

Non-Destructive Evaluation of Iowa Pavements Phase 2:

Development of a Fully Automated Software System for Rapid Analysis/ Processing of the Falling Weight Deflectometer Data

**Final Report
February 2009**



IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract The Office of Special Investigations at Iowa Department of Transportation (DOT) collects FWD data on regular basis to evaluate pavement structural conditions. The primary objective of this study was to develop a fully-automated software system for rapid processing of the FWD data along with a user manual. The software system automatically reads the FWD raw data collected by the JILS-20 type FWD machine that Iowa DOT owns, processes and analyzes the collected data with the rapid prediction algorithms developed during the phase I study. This system smoothly integrates the FWD data analysis algorithms and the computer program being used to collect the pavement deflection data. This system can be used to assess pavement condition, estimate remaining pavement life, and eventually help assess pavement rehabilitation strategies by the Iowa DOT pavement management team. This report describes the developed software in detail and can also be used as a user-manual for conducting simulation studies and detailed analyses.					
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Principal Investigator

Halil Ceylan

Associate Professor

Center for Transportation Research and Education, Iowa State University

Co-Principal Investigator

Kasthurirangan Gopalakrishnan

Research Assistant Professor

Center for Transportation Research and Education, Iowa State University

Research Assistant

Sunghwan Kim, Alper Guclu and M. Birkan Bayrak

Authors

Halil Ceylan, Kasthurirangan Gopalakrishnan, Sunghwan Kim, Alper Guclu, and M. Birkan Bayrak

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A report from
Center for Transportation Research and Education

Iowa State University

2711 South Loop Drive, Suite 4700

Ames, IA 50010-8664

Phone: 515-294-8103

Fax: 515-294-0467

www.intrans.iastate.edu

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EXECUTIVE SUMMARY

This study is a follow-up to the IA DOT Project (CTRE Project 04-177), Nondestructive Evaluation of Iowa Pavements - Phase 1. The objective of this Phase II study is the development of a fully-automated software system for rapid processing of the FWD data accompanied by a user manual. The software system can automatically read the FWD raw data collected by the Iowa DOT's JILS-20 type FWD machine, process and analyze the collected data with the rapid prediction algorithms developed during the phase I study. This report, which can also be used as a user-manual for the software, contains examples or case studies for all three pavement types (flexible, rigid, and composite) illustrating the step-by-step procedure in using the software.

Some of specific features of the fully-automated software system described in this report are summarized below:

- A comprehensive pavement structural analysis toolbox incorporating all three common pavement types (flexible, rigid, and composite)
- Capability of automatically reading the FWD raw data collected by the JILS-20 type FWD machine that Iowa DOT owns
- Integration of all the Artificial Neural Network (ANN) models developed as part of Phase I research into a comprehensive unified framework
- Rapid backcalculation of pavement layer moduli and prediction of critical pavement responses from FWD data (100,000 deflection basins analyzed in less than a second)
- Useful for both project-level and network-level pavement structural evaluation
- Visualization of results through automatic plotting capability
- Commonly used Import/Export options for transporting data
- Automatic generation of output statistics

INTRODUCTION

Evaluating structural condition of existing, in-service pavements is a part of the routine maintenance and rehabilitation activities undertaken by the most Departments of Transportation (DOTs). In the field, the pavement deflection profiles (or basins) gathered from the nondestructive Falling Weight Deflectometer (FWD) test data are typically used to evaluate pavement structural condition. FWD testing is often preferred over destructive testing methods because it is faster than destructive tests and does not entail the removal of pavement materials. This kind of evaluation requires the use of backcalculation type structural analysis to determine pavement layer stiffnesses and as a result estimate pavement remaining life. Although the Office of Special Investigations at Iowa DOT has collected the FWD data on regular basis, the pavement layer moduli backcalculation techniques used so far have been cumbersome and time consuming. Thus, there was a need for more efficient and faster methods.

During the first phase of the Iowa (DOT) Project (CTRE Project 04-177), “Nondestructive Evaluation of Iowa Pavements-Phase I”, advanced yet easy-to-use backcalculation models were developed using the ANN methodology (Ceylan et al, 2007). ANNs are very adaptable and support the real-time applications of the developed models. These ANN models are capable of predicting pavement layer stiffnesses as well as pavement critical responses (forward modeling) from FWD test results. For the three pavement types, over 300 models in total were developed for varying input parameters. The primary pavement types considered were flexible (conventional and full-depth), rigid, and composite.

Predicted flexible pavement parameters were, E_{AC} -modulus of hot-mix asphalt (HMA) or asphalt concrete (AC), K_b -base modulus parameter, E_{Ri} -subgrade resilient modulus, ϵ_{AC} -tensile strain at the bottom of asphalt layer, ϵ_{SG} -compressive strain at the top of subgrade, and σ_D -subgrade deviator stress.

For rigid pavements, E_{PCC} -modulus of portland cement concrete (PCC), k_s -coefficient of subgrade reaction, σ_{PCC} -tensile stress at the bottom of the PCC layer, and radius of relative stiffness (RRS) were predicted.

In the case of composite pavements (CPs), where an AC surface is overlaid on top of an existing PCC pavement, E_{AC} , E_{PCC} , k_s , σ_{PCC} (tensile stress at the bottom of the PCC), and ϵ_{AC} were predicted.

The developed methodology was successfully verified using results from long-term pavement performance (LTPP) FWD test results, as well as Iowa DOT FWD field data. All successfully developed ANN models were incorporated into a Microsoft Excel spreadsheet-based backcalculation software toolbox with a user-friendly interface. The phase I study also concluded that the developed nondestructive pavement evaluation methodology for analyzing the FWD deflection data would be adopted by Iowa DOT pavement and material engineers and technicians, who do not employ any preferable FWD backcalculation analysis technique.

OBJECTIVES

This phase II follow-up study of IA DOT Project (CTRE Project 04-177) focused on the development of a fully-automated software system for rapid processing of the FWD data. The software system can automatically read the FWD raw data collected by the JILS-20 type FWD machine that Iowa DOT owns, process and analyze the collected data with the algorithms being developed during the phase I study. This system smoothly integrates the FWD data analysis algorithms and the computer program being used to collect the pavement deflection data. With the implementation of the developed software system the FWD data can be filtered, processed and analyzed on-the-fly.

PROGRAM USER MANUAL

The password-protected, Excel-based software toolbox was developed using Microsoft Visual Basic programming language and Excel macros. In case of troubleshooting, the user is requested to change the macro security (Tools → Macro → Security) to the “medium” or “low” level to allow macros to run. The Excel spreadsheets provide the user interaction for data editing and pasting, displaying results, charts, and tables, and for displaying statistical information. The Excel sheets include a main menu, analysis menu (for each pavement type), plotting menu, and summary menu.

Program Main Menus

The program starts by displaying the main menu (Figure 1). As a first step, users are expected to select the pavement type (conventional, full-depth flexible, composite or rigid pavements) by clicking on it to activate the selected pavement analysis Excel sheet/interface. There are six Excel pavement analysis sheets, including the conventional flexible pavement analysis module with 9-kip and variable FWD load, the full-depth flexible pavements analysis module with 9-kip and variable FWD load, and the composite and rigid pavement analysis module with 9-kip FWD loading. The software toolbox is programmed to give warning messages if the user clicks anywhere else.

While working with the toolbox, all other Excel features are accessible, including open, close, copy, paste, save, save as, print, and print settings. When the user quits the toolbox, all the charts and results for the analysis, except the last data entered, will be deleted. To retain the results, they should be copied into another spreadsheet.

The ANN information buttons in Figure 2 provide the user general information about the ANN models employed. Six Excel Spreadsheets as shown in Figure 3 appear upon clicking “ANN info show” button. Each of Excel sheets as shown in Figure 4 contain the ANN model information such as the ranges of the data used in the development of ANN models. These Excel sheets can be hid again by clicking on “ANN info hide”.

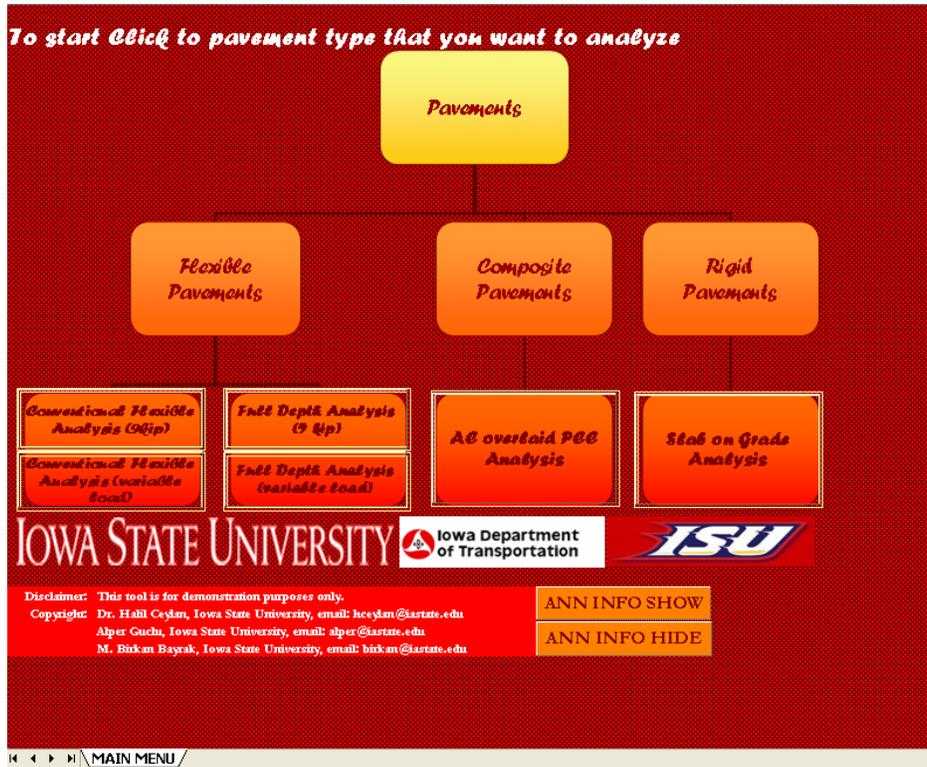


Figure 1. FWD analysis program main menu

Disclaimer: This tool is for demonstration purposes only.
 Copyright: Dr. Halil Ceylan, Iowa State University, email: hceylan@iastate.edu
 Alper Gucu, Iowa State University, email: alper@iastate.edu
 M. Birkan Bayrak, Iowa State University, email: birkan@iastate.edu

ANN INFO SHOW
ANN INFO HIDE

Figure 2. ANN Information button in main menu

Flexible Pavement Analysis, Plotting, and Summary Menus

Pavement analysis menu consists of three main sections: inputs, analysis tool, and outputs. The user can provide the software with the information required for analysis in the inputs section of the pavement analysis menu. The analysis tool allows the user to process the data and analyze with several functions. The results of analysis are provided in the outputs section of the pavement analysis menu. Typical layouts of the conventional and full depth flexible pavement analysis menus are shown in Figure 5.

