15. Drop-Down List of AC-Graded Asphalts with Default Coefficients.

If the binder on the project is PG-graded, you simply click on the up and down arrows of the PG fields in the dialog box until you get the number designations you want. The *A* and *VTS* coefficients for that PG grade are then displayed. Note that coefficients are only available for the PG grades shown in [Table 3](#). It is also noted that the *A* and *VTS* coefficients displayed in the dialog box always correspond to those specified for the last run made. Default values for these coefficients may have been used, or alternatively, coefficients from laboratory test data may have been entered in the *A* and *VTS* fields of the dialog box shown in [Figure 15](#). Thus, these fields will not necessarily display coefficients that correspond to the current AC and/or PG grades displayed in the dialog box.

The results from the temperature corrections are written into the worksheet along the column labeled *Corrected Modulus*. As shown in [Figure 16](#), the column label has a comment box which gives information about the method used to perform the temperature correction. Specifically, the comment box identifies the method, as well as the reference and base pavement temperatures used for the corrections. In addition, if the dynamic modulus equation is selected, the *A* and *VTS* coefficients, reference loading frequency, and aggregate gradation are displayed in the comment box.

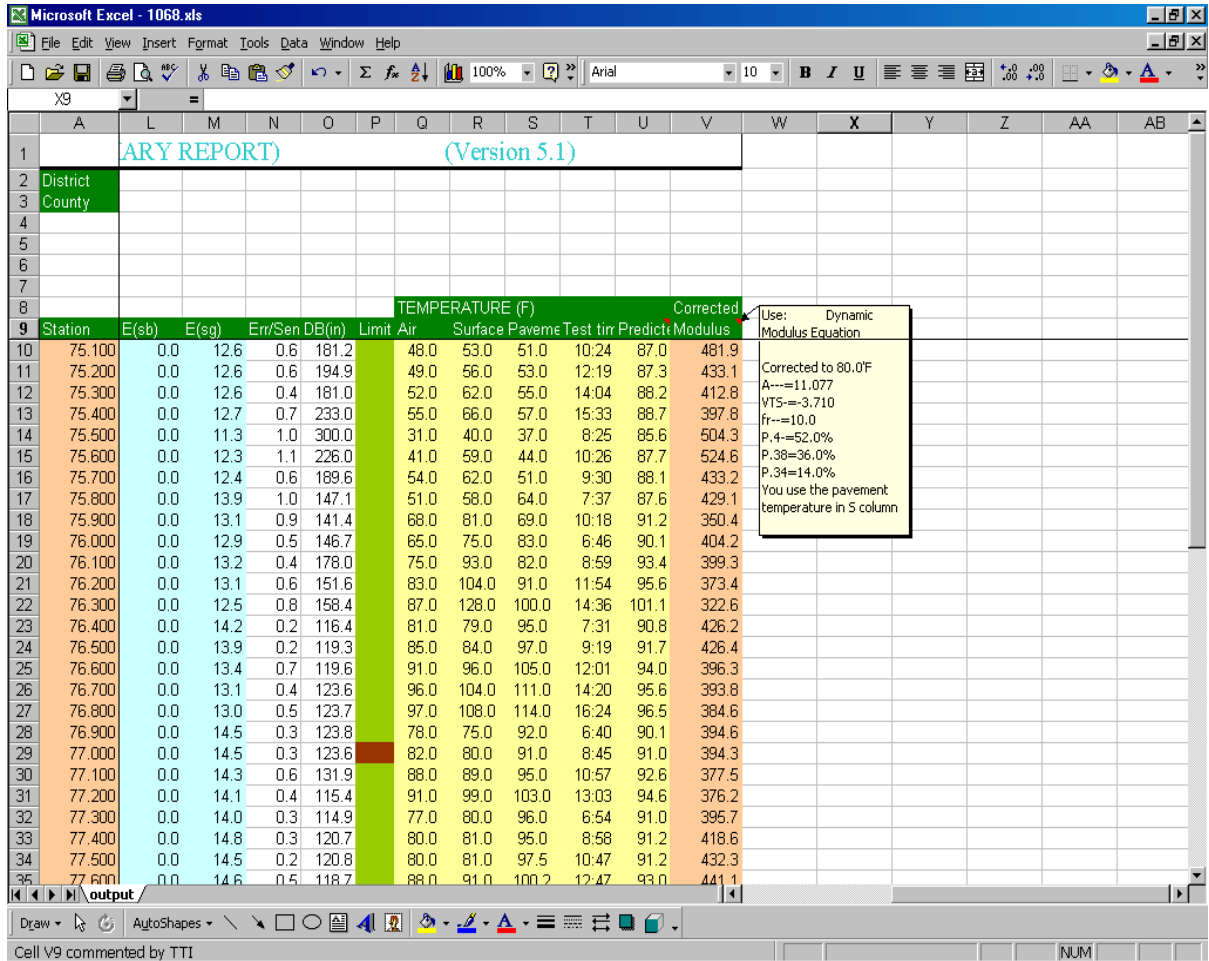


Figure 16. Temperature Corrected Moduli from the Analysis.

MONTHLY MODULUS PREDICTION

In certain instances, it may be necessary to model the seasonal variation in material properties. MTCP permits the user to estimate the monthly variation in asphalt concrete modulus given the mean monthly pavement temperatures for a given project. In the program, the mean monthly pavement temperatures are estimated from the mean monthly air temperatures using the following equation (Asphalt Institute, 1982):

$$MMPT = MMAT \left[1 + \frac{1}{(z+4)} \right] - \frac{34}{(z+4)} + 6 \quad (10)$$

where,

$MMPT$ = mean monthly pavement temperature, °F

$MMAT$ = mean monthly air temperature, °F

z = depth at which pavement temperature is to be predicted, inches

As an aid in using this feature, a database of mean monthly air temperatures has been compiled that covers all counties in the state. This database is built in to MTCP and is used to estimate the mean monthly pavement temperatures. The reference modulus corresponding to the reference temperature is then adjusted to the predicted mean monthly pavement temperatures.

By default, the reference modulus is taken as the average of the corrected moduli for the different stations. Thus, in performing the temperature correction for the backcalculated asphalt concrete moduli, the user may specify a reference temperature that he or she considers representative of the year-round pavement temperatures at the project surveyed. In this instance, the corrected moduli will correspond to average yearly conditions at the site. To evaluate monthly variations, the average of the corrected moduli is adjusted to the predicted mean monthly pavement temperatures in MTCP.

Alternatively, the user may correct the backcalculated moduli to a reference temperature that he or she considers to be representative of the pavement temperatures at the time of the FWD survey. In this instance, the program will predict how the reference modulus, corresponding to conditions at the date of testing, varies with the predicted monthly changes in pavement temperatures at the site surveyed.