Analysis Tool

Inputs

Outputs

Run
Main Menu
Plots
Summary
Filler
Open FWD Dat File

(a)

Analysis Tool

Inputs

Outputs

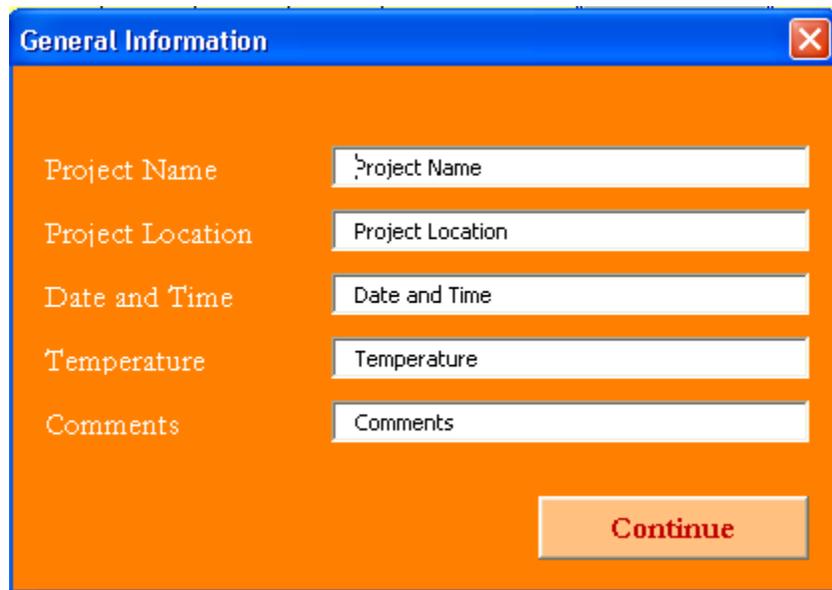
Run
Main Menu
Full Depth Analysis (9 kip)
Plots
Summary
Filler
Open FWD Dat File

(b)

Figure 5. Flexible pavement analyses menus: (a) conventional, (b) full depth

After selecting one of the pavement types from the main menu, a general information window appears. Its purpose is to get information that represents a project site at the beginning of each analysis (see Figure 6.). The user is required to fill in the information to continue with pavement analysis.

General information inputs will be displayed with each graph at the end of the analysis to identify the project information.



The image shows a software window titled "General Information". The window has a blue header bar with the title and a close button (X). The main content area is orange and contains five input fields, each with a label and a text box: "Project Name", "Project Location", "Date and Time", "Temperature", and "Comments". A "Continue" button is positioned at the bottom right of the window.

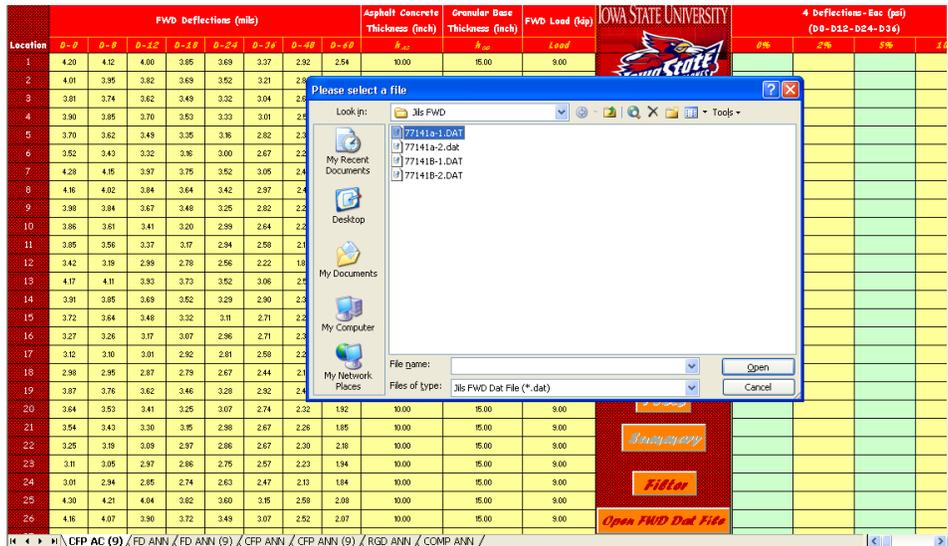
Figure 6. General information window

At the next step, the user is expected to enter the FWD deflection data and other required inputs. These include pavement layer information (layer thicknesses), and FWD load (for variable FWD load analysis). Depending on the pavement type, the number of layers can be changed. The input requirements for conducting conventional flexible pavement analyses include FWD deflection data, asphalt concrete thickness, granular base thickness, and FWD load. The input requirements for conducting full depth asphalt pavement analyses are same as those for conventional flexible pavement analyses except that granular base thickness is not required. If any of the required parameter is missing, the program will display an error message which reads “No Data” in the results section.

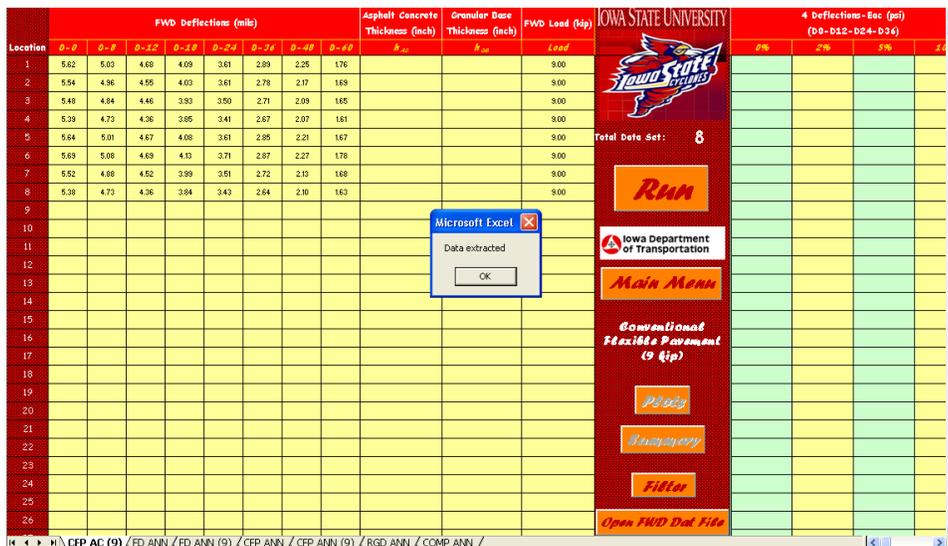
The default units used in the program are US customary units. FWD deflection data (D_0 till D_{60}) should be entered in mils (10^{-3} inches), layer thickness in inches, and FWD load should be in kips. The program will not run correctly if the inputs are entered in different units or if they are out of range. The user is requested to refer to the report for the appropriate ranges of these parameters. Reported results are pavement layer modulus values, strains, and stresses. Modulus and stress values are reported in psi and strains are reported in micro-strains ($\times 10^6$).

User can enter the FWD deflection database manually or obtain those directly from the JILS-20 type FWD raw data files clicking “Open FWD data file”. The “Open FWD data file” command

allows the user to load the FWD raw data files and extract the FWD deflections required as inputs to the automated analysis software as shown in Figure 7. The software allows two types of flexible pavement analysis based on FWD loading amplitude; 9-kip-constant FWD load analysis and variable FWD load analysis. As shown in Figure 8(a), the raw FWD deflection data corresponding to the raw FWD loads are extracted and inputted into the program under variable FWD load analysis. The 9-kip-constant FWD load analysis in Figure 8(b) uses the FWD deflection data normalized to 9 kip-constant FWD load



(a)



(b)

Figure 7. Screen shot of FWD data extraction through open FWD data file button: (a) choosing raw FWD file, (b) FWD data extracted

Location	FWD Deflections (mil)								Asphalt Concrete Thickness (inch)	Granular Base Thickness (inch)	FWD Load (kip)
	0-0	0-8	0-12	0-18	0-24	0-36	0-48	0-60	h_{AC}	h_{GB}	Load
1	3.69	3.42	3.21	2.85	2.57	2.07	1.66	1.32			5.88
2	5.55	5.07	4.73	4.23	3.77	3.01	2.41	1.89			8.59
3	7.37	6.60	6.23	5.58	4.99	3.96	3.16	2.46			11.67
4	8.90	7.95	7.49	6.73	6.00	4.75	4.34	2.98			14.33
5	3.27	3.41	3.21	2.85	2.57	2.06	1.64	1.27			5.93
6	5.95	5.10	4.77	4.28	3.84	3.03	2.42	1.88			8.64
7	7.21	6.65	6.23	5.60	5.02	3.96	3.19	2.44			11.55
8	7.73	7.97	7.48	6.71	6.00	4.80	3.82	3.00			14.28

(a)

Location	FWD Deflections (mil)								Asphalt Concrete Thickness (inch)	Granular Base Thickness (inch)	FWD Load (kip)
	0-0	0-8	0-12	0-18	0-24	0-36	0-48	0-60	h_{AC}	h_{GB}	Load
1	5.65	5.23	4.91	4.36	3.93	3.17	2.54	2.02			9.00
2	5.81	5.31	4.96	4.43	3.95	3.15	2.53	1.98			9.00
3	5.68	5.09	4.80	4.30	3.85	3.05	2.44	1.90			9.00
4	5.59	4.99	4.70	4.23	3.77	2.98	2.73	1.87			9.00
5	4.96	5.18	4.87	4.33	3.90	3.13	2.49	1.93			9.00
6	6.20	5.31	4.97	4.46	4.00	3.16	2.52	1.96			9.00
7	5.62	5.18	4.85	4.36	3.91	3.09	2.49	1.90			9.00
8	4.87	5.02	4.71	4.23	3.78	3.03	2.41	1.89			9.00

(b)

Figure 8. Extracted FWD data: (a) variable FWD load analysis, (b) 9-kip-constant FWD load analysis

Once the FWD deflection data is entered, the user has the option to check the data for anomalies using the data preprocessing unit (Filter command button) for filtering the data. It is optional to use the filtering window. Figure 9. shows the available options for filtering. The two options are:

- Range Check: Deflection basin should form a bowl shape and, therefore, deflections should be in decreasing order. Data that falls outside this range are red colored.
- Model Check: ANN models are normalized according to the model ranges and, therefore, any input outside the range used in ANN training will form a poor quality input. As a result, the model check will determine the outliers and color them in red.

The filtering is applied by changing the color of the input parameter to red (see Figure 10). The analysis results from filtered data are also shown with red color in charts (see Figure 11). Therefore, results for these parameters are also calculated. With this approach, engineers will have a better understanding of the sources of errors.