While the program uses the average of the corrected moduli as the default reference for evaluating monthly variations, the user may specify an alternative reference value for the analysis. This option is described later. At this point, a few guidelines about the selection of the reference modulus are in order.

The user should examine the variation in the corrected moduli for the different stations tested. If the coefficient of variation exceeds 15 percent, the user should ask whether the variability suggests possible differences in pavement materials and layer thicknesses along the route surveyed. He or she should check the measured deflections, backcalculated moduli, predicted depths to bedrock, the average absolute errors per sensor, and whether any of the prescribed limits were reached in the backcalculation. Depending on the results, there may be a need to subsection the FWD data to create homogeneous segments for the MODULUS backcalculation. For this purpose, the MODULUS program may be used to delineate segments of a specified minimum length based on the cumulative difference method. [Michalak and Scullion \(1995\)](#) describe how this option is used in MODULUS.

The user may have to collect additional information on the route to better characterize the pavements for the segments identified. The MODULUS and temperature correction programs are then run on each segment. Results from these runs should be reviewed to establish the need for further analyses.

To predict how the asphalt concrete modulus at the site will vary with temperature changes over the year, click on the **Monthly Modulus Prediction** button of the MTCP main menu. The dialog box shown in [Figure 17](#) is then displayed. This dialog box shows the averages of the daily minimum and daily maximum air temperatures for each month, as determined from the weather station in the county where the project surveyed is located. The average monthly air temperatures are also shown as well as the name, elevation, and location of the weather station. The county ID displayed in the dialog box is read directly from the FWD data file. If for some reason, the county ID in the file is wrong, you may simply type the correct ID in the dialog box or use the up and down buttons beside the *County ID* field to scroll through the weather data for the different counties in Texas. A list of the counties is given in [Figure 18](#) for your reference.

After establishing the county ID for the project, click on the folder tab labeled *Input* in the dialog box. The screen shown in [Figure 19](#) is then displayed where you may specify:

1. the depth at which the mean monthly pavement temperatures will be predicted,
2. the reference temperature, and
3. the reference modulus.

For consistency, the depth and the reference temperature are the same as that specified in the correction of the backcalculated asphalt concrete moduli. For your reference, the thickness of the surface layer is also provided. The reference modulus shown is the average of the corrected moduli, as explained earlier. You may change any of these default values, but you need to make sure that the values you input are consistent with each other.

When you are through specifying the input parameters for this dialog box, click on the **Next** button to continue. The screen shown in [Figure 20](#) is then displayed. You will notice that the mean monthly pavement temperatures are calculated and written into a new worksheet labeled *Month*. In addition, the average monthly air temperatures and the reference modulus are reported in the worksheet. There is also a dialog box where you can specify the equation you want to use for correcting the reference modulus to the predicted mean monthly pavement temperatures. The two choices available are the dynamic modulus and Chen equations. To

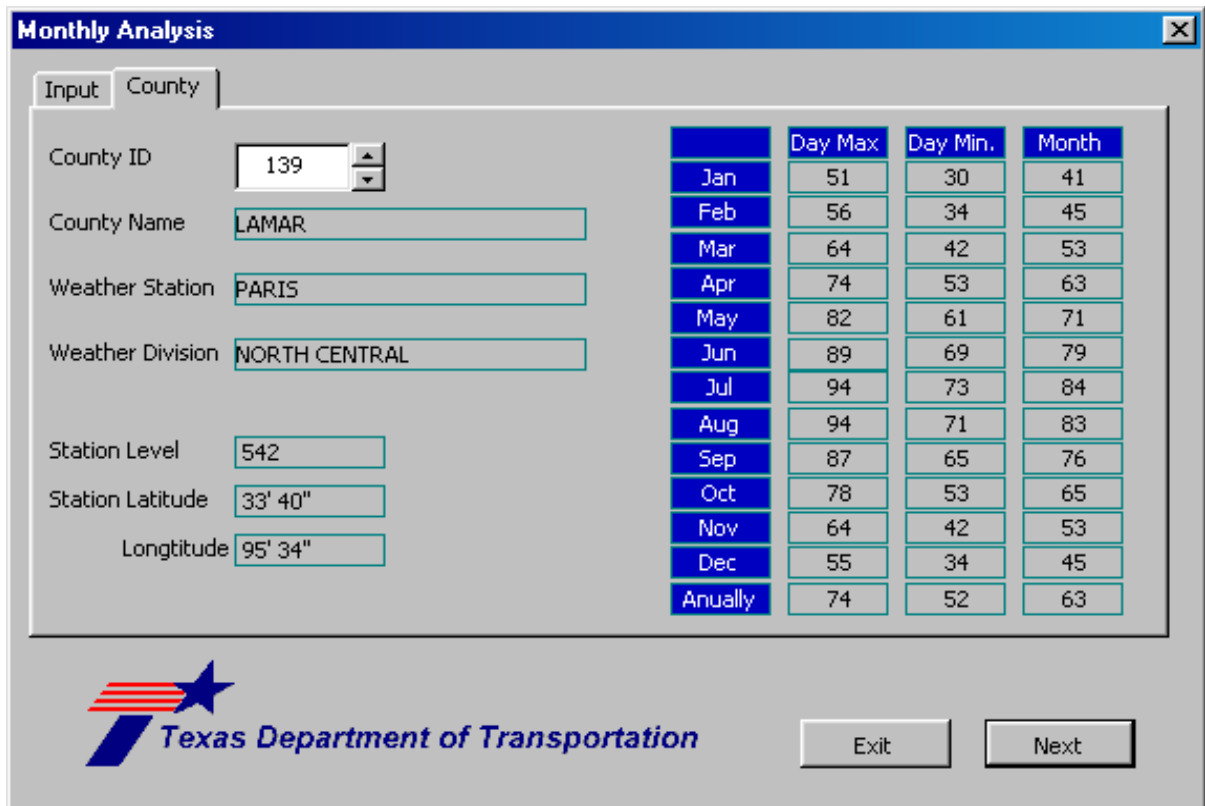


Figure 17. Dialog Box of Monthly Air Temperatures for Specified County.