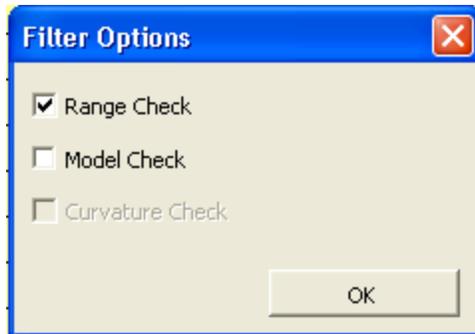
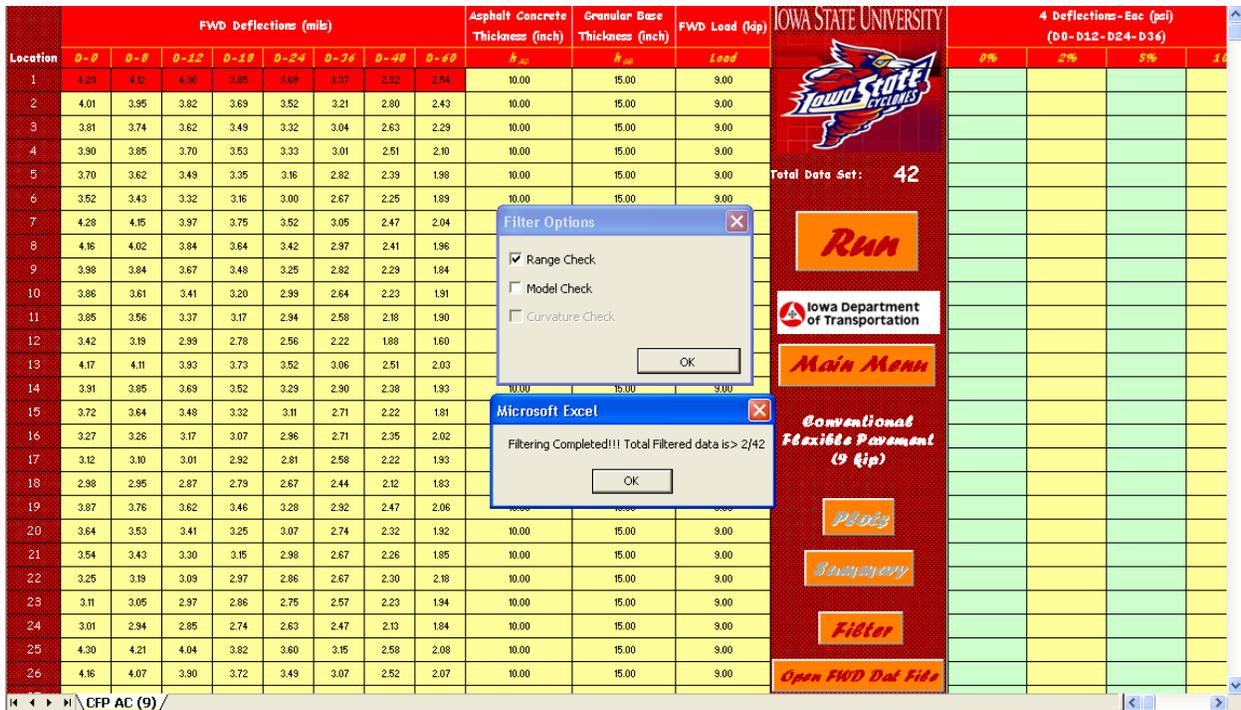


Figure 9. Filter options menu



(a)



(b)

Figure 10. Filtering the FWD data: (a) range check, (b) range and model check

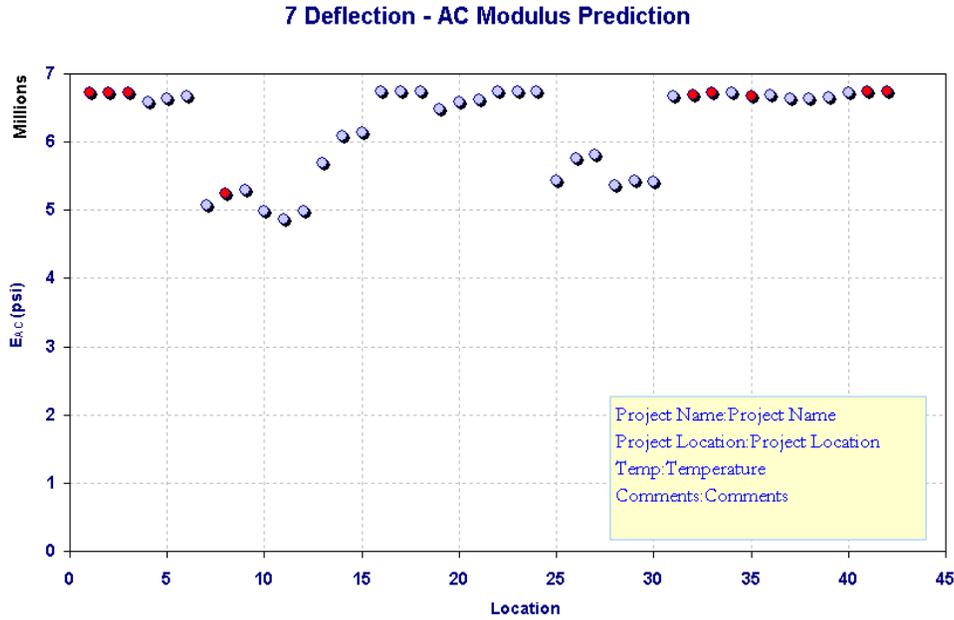


Figure 11. Sample pavement analysis results identifying analysis results from FWD data that falls outside filtering range

After preprocessing the data, clicking the “Run” button will activate a neural network-based analysis of pavements. The program will analyze model by model for the pavement properties. The ANN models employed for flexible pavement analysis are 4, 6, 7, and 8 deflection models with 0%, $\pm 2\%$, $\pm 5\%$ and $\pm 10\%$ noise. Each model has a different number of input parameters depending on the number of deflections. The purpose of introducing noisy patterns in the development of each model was to provide more robust networks that can tolerate the noisy or inaccurate deflection patterns collected from the FWD deflection basins. The detail descriptions of each model are provided in phase I project report (Ceylan et al, 2007).

For each model, the analysis results will be displayed on the right side of the screen. The user should scroll right to see all results. Also, disabled menu commands of plots and the summary will be activated. The conventional flexible pavement analysis results are E_{AC} -modulus of AC, K_b -base modulus parameter, E_{Ri} -subgrade resilient modulus, ϵ_{AC} -tensile strain at the bottom of asphalt layer, ϵ_{SG} -compressive strain at the top of subgrade, and σ_D -subgrade deviator stress. The full depth flexible pavement analysis results are E_{AC} -modulus of AC, E_{Ri} -subgrade resilient modulus, ϵ_{AC} -tensile strain at the bottom of asphalt layer, ϵ_{SG} -compressive strain at the top of subgrade, and σ_D -subgrade deviator stress.

Figure 12 illustrates the sample analysis results of a conventional and a full depth flexible pavement. Failure to supply all the input parameters will be reflected in the results column of that model. The program will automatically write “No Data.” For example, if D_{48} is missing in the input data, then all six- and eight-deflection model columns will display the error message of “No Data.”

At the end of each column, statistical information regarding that model is presented (see Figure 13.). The collection of these statistics is summarized in summary sheets.

Figure 12(a) shows a screenshot of an Excel spreadsheet with a red border on the left side. The spreadsheet contains a large table of numerical data. The columns are labeled with headers such as "Deflection-E1 (in)", "Deflection-E2 (in)", "Deflection-K (in)", "Deflection-E1 (in)", "Deflection-E2 (in)", and "Deflection-K (in)". The data is organized into rows, with some rows containing multiple columns of values. The spreadsheet also includes a sidebar on the left with various icons and text, and a status bar at the bottom.

(a)

Figure 12(b) shows a screenshot of an Excel spreadsheet with a red border on the left side. The spreadsheet contains a large table of numerical data, similar to (a) but with a different layout. The columns are labeled with headers such as "Deflection-E1 (in)", "Deflection-E2 (in)", "Deflection-K (in)", "Deflection-E1 (in)", "Deflection-E2 (in)", and "Deflection-K (in)". The data is organized into rows, with some rows containing multiple columns of values. The spreadsheet also includes a sidebar on the left with various icons and text, and a status bar at the bottom.

(b)

Figure 12. Sample Excel sheet outputs of flexible pavement analysis: (a) conventional, (b) full-depth

Location	4 Deflections-Eac (psi) (D0-D12-D24-D36)				4 Deflections-Eri (psi) (D0-D12-D24-D36)				4 Deflections-K (psi) (D0-D12-D24-D36)				AVG	
	1%	2%	5%	10%	1%	2%	5%	10%	1%	2%	5%	10%		10%
28	5,837,793	2,869,659	4,072,610	3,666,773	-129	1,274	1,615	3,193	1,894	2,082	3,781	5,259	5,413,138	
29	5,898,991	4,355,569	4,496,663	3,987,184	124	1,122	1,823	3,185	1,943	2,757	4,863	6,922	5,459,896	
30	5,838,379	5,193,935	4,830,372	4,281,029	445	1,153	1,998	3,184	2,447	4,985	5,803	7,101	5,446,531	
31	6,730,921	6,060,596	5,852,932	5,085,998	1,064	3,071	3,858	5,752	12,173	12,716	11,988	8,784	6,698,800	
32	6,731,745	6,137,374	5,879,580	5,120,352	1,398	4,120	4,800	6,346	12,765	12,974	12,192	8,680	6,709,121	
33	6,736,795	6,226,403	5,953,644	5,226,999	1,477	4,771	5,436	7,085	13,064	13,094	12,358	9,484	6,728,656	
34	6,626,582	6,041,129	5,754,582	5,037,018	1,514	3,545	4,677	6,393	12,555	12,863	11,967	8,321	6,725,546	
35	6,588,483	6,043,129	5,684,056	5,057,589	1,936	4,518	5,554	7,068	12,962	12,764	11,656	8,610	6,697,665	
36	6,609,326	6,056,991	5,637,900	5,107,871	2,411	5,733	6,503	7,962	13,028	12,793	11,448	9,264	6,707,172	
37	6,724,977	2,283,807	5,489,244	4,041,840	-388	1,494	1,438	2,753	1,878	2,053	4,524	2,755	6,670,524	
38	6,720,859	2,564,135	5,458,264	4,274,015	-318	1,267	1,576	2,882	1,889	2,532	4,853	3,874	6,661,258	
39	6,724,788	3,190,814	5,458,016	4,527,168	-248	1,140	1,692	2,975	1,973	4,004	6,086	5,519	6,674,341	
40	6,737,485	4,670,367	5,529,023	5,460,092	-186	1,262	2,387	3,638	3,414	8,986	8,244	9,993	6,734,364	
41	6,737,497	5,154,658	5,584,627	5,639,863	-156	1,645	2,712	3,593	9,134	12,053	10,878	10,268	6,736,521	
42	6,737,498	5,859,215	5,758,910	5,690,307	77	2,633	2,843	4,510	11,343	12,973	11,860	10,035	6,736,924	
43														
44	AVERAGE	6,358,385	5,339,434	5,508,288	5,080,658	945	2,640	3,233	4,835	8,261	9,739	9,495	8,424	6,264,643
45	STDEV	623,113	1,059,948	435,888	528,246	1,331	1,582	1,538	1,561	4,518	3,653	2,734	1,931	633,722
46	CV	10%	26%	8%	11%	141%	60%	48%	32%	55%	38%	29%	23%	10%
47														
48														
49														
50														
51														
52														

Figure 13. Sample Excel sheet output statistics of pavement analysis

The plot button will be enabled after the backcalculation analysis is complete. The plot option window appears after clicking on the plot button (see Figure 14). With this window, the user can select the models to display on charts. Selected models will be plotted in the form of backcalculated parameter versus FWD test location. Provided that the data is from a specified section, the first data will be represented as the starting point, and each subsequent data is assumed to correspond to FWD test locations along the path of the pavement system. Filtered data from the preprocessor will be displayed in red, whereas all others will be in blue. The upper right corner will display a textbox containing general information about the project. Figure 15 and Figure 16 illustrate color-coded conventional and the full depth flexible pavement analysis results, respectively, from 4-deflection ANN model with 0 % noise.