DISTRICT 1

(Paris)
 60 Delta
 75 Fannin
 81 Franklin
 92 Grayson
 113 Hopkins
 117 Hunt
 139 Lamar
 190 Rains
 194 Red River

DISTRICT 2

(Fort Worth)
 73 Erath
 112 Hood
 120 Jack
 127 Johnson
 182 Palo Pinto
 184 Parker
 213 Somervell
 220 Tarrant
 249 Wise

DISTRICT 3

(Wichita Falls)
 5 Archer
 12 Baylor
 39 Clay
 49 Cook
 169 Montague
 224 Throckmorton
 243 Wichita
 244 Wilbarger
 252 Young

DISTRICT 4

(Amarillo)
 6 Armstrong
 33 Carson
 56 Dallam
 59 Deaf Smith
 91 Gray
 99 Hansford
 104 Hartley
 107 Hemphill
 118 Hutchinson
 148 Lipscomb
 171 Moore
 179 Ochiltree
 180 Oldham
 188 Potter
 191 Randall
 197 Roberts
 211 Sherman

DISTRICT 5

(Lubbock)
 9 Bailey
 35 Castro
 40 Cochran
 54 Crosby
 58 Dawson
 78 Floyd
 84 Gaines
 86 Garza
 96 Hale
 111 Hockley
 140 Lamb
 152 Lubbock
 153 Lym
 185 Parmer
 219 Swisher
 223 Terry
 251 Yoakum

DISTRICT 6

(Odessa)
 2 Andrews
 52 Crane
 69 Ector
 151 Loving
 156 Martin
 165 Midland
 186 Pecos
 195 Reeves
 222 Terrell
 231 Upton
 238 Ward
 248 Winkler

DISTRICT 7

(San Angelo)
 41 Coke
 48 Concho
 53 Crockett
 70 Edwards
 88 Glasscock
 119 Irion
 134 Kimble
 164 Menard
 192 Reagan
 193 Real
 200 Runnels
 207 Schleicher
 216 Sterling
 218 Sutton
 226 Tom Green

DISTRICT 8

(Arlene)
 17 Borden
 30 Callahan
 77 Fisher
 105 Haskell
 115 Howard
 128 Jones
 132 Kent
 168 Mitchell
 177 Nolan
 208 Scurry
 209 Shackelford
 217 Stonewall
 221 Taylor

DISTRICT 9

(Waco)
 14 Bell
 18 Bosque
 50 Coryell
 74 Falls
 98 Hamilton
 110 Hill
 147 Limestone
 161 McLennan

DISTRICT 10

(Tyler)
 1 Anderson
 37 Cherokee
 93 Gregg
 108 Henderson
 201 Rusk
 212 Smith
 234 Van Zandt
 250 Wood

DISTRICT 11

(Lufkin)
 3 Angelina
 114 Houston
 174 Nacogdoches
 187 Polk
 202 Sabine
 203 San Augustine
 204 San Jacinto
 210 Shelby
 228 Trinity

DISTRICT 12

(Houston)
 20 Brazoria
 80 Fort Bend
 85 Galveston
 102 Harris
 170 Montgomery
 237 Waller

DISTRICT 13

(Yoakum)
 8 Austin
 29 Calhoun
 45 Colorado
 62 DeWitt
 76 Fayette
 90 Gonzales
 121 Jackson
 143 Lavaca
 158 Matagorda
 235 Victoria
 241 Wharton

DISTRICT 14

(Austin)
 11 Bastrop
 16 Blanco
 27 Burnet
 28 Caldwell
 87 Gillespie
 106 Hays
 144 Lee
 150 Llano
 157 Mason
 227 Travis
 246 Williamson

DISTRICT 15

(San Antonio)
 7 Atascosa
 10 Bandera
 15 Bexar
 46 Comal
 83 Frio
 95 Guadalupe
 131 Kendall
 133 Kerr
 162 McMullen
 163 Medina
 232 Uvalde
 247 Wilson

DISTRICT 16

(Corpus Christi)
 4 Aransas
 13 Bee
 89 Goliad
 126 Jim Wells
 129 Karnes
 137 Kleberg
 149 Live Oak
 178 Nueces
 196 Refugio
 205 San Patricio

DISTRICT 17

(Bryan)
 21 Brazos
 26 Burleson
 82 Freestone
 94 Grimes
 145 Leon
 154 Madison
 166 Milam
 198 Robertson
 236 Walker
 239 Washington

DISTRICT 18

(Dallas)
 43 Collin
 57 Dallas
 61 Denton
 71 Ellis
 130 Kaufman
 175 Navarro
 199 Rockwall

DISTRICT 19

(Atlanta)
 19 Bowie
 32 Camp
 34 Cass
 103 Harrison
 155 Marion
 172 Morris
 183 Panola
 225 Titus
 230 Upshur

DISTRICT 20

(Beaumont)
 36 Chambers
 101 Hardin
 122 Jasper
 124 Jefferson
 146 Liberty
 176 Newton
 181 Orange
 229 Tyler

DISTRICT 21

(Pharr)
 24 Brooks
 31 Cameron
 109 Hildago
 125 Jim Hogg
 66 Kenedy
 214 Starr
 245 Willacy
 253 Zapata

DISTRICT 22

(Laredo)
 64 Dimmit
 67 Duval
 136 Kinney
 142 La Salle
 159 Maverick
 233 Val Verde
 240 Webb
 254 Zavala

DISTRICT 23

(Brownwood)
 25 Brown
 42 Coleman
 47 Comanche
 68 Eastland
 141 Lampasas
 160 McCulloch
 167 Mills
 206 San Saba
 215 Stephens

DISTRICT 24

(El Paso)
 22 Brewster
 55 Culberson
 72 El Paso
 116 Hudspeth
 123 Jeff Davis
 189 Presidio

DISTRICT 25

(Childress)
 23 Briscoe
 38 Childress
 44 Collingsworth
 51 Cottle
 63 Dickens
 65 Donley
 79 Foard
 97 Hall
 100 Hardeman
 135 King
 138 Knox
 173 Motley
 242 Wheeler

Figure 18. List of Texas Counties by District (TxDOT, 1998).