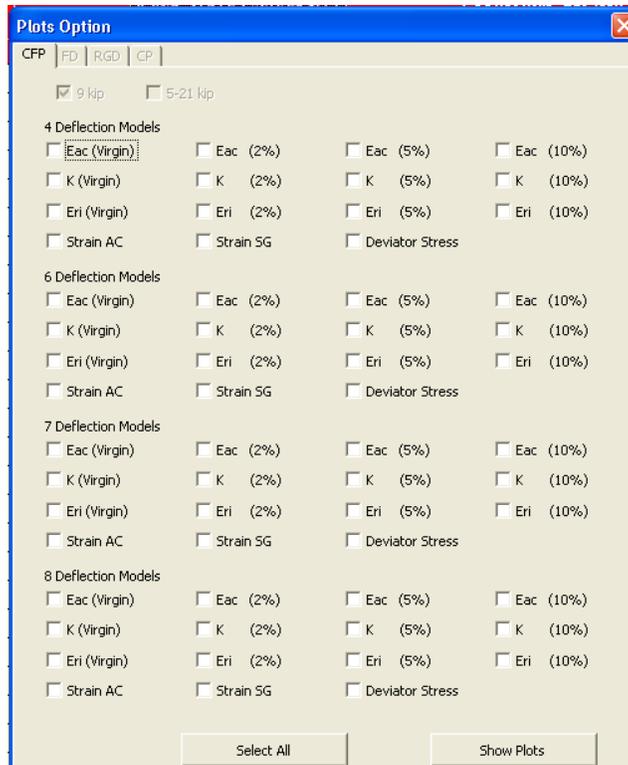


Figure 14. Plot option window

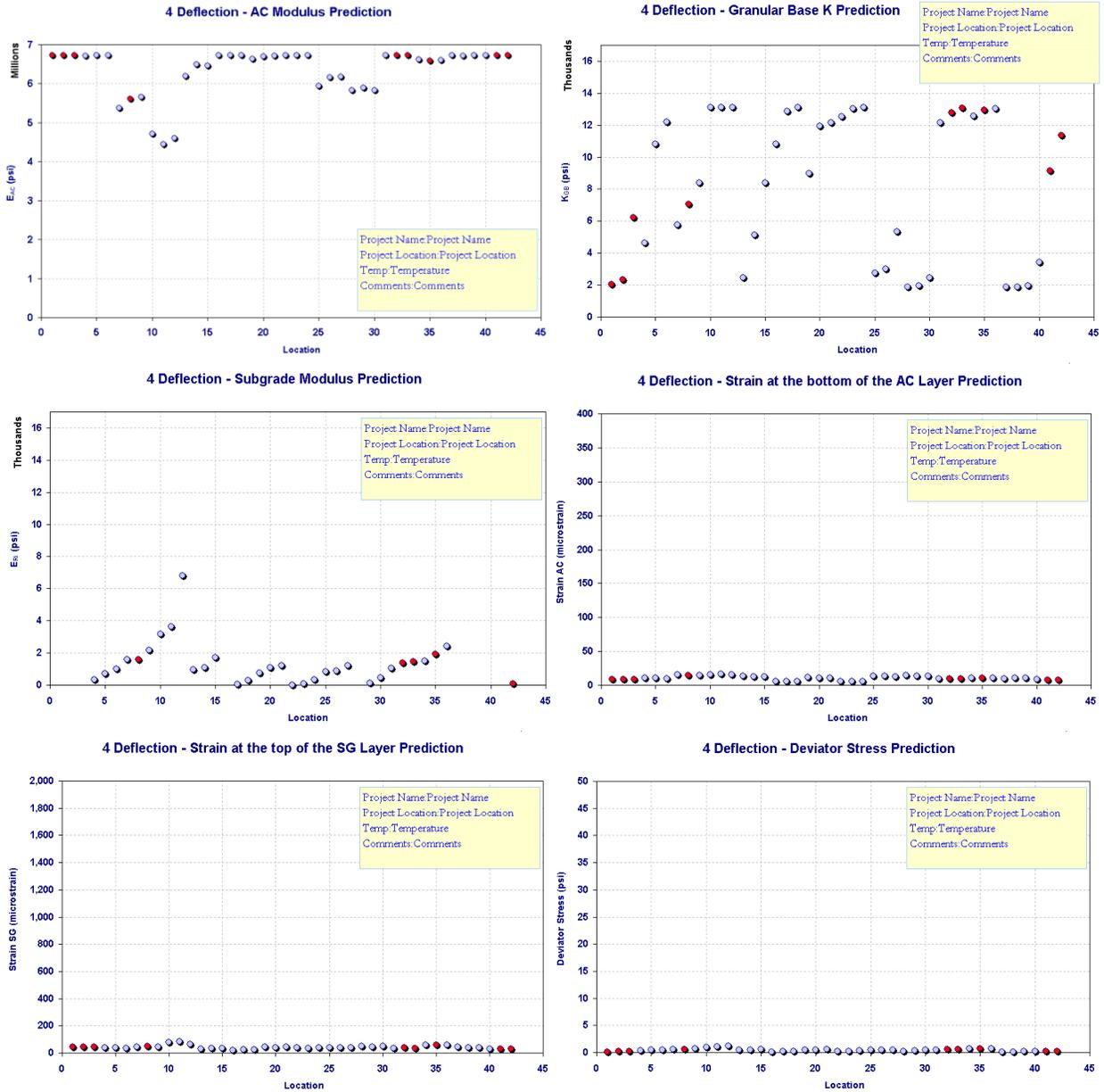


Figure 15. Sample Excel plots for conventional pavement analysis results

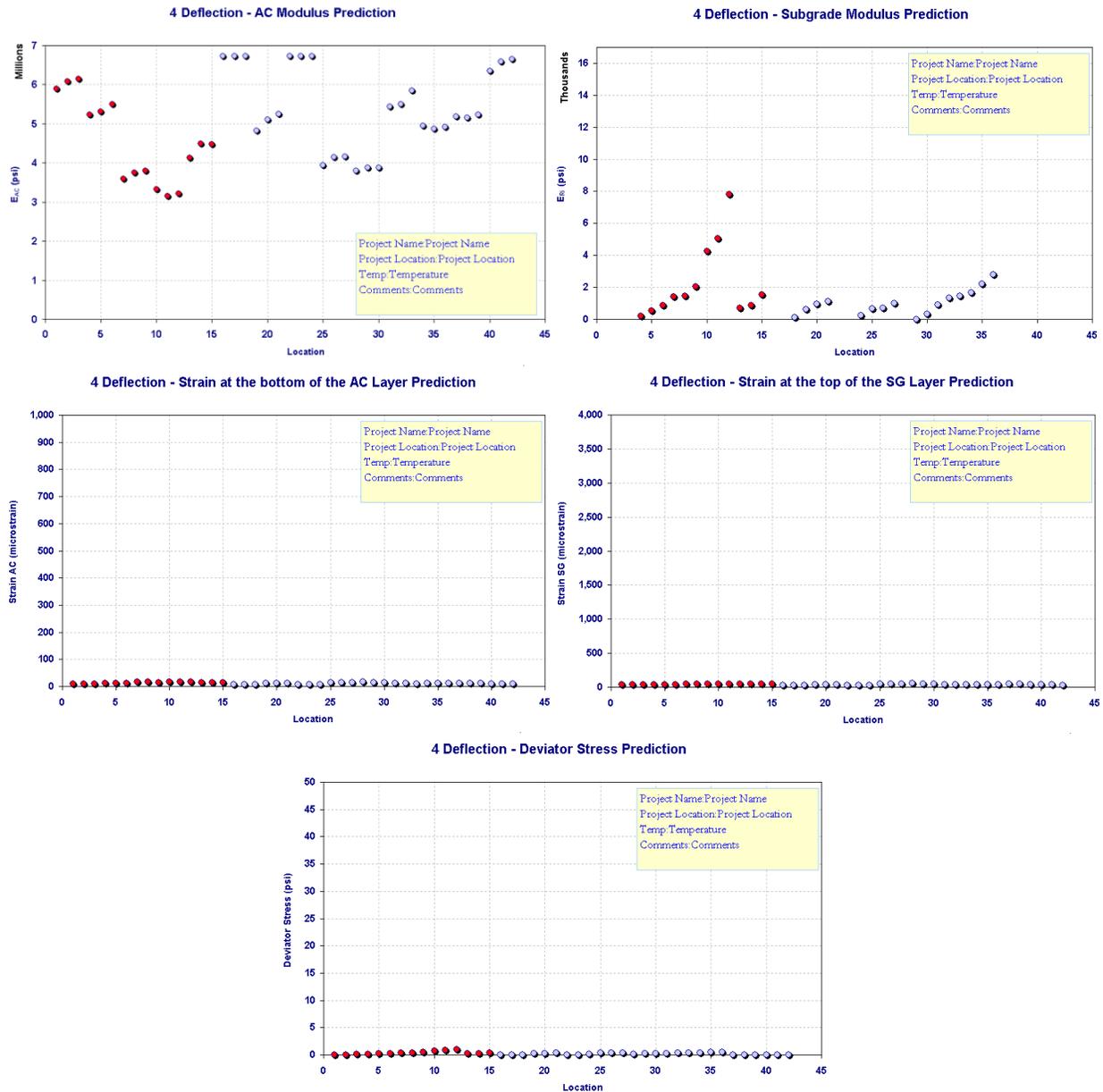


Figure 16. Sample Excel plots for full-depth asphalt pavement analysis results

The Summary button within the pavement analysis Excel spreadsheet is disabled until the “Run” button is clicked. It summarizes the statistical output information for each model. It opens up a new Excel sheet with tables of each output and summary statistics for every model (see Figure 17). The reported statistical information include:

- Average (or mean value): The average value along the section.
- Standard deviation: A common measure of the dispersion. It shows how widely the data is spread from the mean value.
- Coefficient of variation (CV): CV is a measure of the dispersion of probability distribution. It is the ratio of the standard deviation to the mean. It allows the user to

compare the CV of populations that have different mean values. It is reported as a percentage.