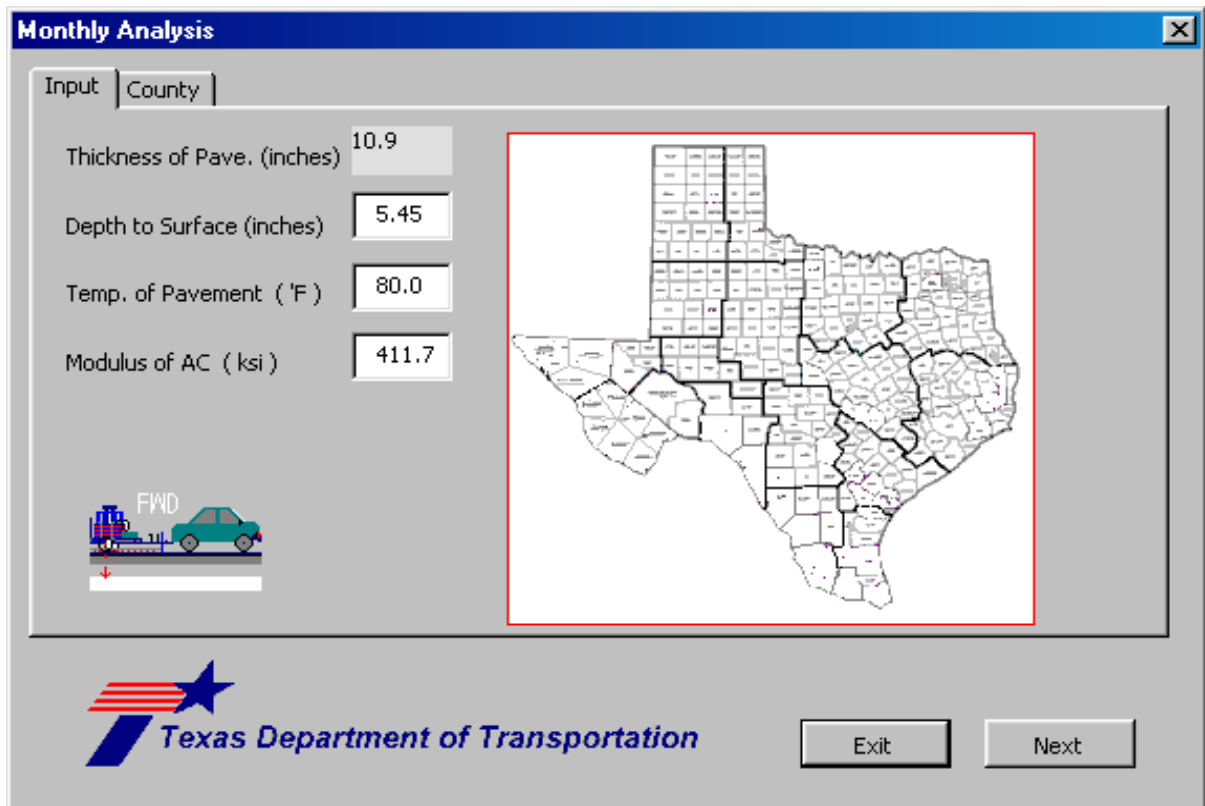


Figure 19. Dialog Box of Input Parameters for the Monthly Modulus Prediction.

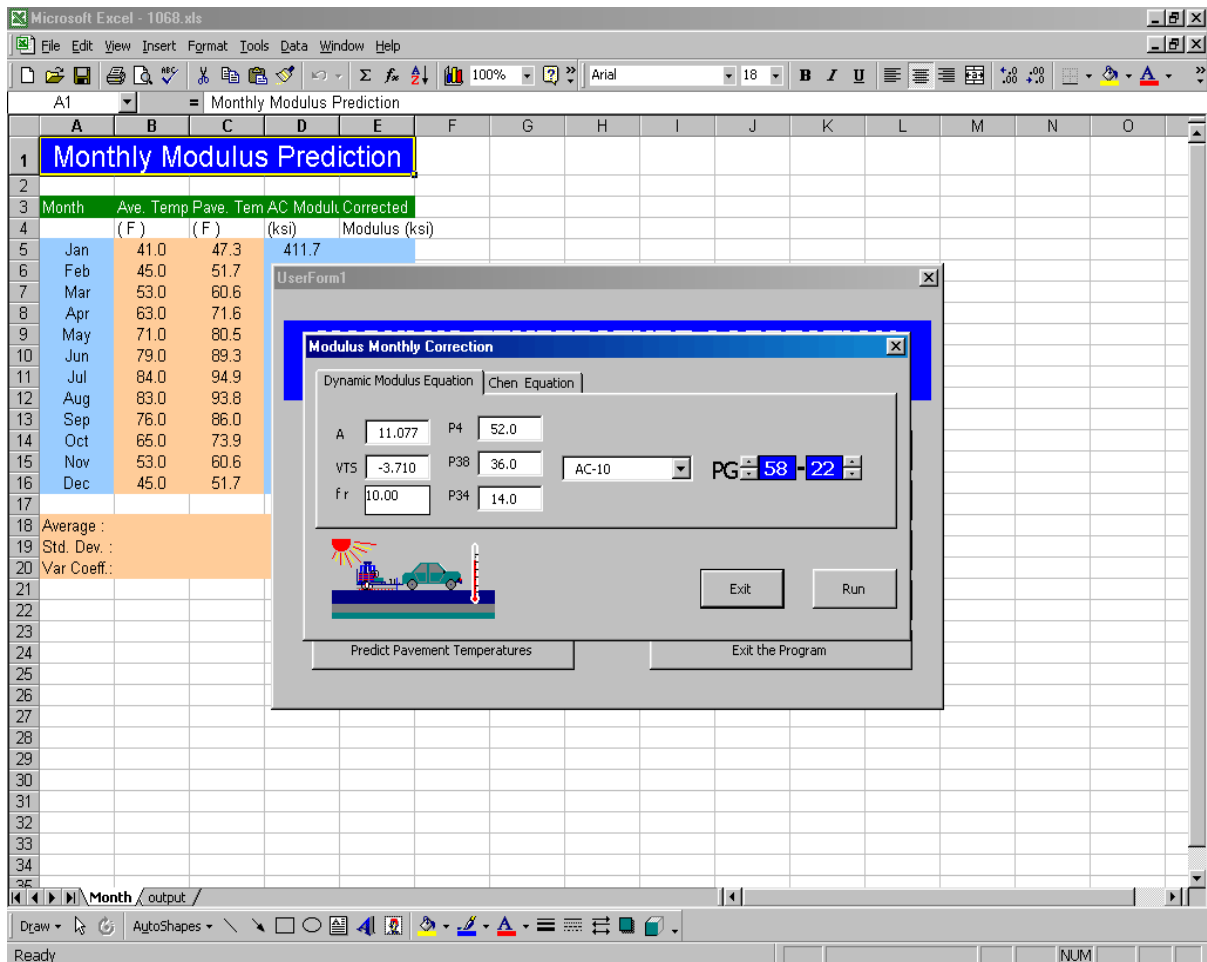


Figure 20. Dialog Box to Specify Equation for Monthly Modulus Prediction.

specify which equation to use, simply click on its folder tab. Note that if you used the dynamic modulus equation to correct the backcalculated AC moduli, the *A* and *VTS* coefficients you previously specified are displayed in the dialog box as well as the reference loading frequency and the gradation of the asphalt mix. While you may change these variables in the dialog box, it is important that the values you enter are consistent with the method employed to correct the backcalculated AC moduli. In most applications, it is likely that you would only have to click on the **Run** button of the dialog box to perform the monthly modulus predictions based on the dynamic modulus equation without having to change any of the data shown. To select the Chen equation, click on its folder tab and then on the **Run** button of the dialog box to perform the analysis.

Figure 21 illustrates the output from the evaluation of monthly modulus variation. The predicted modulus for each month is written in the last column of the worksheet. The label for this column also has a comment box that reports the parameters used in correcting the reference

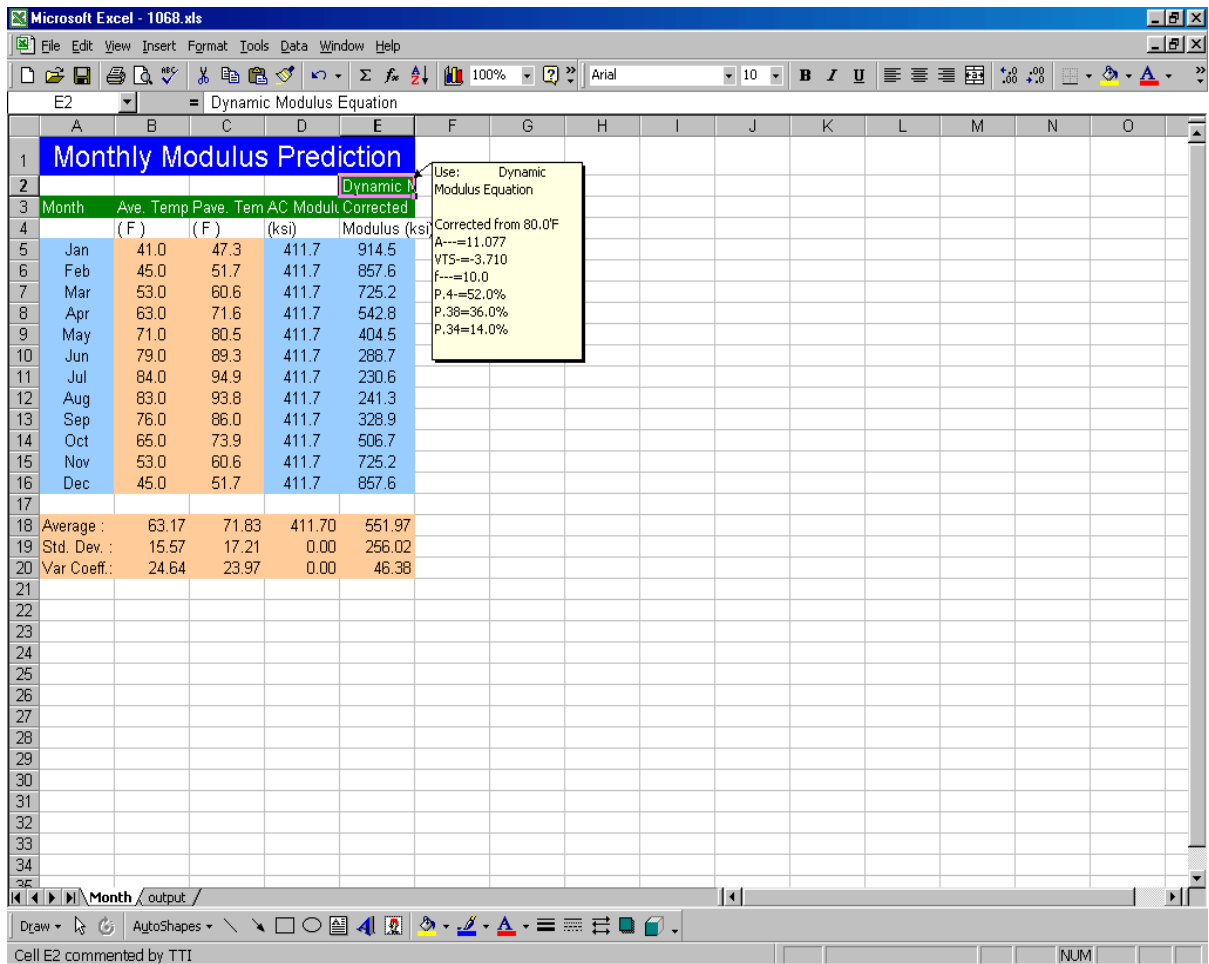


Figure 21. Illustration of Output from Monthly Modulus Prediction.

modulus to the predicted mean monthly pavement temperatures. You may resize the box as necessary using Excel's *Edit Comment* function to view the information.

CHAPTER III

MTCP OUTPUT

GETTING OUTPUT OF ANALYSIS RESULTS

As presented in [Chapter II](#), there are two worksheets created by MTCP which have the input data used in the analyses as well as the results. The *output* worksheet contains the summary output from the MODULUS backcalculation; the measured air, surface, and pavement temperatures from the FWD survey; the predicted pavement temperatures; and the corrected asphalt concrete moduli. The other worksheet, labeled *Month*, has the monthly average air temperatures, the predicted mean monthly pavement temperatures, and the predicted monthly variation in asphalt concrete modulus for the material tested. You may print each of these worksheets using the *Print* function available in Excel. You may also produce charts of the results by clicking the *Plot Output* button of the MTCP main menu. This will bring up the chart selection menu illustrated in [Figure 22](#).

[Table 4](#) describes the chart options available from the menu. The default worksheet names shown in the [table](#) are reserved for program use. You may not use any of these names to label worksheets that you manually create in the Excel spreadsheet. Note that the charts which may be produced depend on the main menu functions that have already been executed. For example, neither the FWD nor MODULUS summary output data may be plotted until the data files have been read by MTCP. Similarly, the corrected asphalt concrete moduli and the predicted monthly variations in the AC modulus cannot be plotted until the temperature corrections and the monthly modulus predictions have been made.

To select a chart from the menu, simply click on its checkbox. You may select all charts at once by clicking on the *Select All* button of the menu. If you wish to undo any selection, click again on the chart's checkbox. To undo all selections at once, click the *Clear* button of the menu. The button labeled *Reverse Select* will undo previous selections you have made while at the same time checking the boxes of charts not previously selected. Thus, *Reverse Select* has the same effect as *Clear* if all of the available charts were previously selected.