Prediction	Statistics			Details		
	Average (psi)	Std Dev (psi)	CV	Model	Deflection	Noise
E _{cc}	6310.05	621.113	10%	CFP0-4	4	0
	3339.434	1,039.948	20%	CFP0-4	4	2
	3308.208	433.888	8%	CFP0-4	4	5
	3,000.658	328.246	11%	CFP0-4	4	10
	6,264.659	631.722	10%	CFP0-6	6	0
	3,916.766	691.872	12%	CFP0-6	6	2
	3,398.138	677.394	12%	CFP0-6	6	5
	3,200.456	398.689	12%	CFP0-6	6	10
	6,239.816	646.972	10%	CFP0-7	7	0
	3,817.698	634.497	12%	CFP0-7	7	2
	3,483.323	329.022	10%	CFP0-7	7	5
	3,303.388	632.164	11%	CFP0-7	7	10
	6,229.968	617.000	11%	CFP0-8	8	0
	3,896.143	686.003	12%	CFP0-8	8	2
	3,349.946	729.373	13%	CFP0-8	8	5
3,409.378	372.266	11%	CFP0-8	8	10	

Note: E_{cc} predictions are limited to ranges between 100,000 and 6,000,000 psi.

Prediction	Statistics			Details		
	Average (psi)	Std Dev (psi)	CV	Model	Deflection	Noise
E _{bc}	943	1,331	141%	CFP0-4	4	0
	2,640	1,582	60%	CFP0-4	4	2
	3,233	1,338	48%	CFP0-4	4	5
	4,833	1,361	32%	CFP0-4	4	10
	1,610	1,183	79%	CFP0-6	6	0
	1,933	1,033	54%	CFP0-6	6	2
	2,478	1,044	42%	CFP0-6	6	5
	2,840	1,002	35%	CFP0-6	6	10
	1,376	1,191	70%	CFP0-7	7	0
	2,049	993	48%	CFP0-7	7	2
	2,711	1,110	42%	CFP0-7	7	5
	3,122	1,134	36%	CFP0-7	7	10
	1,317	1,174	77%	CFP0-8	8	0
	1,381	1,063	67%	CFP0-8	8	2
	1,184	1,472	46%	CFP0-8	8	5
1,107	1,042	34%	CFP0-8	8	10	

Note: E_{bc} predictions are limited to ranges between 1,000 and 15,000 psi.

Prediction	Statistics			Details		
	Average (psi)	Std Dev (psi)	CV	Model	Deflection	Noise
K _{cc}	8.261	4.318	35%	CFP0-4	4	0
	9.739	3.833	39%	CFP0-4	4	2
	9.495	2.714	29%	CFP0-4	4	5
	8.424	1.981	23%	CFP0-4	4	10
	3.769	4.485	84%	CFP0-6	6	0
	6.920	4.628	67%	CFP0-6	6	2
	6.424	4.015	63%	CFP0-6	6	5
	6.882	2.693	39%	CFP0-6	6	10
	6.366	4.729	75%	CFP0-7	7	0
	7.156	4.710	66%	CFP0-7	7	2
	6.687	4.238	63%	CFP0-7	7	5
	7.084	3.348	47%	CFP0-7	7	10
	6.201	3.001	41%	CFP0-8	8	0
	8.178	4.396	56%	CFP0-8	8	2
	6.392	4.308	68%	CFP0-8	8	5
7.207	3.069	43%	CFP0-8	8	10	

Note: E_{bc} predictions are limited to ranges between 1,000 and 15,000 psi.

Prediction	Statistics			Details		
	Average	Std Dev	CV	Model	Deflection	Noise
E _{cc}	37	3	28%	CFP0-4	4	
	17	3	27%	CFP0-6	6	
	12	3	24%	CFP0-7	7	
E _{bc}	12	3	24%	CFP0-8	8	
	42	13	30%	CFP0-4	4	
	27	19	71%	CFP0-6	6	
E _{sc}	30	18	59%	CFP0-7	7	
	28	19	68%	CFP0-8	8	
	0	0	34%	CFP0-4	4	
σ _p	0	0	33%	CFP0-6	6	
	0	0	33%	CFP0-7	7	
	0	0	30%	CFP0-8	8	

CFP9 Summary / CFP4-Eac(9 Kip) / CFP4-Eac-2%(9 Kip) / CFP4-Eac-5%(9 Kip) / CFP4-Eac-10%(9 Kip) / CFP4-Eri(9 Kip) / CFP4-Eri-2%(9 Kip) / CFP4-Eri-5%(9 Kip) / CFP4-Eri-10%(9 Kip)

(a)

Prediction	Statistics			Details		
	Average (psi)	Std Dev (psi)	CV	Model	Deflection	Noise
E _{cc}	3,883.869	1,827,629	47%	FD9-4	4	0
	3,883.869	1,827,629	47%	FD9-4	4	2
	4,028,344	3,883,626	97%	FD9-4	4	5
	3,628,254	628,701	17%	FD9-4	4	10
	4,708,777	1,827,629	38%	FD9-6	6	0
	4,338,332	1,032,326	24%	FD9-6	6	2
	4,123,429	1,038,482	25%	FD9-6	6	5
	3,883,623	983,879	25%	FD9-6	6	10
	4,328,768	1,188,248	27%	FD9-7	7	0
	4,383,070	1,088,478	25%	FD9-7	7	2
	4,082,882	1,183,894	29%	FD9-7	7	5
	3,846,227	983,238	25%	FD9-7	7	10
	4,678,324	1,107,348	24%	FD9-8	8	0
	4,383,680	1,082,702	24%	FD9-8	8	2
	4,084,608	983,889	24%	FD9-8	8	5
3,843,881	983,889	26%	FD9-8	8	10	

Note: E_{cc} predictions are limited to ranges between 100,000 and 6,000,000 psi.

Prediction	Statistics			Details		
	Average	Std Dev	CV	Model	Deflection	Noise
E _{cc}	0	0	0%	FD9-4	4	
	0	0	0%	FD9-6	6	
	0	0	0%	FD9-7	7	
E _{bc}	0	0	0%	FD9-8	8	
	0	0	0%	FD9-4	4	
	0	0	0%	FD9-6	6	
E _{sc}	0	0	0%	FD9-7	7	
	0	0	0%	FD9-8	8	
	0	0	0%	FD9-4	4	
σ _p	0	0	0%	FD9-6	6	
	0	0	0%	FD9-7	7	
	0	0	0%	FD9-8	8	

Note: Strain AC predictions are limited to ranges between 0 and 1000 microstrain.
 Note: Strain SC predictions are limited to ranges between 0 and 4000 microstrain.
 Note: Deviator Stress predictions are limited to ranges between 0 and 25 psi.

FD9 Summary /

(b)

Figure 17. Output statistics summary sheet for flexible pavement: (a) conventional, (b) full-depth

Rigid Pavement Analysis, Plotting, and Summary Menus

Similar to flexible pavement analysis menu, the rigid pavement analysis menu consists of three main sections: inputs, analysis tool, and outputs as shown in Figure 18. Required input parameters for rigid pavement analysis are deflection data, pavement layer information (layer thicknesses, degree of bonding, and estimated moduli ratio), and FWD load. To simplify the ANN-based backcalculation methodology, PCC layer and base layer thicknesses are combined into one thickness value (effective PCC thickness) through the concept of equivalent thickness (Ceylan et al, 2007). While conducting the analysis, the effective PCC thickness can be automatically calculated from pavement layer information and used in the backcalculation analysis.

The analysis tool functionalities in the rigid pavement analysis menu are identical to those in flexible pavement analysis menu except two additional functions-“equation” and “show normalization.” The “Equation” button, once clicked, is meant to provide the equations sheet as shown in Figure 19. This equation sheet summarizes the equations used for calculation of effective PCC thickness for fully bonded PCC layers, unbonded PCC layers and partially bonded PCC layers. The “show normalization” button is enabled only after the backcalculation analysis is complete. The raw FWD deflection data corresponding to the raw FWD loads are normalized to the 9-kip constant FWD load during backcalculation analysis. As shown in Figure 20, the normalized FWD data can be shown or hid in rigid pavement analysis menu by clicking “show normalization” or “hide normalization.” Preprocessing the data for rigid pavement analysis such as obtaining and filtering the FWD data is same as that for flexible pavement analysis.