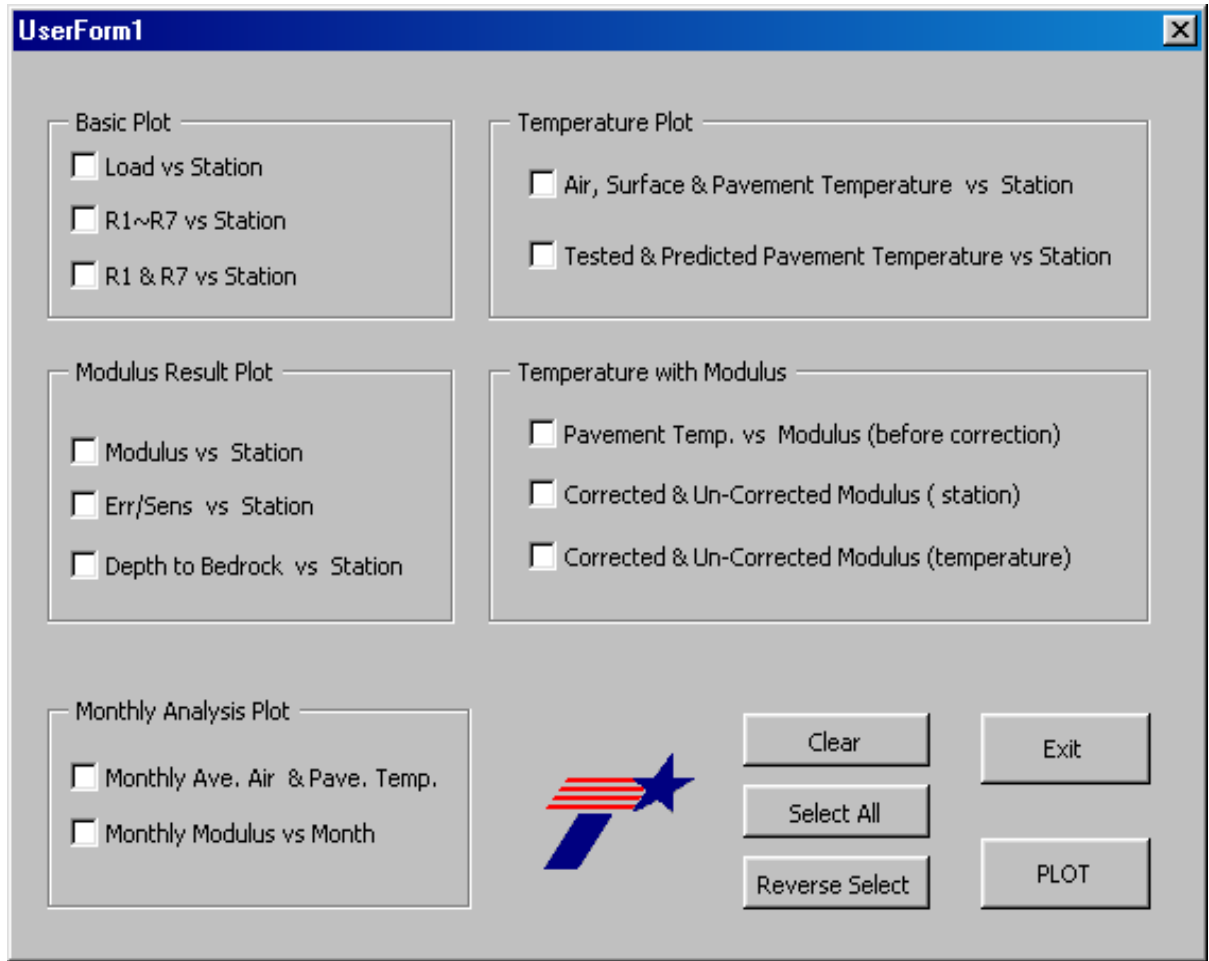


Figure 22. MTCP Plot Menu.

Table 4. Available Charts in MTCP.

Chart Group	Chart Label	Description	Default Worksheet Name
Basic Plot	Load vs Station	Plot of measured FWD load for stations tested	Load
	R1 ~ R7	FWD sensor deflections plotted for each station	Deflec-1
	R1 & R7	Plot of FWD sensor 1 and sensor 7 deflections by station	Deflec-2
Modulus Result Plot	Modulus vs Station	Plot of backcalculated layer moduli for each station	Modu
	Err/Sens vs Station	Plot of the average absolute errors per sensor for the different stations tested	Err
	Depth to Bedrock vs Station	Plot of the depths to bedrock predicted from the sensor displacements measured at the different stations	DB
Monthly Analysis Plot	Monthly Ave. Air & Pave. Temp.	Mean monthly average air temperatures and predicted mean monthly pavement temperatures at the project surveyed	Month-1
	Monthly Modulus vs Month	Bar chart of predicted monthly variations in AC modulus	Month-2
Temperature Plot	Air, Surface, & Pavement Temp. vs Station	Plot of air, surface, and pavement temperatures by station	Temp-1
	Tested & Calculated Pavement Temperature vs Station	Plot of measured vs predicted pavement temperatures by station	Temp-2
Temperature with Modulus	Pavement Temp. vs Modulus (before correction)	Plot of backcalculated AC modulus versus pavement temperature	Mod-Temp-1
	Corrected & Un-corrected Modulus (station)	Plot of corrected and backcalculated AC moduli by station	Mod-Temp-3
	Corrected & Un-corrected Modulus (temperature)	Plot of corrected and backcalculated AC moduli versus pavement temperature	Mod-Temp-4

Once you have made your selections, click on the **PLOT** button. Each chart selected gets drawn on a separate worksheet. [Table 4](#) identifies the worksheets assigned to the different charts. To view the charts, first leave the plot menu by clicking on its **Exit** button. This brings you back to the program main menu. From here, click on **Exit the Program**. You may then view a particular chart by clicking on its worksheet tab which you may identify from [Table 4](#). [Figures 23](#) and [24](#) illustrate two of the charts that you may produce from MTCP. To print a given chart, simply bring that chart into view by clicking on its worksheet tab. Then use Excel's *Print* function to get a hardcopy.

The plots that you generate in the spreadsheet are automatically updated as data get changed. This situation occurs, for example, when you do another analysis using a temperature correction equation that is different from that used to generate the charts initially. In this instance, you do not have to rerun the plot function to get the same charts using the new analysis results. However, you have the option to generate additional charts that were not selected in the previous analysis.

You may also rename the chart worksheets in Excel. To use a name different from the default value given in [Table 4](#), simply double click the tab of the worksheet you wish to rename. Then type in the label that you want that worksheet to have and press the *Enter* key. Alternatively, you may right click on the worksheet tab and select the *Rename* function in Excel to re-label the selected worksheet.

SAVING THE ANALYSIS RESULTS

Once you finish with your analysis, you may save your results by using Excel's *Save* or *Save As* function. To do this, you must first exit the MTCP main menu by clicking on **Exit the Program**. Then you may click on the *Save* icon in the top toolbar to save your results using the default file name assigned by the program. The Excel spreadsheet, with all the accompanying data and charts, is saved in a file with the same name as the MODULUS summary output file but with the extension *XLS*.