Section	INPUTS							Slab on Grade Analysis	Coefficient of Subgrade Reaction (psi/ft)				
	RWD/FWD Deflections (kips)	RWD/FWD Load (kips)	Effective Thickness (calculated) (inches)	PCC Thickness (inches)	Base Thickness (inches)	Degree of Bonding (S)	Estimated Moduli Ratio		R	Z1	Z2	Z3	
1	2.23	2.17	2.10	2.41	1.92	0.00	0.00	0.20	1.119	1.047	1.101	1.110	
2	2.49	2.62	2.83	2.48	2.29	2.87	1.81	0.00	0.20	2.97	2.84	2.60	2.48
3	3.24	3.18	3.04	2.94	2.78	2.90	2.18	0.00	0.20	2.81	2.99	2.61	2.49
4	2.34	2.23	2.20	2.15	2.03	1.84	1.78	0.00	0.20	1.99	1.97	2.06	1.94
5	2.79	2.71	2.61	2.50	2.37	2.14	1.81	0.00	0.20	2.41	2.40	2.49	2.34
6	3.49	3.40	3.23	3.10	2.98	2.71	2.34	0.00	0.20	3.39	3.38	3.29	3.23
7	1.70	1.74	1.64	1.59	1.46	1.20	1.00	0.00	0.20	1.67	1.67	1.72	1.61
8	3.40	3.44	3.33	3.20	3.08	2.80	2.47	0.00	0.20	3.37	3.37	3.27	3.14
9	4.54	4.67	4.94	4.74	4.62	4.30	3.87	0.00	0.20	4.70	4.64	4.77	4.63
10	2.18	2.13	2.14	2.13	2.05	1.92	1.84	0.00	0.20	1.99	1.99	1.99	1.94
11	3.82	3.67	3.74	3.22	3.00	2.79	2.46	0.00	0.20	3.72	3.71	3.71	3.64
12	4.15	4.04	3.91	3.77	3.61	3.24	2.87	0.00	0.20	3.76	3.77	3.69	3.72
13	2.44	2.54	2.51	2.41	2.30	2.12	1.81	0.00	0.20	1.65	1.64	1.71	1.61
14	3.32	3.27	3.16	3.03	2.88	2.41	2.24	0.00	0.20	3.13	3.13	3.09	3.01
15	4.47	3.97	3.93	3.69	3.53	3.23	2.84	0.00	0.20	3.74	3.72	3.76	3.67
16	2.43	2.36	2.40	2.30	2.23	1.99	1.72	0.00	0.20	2.34	2.33	2.31	2.24
17	3.40	3.40	3.30	3.17	3.01	2.71	2.26	0.00	0.20	3.34	3.33	3.24	3.10
18	4.43	3.96	3.76	3.57	3.44	3.04	2.64	0.00	0.20	3.44	3.44	3.33	3.19
19	2.86	2.81	2.82	2.71	2.60	2.41	1.98	0.00	0.20	2.80	2.80	2.81	2.71
20	3.22	3.10	3.02	2.92	2.79	2.63	2.24	0.00	0.20	3.07	3.04	2.93	2.80
21	3.11	3.19	3.09	3.07	2.90	2.64	2.45	0.00	0.20	3.11	3.11	3.07	3.01
22	2.84	2.80	2.83	2.73	2.63	2.46	1.81	0.00	0.20	1.61	1.61	1.61	1.59
23	3.21	3.16	3.07	2.98	2.82	2.67	2.24	0.00	0.20	3.11	3.11	3.07	3.01
24	3.19	3.19	3.14	3.00	2.84	2.67	2.41	0.00	0.20	3.14	3.14	3.09	3.02
25	2.62	2.61	2.76	2.60	2.50	2.34	2.10	0.00	0.20	2.61	2.61	2.61	2.54
26	3.01	3.02	2.81	2.74	2.58	2.47	2.40	0.00	0.20	2.74	2.74	2.74	2.68
27	4.30	4.20	4.05	3.97	3.74	3.29	2.85	0.00	0.20	4.10	4.10	4.10	4.00
28	2.17	2.17	2.19	2.18	2.04	1.94	1.80	0.00	0.20	2.17	2.17	2.17	2.10
29	3.84	3.82	3.41	3.28	3.16	2.81	2.54	0.00	0.20	3.82	3.82	3.82	3.74
30	4.30	4.33	4.21	4.03	3.81	3.57	3.23	0.00	0.20	4.16	4.16	4.16	4.05
31	1.71	1.71	1.51	1.54	1.60	1.60	1.60	0.00	0.20	1.119	1.119	1.114	1.110
32	2.32	2.24	2.16	2.01	1.97	1.81	1.60	0.00	0.20	1.80	1.72	1.64	1.57
33	2.70	2.63	2.62	2.40	2.31	2.14	2.03	0.00	0.20	2.16	2.16	2.16	2.11
34	3.37	3.30	3.22	3.11	2.91	1.82	1.60	0.00	0.20	2.74	2.72	2.60	2.51
35	4.41	3.18	3.74	3.61	3.40	3.04	2.64	0.00	0.20	3.41	3.41	3.41	3.40

Figure 18. Rigid pavement analysis menu

Effective thickness for fully bonded PCC layers as:

$$h_{e-f} = \left\{ h_1^3 + \frac{E_2}{E_1} h_2^3 + 12 \left[\left(x_{ne} - \frac{h_1}{2} \right)^2 h_1 + \frac{E_2}{E_1} \left(h_1 - x_{ne} + \frac{h_2}{2} \right)^2 h_2 \right] \right\}^{1/3}$$

$$x_{ne} = \frac{E_1 h_1 \frac{h_1}{2} + E_2 h_2 \left(h_1 + \frac{h_2}{2} \right)}{E_1 h_1 + E_2 h_2}$$



Effective thickness for unbonded PCC layers as:

$$h_{e-u} = \left(h_1^3 + \frac{E_2}{E_1} h_2^3 \right)^{1/3}$$

Effective thickness for partially bonded PCC layers as:

$$h_{e-p} = (1-x)h_{e-u} + (x)h_{e-f}$$

$$x = \frac{h_{e-p} - h_{e-u}}{h_{e-f} - h_{e-u}}$$



- h_{e-f} = Effective thickness of the fully bonded PCC layers
- h_{e-u} = Effective thickness of the unbonded PCC layers
- h_{e-p} = Effective thickness of the partially bonded PCC layers
- E_1 or E_2 = Elastic modulus for layer 1 or 2
- h_1 or h_2 = Thickness for layer 1 or 2
- x_{ne} = Neutral axis distance from top of layer
- x = degree of bonding which ranges between 0 and 1

k - coefficient of subgrade reaction and Epcc equations in terms of l - radius of relative stiffness

$$k = \left(\frac{P}{8D_l \ell_r^3} \right) \left\{ 1 + \left(\frac{1}{2\pi} \right) \left[\ln \left(\frac{a}{2\ell_r} \right) - 0.673 \right] \left(\frac{a}{\ell_r} \right)^2 \right\}$$

$$E_{pcc} = \left(\frac{12\ell_r^3 k(1-\mu^2)}{h_{pcc}^3} \right)$$

Figure 19. Screen shot of Equations sheet

Location	INPUTS															
	HWDIFVD Deflections (mils)								HWDIFVD Load (kips)	Effective Thickness (calculated) (inch)	PCC Thickness (inch)	Base Thickness (inch)	Degree of Bonding (%)	Estimated Moduli Ratio		
	D-6	D-8	D-12	D-18	D-24	D-36	D-48	D-60	Load	A _{ave}	A _{PCC}	A _{base}	%	(E _{base} /E _{PCC})		
1	2.23	2.17	2.10	2.01	1.92	0.00	0.00	0.00	9.34	10.24	10.20	4.00	0	0.20		
2	2.69	2.62	2.53	2.42	2.29	2.07	1.81	0.00	12.18	10.24	10.20	4.00	0	0.20		
3	3.26	3.18	3.06	2.94	2.78	2.50	2.18	1.90	14.67	10.24	10.20	4.00	0	0.20		
4	2.34	2.28	2.20	2.12	2.03	1.84	1.70	0.49	9.22	10.24	10.20	4.00	0	0.20		
5	2.79	2.71	2.61	2.50	2.37	2.14	1.88	1.77	11.94	10.24	10.20	4.00	0	0.20		
6	3.49	3.40	3.28	3.13	2.95	2.71	2.34	2.07	14.81	10.24	10.20	4.00	0	0.20		
7	2.79	2.74	2.64	2.55	2.42	2.20	1.92	0.00	9.26	10.24	10.20	4.00	0	0.20		
8	3.48	3.44	3.33	3.20	3.05	2.80	2.47	2.15	11.88	10.24	10.20	4.00	0	0.20		
9	4.14	4.07	3.94	3.81	3.62	3.30	2.87	2.52	14.71	10.24	10.20	4.00	0	0.20		
10	2.88	2.83	2.74	2.63	2.51	2.29	2.20	1.96	9.43	10.24	10.20	4.00	0	0.20		
11	3.52	3.47	3.36	3.22	3.08	2.79	2.46	2.39	12.26	10.24	10.20	4.00	0	0.20		
12	4.12	4.04	3.91	3.77	3.58	3.26	2.87	2.74	14.78	10.24	10.20	4.00	0	0.20		
13	2.64	2.59	2.51	2.41	2.30	2.12	1.88	0.59	9.36	10.24	10.20	4.00	0	0.20		
14	3.32	3.27	3.16	3.03	2.88	2.61	2.29	2.25	12.10	10.24	10.20	4.00	0	0.20		
15	4.07	3.97	3.83	3.69	3.53	3.23	2.84	2.53	14.52	10.24	10.20	4.00	0	0.20		
16	2.61	2.56	2.48	2.36	2.23	1.99	1.72	1.49	9.43	10.24	10.20	4.00	0	0.20		
17	3.49	3.41	3.30	3.17	3.01	2.71	2.35	2.09	12.18	10.24	10.20	4.00	0	0.20		
18	4.03	3.95	3.79	3.67	3.44	3.06	2.64	2.33	14.94	10.24	10.20	4.00	0	0.20		
19	2.56	2.51	2.42	2.31	2.20	2.01	1.95	1.74	9.57	10.24	10.20	4.00	0	0.20		
20	3.22	3.13	3.02	2.92	2.78	2.53	2.24	2.20	12.43	10.24	10.20	4.00	0	0.20		
21	3.81	3.75	3.59	3.47	3.30	3.04	2.65	2.31	15.22	10.24	10.20	4.00	0	0.20		
22	2.54	2.50	2.43	2.33	2.23	2.06	1.82	1.76	9.27	10.24	10.20	4.00	0	0.20		
23	3.21	3.16	3.07	2.95	2.82	2.57	2.24	1.99	12.26	10.24	10.20	4.00	0	0.20		
24	3.85	3.76	3.64	3.50	3.34	3.07	2.68	2.36	14.97	10.24	10.20	4.00	0	0.20		
25	2.92	2.86	2.76	2.66	2.52	2.26	2.18	1.90	9.29	10.24	10.20	4.00	0	0.20		
26	3.69	3.62	3.51	3.36	3.18	2.87	2.49	2.34	12.18	10.24	10.20	4.00	0	0.20		
27	4.30	4.20	4.05	3.87	3.66	3.29	2.86	2.39	14.78	10.24	10.20	4.00	0	0.20		

(a)

Location	INPUTS																						
	HWDIFVD Deflections (mils)								HWDIFVD Load (kips)	9 kip Normalization				Effective Thickness (calculated) (inch)	PCC Thickness (inch)	Base Thickness (inch)	Degree of Bonding (%)	Estimated Moduli Ratio					
	D-6	D-8	D-12	D-18	D-24	D-36	D-48	D-60	Load	D-6	D-8	D-12	D-18	D-24	D-36	D-48	D-60	Load	A _{ave}	A _{PCC}	A _{base}	%	(E _{base} /E _{PCC})
1	2.23	2.17	2.10	2.01	1.92	0.00	0.00	0.00	9.34	2.15	2.09	2.02	1.94	1.85	0.00	0.00	0.00	9.00	10.24	10.20	4.00	0	0.20
2	2.69	2.62	2.53	2.42	2.29	2.07	1.81	0.00	12.18	1.99	1.94	1.87	1.79	1.69	1.53	1.34	0.00	9.00	10.24	10.20	4.00	0	0.20
3	3.26	3.18	3.06	2.94	2.78	2.50	2.18	1.90	14.67	2.00	1.95	1.88	1.80	1.71	1.53	1.34	1.17	9.00	10.24	10.20	4.00	0	0.20
4	2.34	2.28	2.20	2.12	2.03	1.84	1.70	0.49	9.22	2.28	2.23	2.15	2.07	1.98	1.80	1.66	0.49	9.00	10.24	10.20	4.00	0	0.20
5	2.79	2.71	2.61	2.50	2.37	2.14	1.88	1.77	11.94	2.30	2.04	1.97	1.88	1.79	1.61	1.42	1.33	9.00	10.24	10.20	4.00	0	0.20
6	3.49	3.40	3.28	3.13	2.95	2.71	2.34	2.07	14.81	2.32	2.07	1.99	1.90	1.79	1.65	1.42	1.26	9.00	10.24	10.20	4.00	0	0.20
7	2.79	2.74	2.64	2.55	2.42	2.20	1.92	0.00	9.26	2.71	2.66	2.57	2.48	2.35	2.14	1.87	0.00	9.00	10.24	10.20	4.00	0	0.20
8	3.48	3.44	3.33	3.20	3.05	2.80	2.47	2.15	11.88	2.64	2.61	2.52	2.42	2.31	2.12	1.87	1.63	9.00	10.24	10.20	4.00	0	0.20
9	4.14	4.07	3.94	3.81	3.62	3.30	2.87	2.52	14.71	2.53	2.49	2.41	2.33	2.21	2.02	1.76	1.54	9.00	10.24	10.20	4.00	0	0.20
10	2.88	2.83	2.74	2.63	2.51	2.29	2.20	1.96	9.43	2.75	2.70	2.62	2.51	2.40	2.19	2.10	1.87	9.00	10.24	10.20	4.00	0	0.20
11	3.52	3.47	3.36	3.22	3.08	2.79	2.46	2.39	12.26	2.58	2.55	2.47	2.38	2.28	2.05	1.81	1.75	9.00	10.24	10.20	4.00	0	0.20
12	4.12	4.04	3.91	3.77	3.58	3.26	2.87	2.74	14.78	2.51	2.46	2.38	2.30	2.18	1.99	1.75	1.67	9.00	10.24	10.20	4.00	0	0.20
13	2.64	2.59	2.51	2.41	2.30	2.12	1.88	0.59	9.36	2.54	2.49	2.41	2.32	2.21	2.04	1.81	0.57	9.00	10.24	10.20	4.00	0	0.20
14	3.32	3.27	3.16	3.03	2.88	2.61	2.29	2.25	12.10	2.47	2.43	2.35	2.25	2.14	1.94	1.70	1.67	9.00	10.24	10.20	4.00	0	0.20
15	4.07	3.97	3.83	3.69	3.53	3.23	2.84	2.53	14.52	2.52	2.46	2.37	2.29	2.19	2.00	1.76	1.57	9.00	10.24	10.20	4.00	0	0.20
16	2.61	2.56	2.48	2.36	2.23	1.99	1.72	1.49	9.43	2.49	2.44	2.37	2.25	2.13	1.90	1.64	1.42	9.00	10.24	10.20	4.00	0	0.20
17	3.49	3.41	3.30	3.17	3.01	2.71	2.35	2.09	12.18	2.58	2.52	2.44	2.34	2.22	2.00	1.74	1.54	9.00	10.24	10.20	4.00	0	0.20
18	4.03	3.95	3.79	3.67	3.44	3.06	2.64	2.33	14.94	2.43	2.38	2.28	2.21	2.07	1.84	1.59	1.40	9.00	10.24	10.20	4.00	0	0.20
19	2.56	2.51	2.42	2.31	2.20	2.01	1.95	1.74	9.57	2.41	2.36	2.28	2.17	2.07	1.89	1.63	1.64	9.00	10.24	10.20	4.00	0	0.20
20	3.22	3.13	3.02	2.92	2.78	2.53	2.24	2.20	12.43	2.33	2.27	2.19	2.11	2.01	1.83	1.62	1.59	9.00	10.24	10.20	4.00	0	0.20
21	3.81	3.75	3.59	3.47	3.30	3.04	2.65	2.31	15.22	2.25	2.22	2.12	2.05	1.95	1.80	1.57	1.37	9.00	10.24	10.20	4.00	0	0.20
22	2.54	2.50	2.43	2.33	2.23	2.06	1.82	1.76	9.27	2.47	2.43	2.36	2.26	2.17	2.00	1.77	1.71	9.00	10.24	10.20	4.00	0	0.20
23	3.21	3.16	3.07	2.95	2.82	2.57	2.24	1.99	12.26	2.36	2.32	2.25	2.17	2.07	1.89	1.64	1.46	9.00	10.24	10.20	4.00	0	0.20
24	3.85	3.76	3.64	3.50	3.34	3.07	2.68	2.36	14.97	2.31	2.28	2.19	2.10	2.01	1.85	1.61	1.42	9.00	10.24	10.20	4.00	0	0.20
25	2.92	2.86	2.76	2.66	2.52	2.26	2.18	1.90	9.29	2.83	2.77	2.67	2.58	2.44	2.19	2.11	1.84	9.00	10.24	10.20	4.00	0	0.20
26	3.69	3.62	3.51	3.36	3.18	2.87	2.49	2.34	12.18	2.73	2.67	2.59	2.49	2.35	2.12	1.84	1.73	9.00	10.24	10.20	4.00	0	0.20
27	4.30	4.20	4.05	3.87	3.66	3.29	2.86	2.39	14.78	2.62	2.56	2.47	2.36	2.23	2.00	1.74	1.46	9.00	10.24	10.20	4.00	0	0.20

(b)

Figure 20. Screen shot of inputs in rigid pavement analysis menu: (a) hide normalization, (b) show normalization

Similar to flexible pavement analysis, the program can analyze model by model by clicking the “Run” button after preprocessing the data. The ANN models employed for rigid pavement analysis are 4-, 6-, 7-, and 8-deflection models with 0%, ±2%, ±5% and ±10% noise. Each model has a different number of input parameters depending on the number of deflections. The purpose of introducing noisy patterns in the development of each model was to provide more robust networks that can tolerate the noisy or inaccurate deflection patterns collected from the FWD deflection basins. Detailed descriptions of each model are provided in phase I project report (Ceylan et al, 2007).

For each model, the analysis results will be displayed on the right side of the screen. The user should scroll right to see all results. Also, disabled menu commands of Plots and Summary will be activated after the analysis is complete. The rigid pavement analysis results are E_{PCC} -modulus of PCC, k_s -coefficient of subgrade reaction, σ_{PCC} -tensile stress at the bottom of the PCC layer, and radius of relative stiffness (RRS)

Figure 21 illustrates the sample analysis results from a rigid pavement run. Figure 22 illustrates color-coded rigid pavement analysis results of 4-deflection ANN model with 0 % noise which are generated from the plotting function. Figure 23 illustrates sample Excel sheet with the output tables and their statistics for every model generated by clicking “summary” button.

4 Deflection Model (D9-D8-D12-D18-D24-D36-D48-D60)									
accdb	Coefficient of Subgrade Reaction (pr/in)				PCC Modulus (psi)				Radius of Relative Stiffness (inck)
	k_s	k_s	k_s	k_s	E_{PCC}	E_{PCC}	E_{PCC}	E_{PCC}	RRS
1	5,118	5,118	5,118	5,078	5,232,368	5,038,245	5,444,897	5,034,362	97
2	456	733	788	764	6,579,181	3,742,382	3,816,425	3,945,425	92
3	237	224	228	224	16,239,364	16,379,334	16,482,335	16,382,384	92
4	236	413	422	428	8,257,384	5,887,817	5,582,864	5,197,453	93
5	283	183	184	178	16,217,438	16,272,347	16,214,136	15,142,557	96
6	247	283	283	283	16,283,861	16,373,283	16,336,236	16,284,538	93
7	383	541	522	528	5,835,582	2,837,554	2,814,918	2,617,846	93
8	128	145	145	141	16,378,141	16,383,417	16,864,888	16,738,333	97
9	165	153	158	156	16,446,334	16,418,435	16,872,518	16,854,478	95
10	116	186	187	187	16,748,473	16,315,435	16,188,858	16,855,858	95
11	141	128	127	126	16,288,483	16,218,323	16,818,568	16,655,888	98
12	143	137	136	135	16,888,857	16,158,343	16,787,538	16,652,222	93
13	264	368	375	363	7,257,883	5,252,358	5,847,884	4,672,837	93
14	152	151	156	155	16,248,384	16,248,425	16,814,185	16,862,242	98
15	153	152	151	147	16,219,853	16,248,858	16,824,233	16,884,163	97
16	288	183	188	188	19,221,851	16,255,175	16,345,868	16,862,823	98
17	175	165	163	163	16,386,789	16,197,383	16,731,422	16,655,862	93
18	284	191	191	198	16,274,852	16,216,111	16,443,736	16,418,884	91
19	194	162	162	161	16,746,388	16,487,813	16,538,555	16,855,888	95
20	154	138	138	137	16,241,383	16,483,458	16,481,412	16,196,284	94
21	185	178	177	177	16,445,423	16,881,881	16,235,189	16,482,185	95
22	155	124	124	123	16,742,822	16,383,857	16,381,388	16,444,518	93
23	172	165	164	162	16,888,211	16,374,672	16,158,353	16,881,425	96
24	177	178	168	167	16,448,644	16,818,787	16,385,858	16,476,933	96
25	127	146	147	145	16,823,191	16,188,483	16,218,556	16,884,833	94
26	155	143	141	137	16,384,846	16,237,461	16,864,478	16,734,193	96
27	191	184	184	182	16,818,685	16,237,281	16,888,888	16,637,588	98
28	193	183	184	183	16,738,758	16,319,333	16,872,837	16,814,917	95
29	125	114	114	114	16,223,223	16,251,651	16,885,251	16,784,781	93
30	127	113	128	119	16,728,383	16,216,558	16,738,734	16,653,881	92
31	1,118	1,118	1,117	1,887	721,218	1,887,738	3,125,862	4,913,333	15
32	788	1,847	1,842	1,813	4,628,711	3,155,283	3,481,342	3,234,564	26
33	187	161	165	165	16,748,632	16,719,283	16,749,328	16,534,888	98
34	337	676	638	637	6,833,853	3,374,916	2,955,582	3,166,726	92
35	243	223	227	223	16,889,199	16,748,627	16,887,915	16,458,638	94
36	218	284	283	284	16,687,521	16,815,288	16,654,473	16,622,742	94
37	188	187	118	187	16,743,423	16,138,193	16,231,282	16,476,323	91
38	155	123	124	122	16,748,164	16,532,248	16,744,553	16,537,884	94
39	141	123	123	128	16,745,483	16,451,455	16,451,455	16,517,348	96
40									
41	248	273	274	274	19,522,435	12,333,813	12,638,386	11,847,338	91
42	237	288	282	275	6,828,334	5,242,268	5,888,283	4,568,373	94
43	183X	183X	183X	182X	36X	48X	88X	98X	27X