If you do not wish to use the default file name, you may save the spreadsheet using the *Save As* function in Excel's *File* menu. Click on *File* at the top of the spreadsheet, then on *Save As*. A dialog box will then be displayed where you can specify the name of the file where the results will be saved. In addition, you may specify the drive and subdirectory

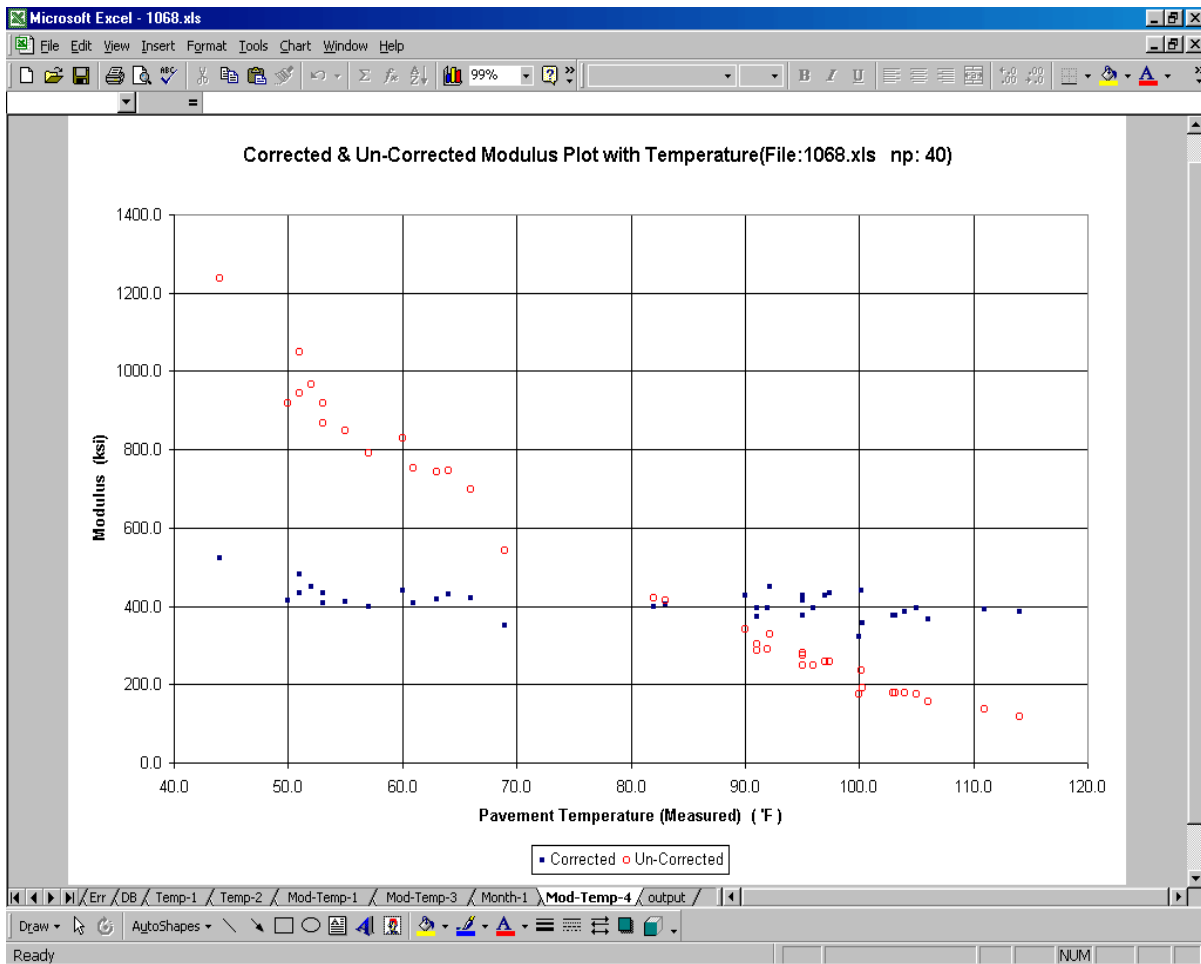


Figure 23. Example Plot of Corrected and Backcalculated AC Moduli vs Pavement Temperature.

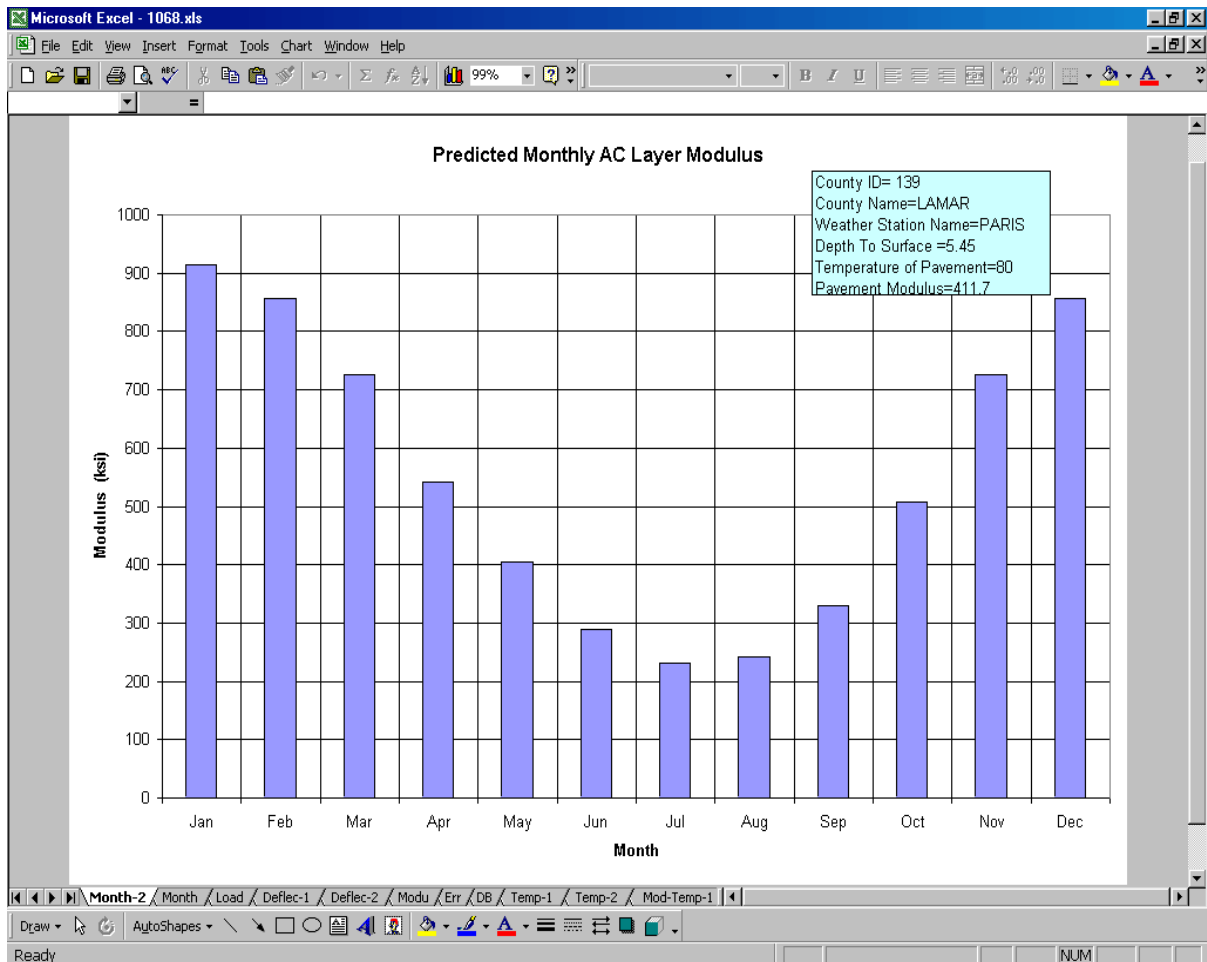


Figure 24. Example Plot of Predicted Monthly Variations in AC Modulus.

where this file will be written. By default, the file is written in the same subdirectory where MTCP was loaded. You may open the spreadsheet in Excel at a later time should you wish to conduct additional analyses with the same MODULUS and FWD input files used to generate the spreadsheet.

After saving your results, you may exit Excel by clicking on *File*, then on *Exit* or by clicking on the *X* button at the top right corner of the spreadsheet. Alternatively, you may conduct a new analysis with a different set of input data. To perform a new analysis, reload the main menu by pressing *Ctrl+Shift+M*. Then clear the results of the previous analysis by clicking on the *Clear Program Sheets* button of the main menu. The dialog box shown in [Figure 25](#) will be displayed to confirm that you wish to delete the worksheets created by the program. If you have saved the results, you may click on *Yes* in the dialog box. Otherwise, click *No* for an opportunity to save the existing spreadsheet as described previously.

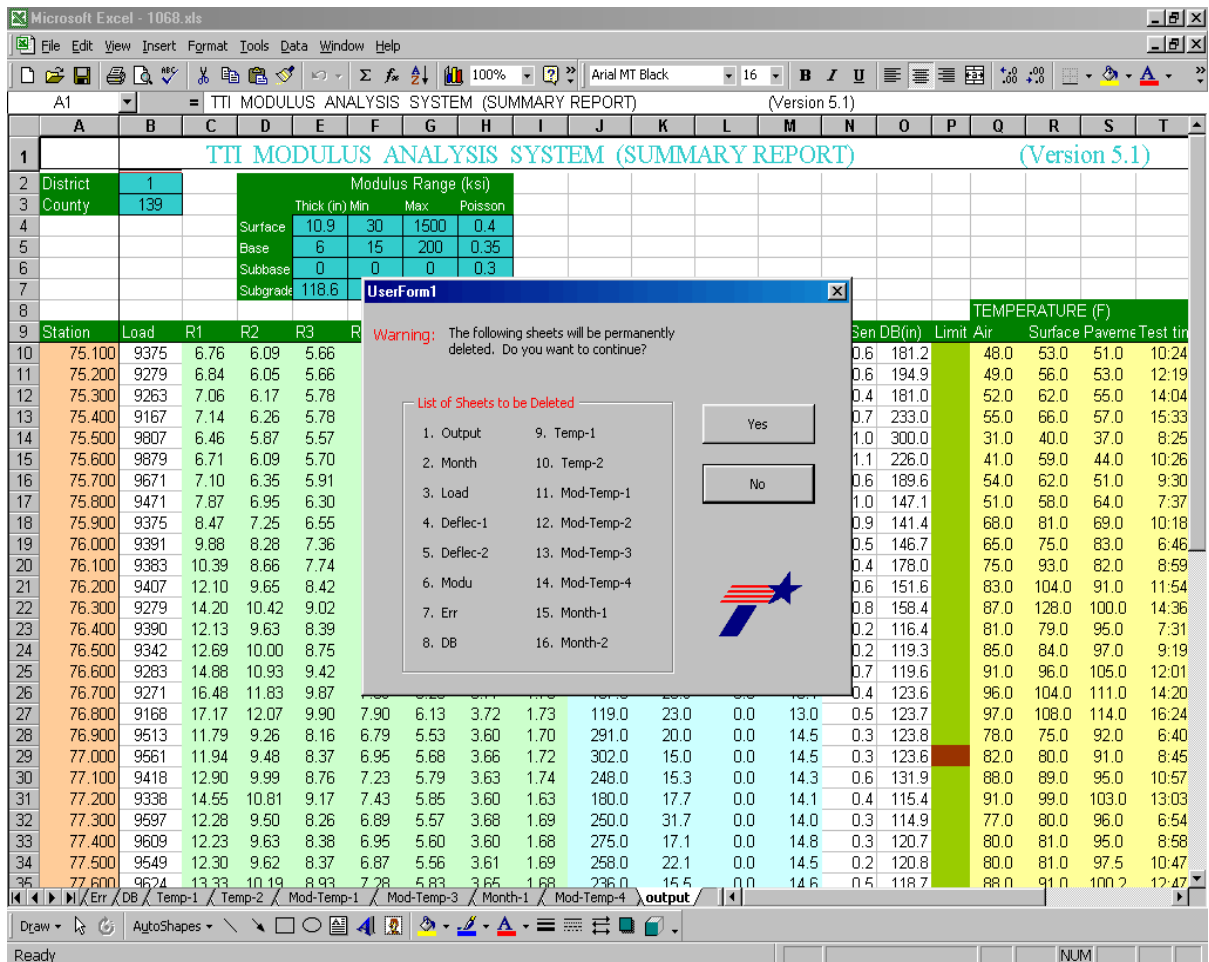


Figure 25. Dialog Box to Delete Program Worksheets Prior to a New Analysis.

After the existing program worksheets have been deleted, the main menu is again displayed. From here, the user may read another MODULUS output file and conduct a new analysis as described in this user's guide. It is noted that the *Clear Program Sheets* function will only delete the worksheets created by the program (identified in the dialog box shown in Figure 25). Worksheets that were manually created by the user during the previous analysis are not deleted.

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APPENDIX: FLOW CHART OF MODULUS TEMPERATURE CORRECTION PROGRAM