Figure 21. Sample Excel sheet of rigid pavement analysis outputs

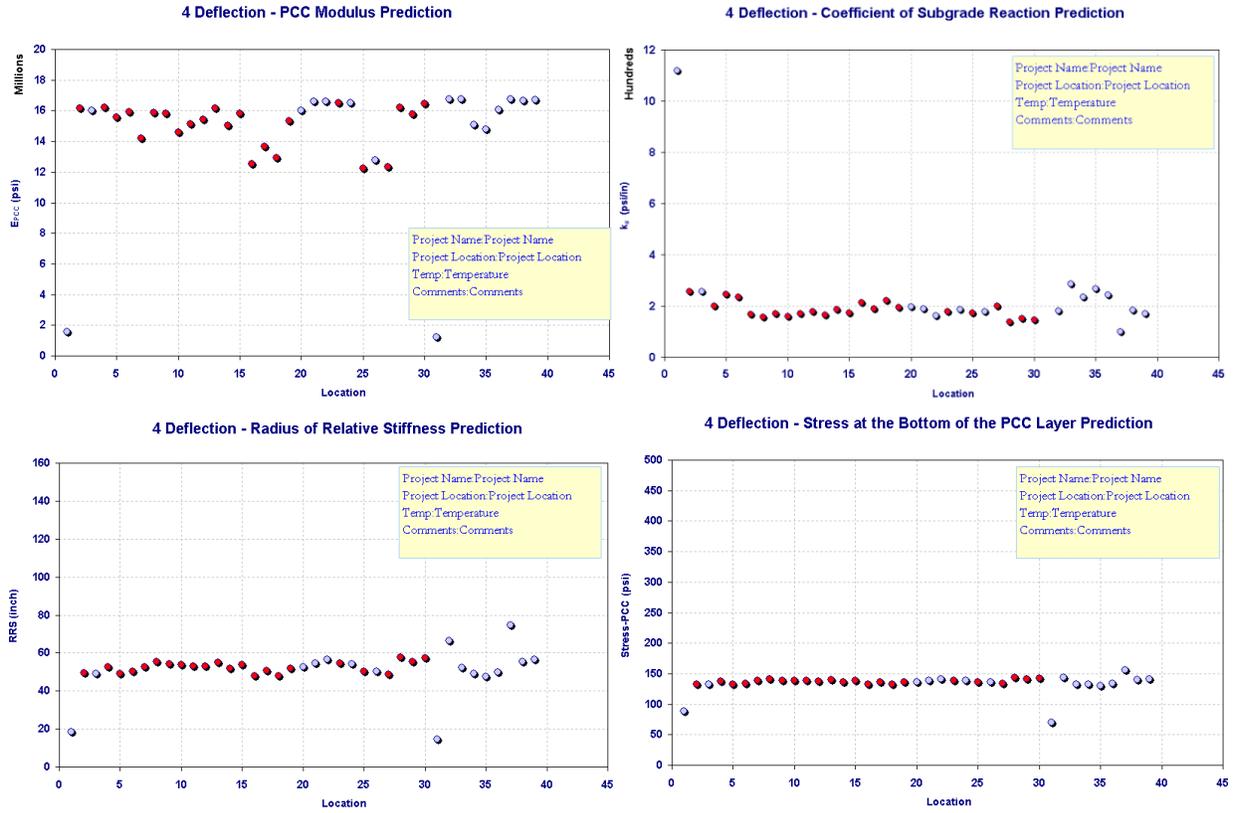


Figure 22. Sample Excel sheet rigid pavement analysis charts

Prediction	Statistic			Detail		
	Average (pr/in)	Std Dev (pr/in)	CV	Model	Deflection	Noise
k _s	235	211	90%	RGD-4	4	0
	233	208	90%	RGD-4	4	2
	240	207	86%	RGD-4	4	5
	229	210	92%	RGD-4	4	10
	248	241	97%	RGD-6	6	0
	272	262	104%	RGD-6	6	2
	269	263	103%	RGD-6	6	5
	271	261	104%	RGD-6	6	10
	253	235	93%	RGD-7	7	0
	296	314	106%	RGD-7	7	2
	297	316	107%	RGD-7	7	5
	296	309	105%	RGD-7	7	10
	248	237	95%	RGD-8	8	0
	273	260	103%	RGD-8	8	2
274	262	103%	RGD-8	8	5	
271	275	102%	RGD-8	8	10	

Prediction	Statistic			Detail		
	Average (pr)	Std Dev (pr)	CV	Model	Deflection	Noise
E _{pcc}	14,160,415	3,423,313	24%	RGD-4	4	0
	13,360,405	2,990,598	22%	RGD-4	4	2
	12,552,625	2,471,968	20%	RGD-4	4	5
	11,051,464	2,252,624	20%	RGD-4	4	10
	13,504,637	4,368,968	36%	RGD-6	6	0
	12,894,259	5,362,188	42%	RGD-6	6	2
	12,558,210	5,020,503	40%	RGD-6	6	5
	11,705,695	4,611,061	39%	RGD-6	6	10
	13,402,738	5,107,266	38%	RGD-7	7	0
	12,731,537	5,438,104	43%	RGD-7	7	2
	12,308,881	5,095,301	41%	RGD-7	7	5
	11,704,016	4,737,350	40%	RGD-7	7	10
	13,522,435	4,828,531	36%	RGD-8	8	0
	12,833,819	5,242,759	41%	RGD-8	8	2
12,630,886	5,080,209	40%	RGD-8	8	5	
11,847,938	4,550,979	38%	RGD-8	8	10	

Note: k_s predictors are limited to range between 50 and 1,000 pr/in.

Back

Note: E_{pcc} predictors are limited to range between 1,000,000 and 15,000,000 pr.

Prediction	Statistic			Detail		
	Average (in)	Std Dev (in)	CV	Model	Deflection	Noise
RRS	50	10	19%	RGD-4	4	0
	51	14	28%	RGD-6	6	0
	51	15	29%	RGD-7	7	0
	51	14	27%	RGD-8	8	0

Prediction	Statistic			Detail	
	Average	Std Dev	CV	Model	Deflection
σ _{pcc}	130	14	11%	RGD-4	4
	135	18	13%	RGD-6	6
	134	17	13%	RGD-7	7
	135	16	12%	RGD-8	8

Note: RRS predictors are limited to range between 15 and 141 in.

Note: PCC Stress predictors are limited to range between 20 and 400 pr.

Figure 23. Output statistics summary sheet for rigid pavement analysis

Composite Pavement Analysis, Plotting, and Summary Menus

The AC overlaid PCC-type composite pavement analysis menu also consists of three main sections: inputs, analysis tool, and outputs as shown in Figure 24. Required input parameters for composite pavement analysis are deflection data, pavement layer information (layer thicknesses, PCC modulus predictions, and coefficient of subgrade reaction predictions), and FWD load. The analysis tool functionalities in composite analysis menu are identical to those in flexible pavement analysis menu. This means preprocessing of the data for composite pavement analysis is same as that for flexible pavement analysis.

Similar to flexible and rigid pavement analysis, the program analyzes the data model by model by clicking the “Run” button after preprocessing the data. The ANN models employed for composite pavement analysis are 4-, 6-, 7-, and 8- deflection models with 0%, ±2%, ±5% and ±10% noise. Each model has a different number of input parameters depending on the number of deflections and a different level of noise to provide more robust networks. Detailed descriptions of each model are provided in phase I project report (Ceylan et al, 2007).

For each model, the analysis results will be displayed on the right side of the screen. The user should scroll right to see all results. Also, disabled menu commands of plots and the summary will be activated. The composite pavement analysis results are E_{AC}-modulus of AC, E_{PCC}-modulus of PCC, k_s-coefficient of subgrade reaction, ε_{AC}-tensile strain at the bottom of asphalt

layer, and σ_{PCC} -tensile stress at the bottom of the PCC layer.

Figure 25 illustrates sample analysis results for a composite pavement section. Figure 26 illustrates color-coded composite pavement analysis results of 4-deflection model with 0 % noise which are generated from the plotting function. Figure 27 illustrates sample Excel sheet with tables of each output and their statistics for every generated model by clicking “summary” button.

Location	FWD Deflections (mil)								Asphalt Concrete Thickness	Portland Cement Concrete	Epoxy Prediction (psi)	k Prediction (psif/in)	Eac 4 Deflections (psi) (D12-D24-D36)				(D0-
	D-0	D-8	D-12	D-18	D-24	D-36	D-48	D-60	A _{acc}	A _{acc}	E _{acc}			Es	Es	Es	Es
1	2.50	2.19	2.08	1.99	1.93	0.00	0.00	0.00	10.00	10.00				3,362,500	3,353,907	3,236,212	1,667,776
2	3.01	2.61	2.46	2.36	2.24	2.05	2.05	0.00	10.00	10.00				1,094,829	1,218,713	1,885,600	2,051,545
3	3.65	3.16	2.98	2.86	2.71	2.44			10.00	10.00							
4	2.98	2.63	2.45	2.31	2.16	1.89			10.00	10.00							
5	3.82	3.31	3.09	2.91	2.74	2.38			10.00	10.00							
6	4.57	3.94	3.63	3.49	3.25	2.85	2.35	2.20	10.00	10.00							
7	3.41	3.07	2.88	2.72	2.54	2.17	2.00	0.00	10.00	10.00				1,352,536	1,449,436	1,639,213	1,819,741
8	4.31	3.87	3.65	3.43	3.19	2.72	2.23	2.12	10.00	10.00				1,105,947	1,174,549	1,406,344	1,668,527
9	5.16	4.59	4.35	4.08	3.77	3.22	2.61	2.28	10.00	10.00				896,930	913,876	1,121,740	1,396,118
10	3.42	2.94	2.83	2.43	2.23	1.95	1.92	0.00	10.00	10.00				788,556	785,320	787,003	1,231,608
11	4.30	3.95	3.28	3.03	2.80	2.41	2.02	0.00	10.00	10.00				698,524	630,006	612,382	950,001
12	5.22	4.30	3.98	3.68	3.39	2.92	2.47	2.27	10.00	10.00				510,563	520,648	468,696	772,525
13	3.62	3.10	2.91	2.76	2.62	2.35	1.99	0.00	10.00	10.00				968,732	894,403	1,077,604	1,657,890
14	4.85	3.97	3.65	3.49	3.28	2.92	2.50	2.43	10.00	10.00				699,090	704,099	916,814	1,239,901
15	5.40	4.60	4.33	4.13	3.88	3.46	2.96	2.54	10.00	10.00				568,797	592,823	617,571	1,041,449
16	4.36	4.00	3.79	3.57	3.33	2.89	2.38	2.25	10.00	10.00				1,320,304	1,445,332	1,691,148	1,775,395
17	5.37	4.88	4.60	4.35	4.04	3.48	2.85	2.53	10.00	10.00				954,938	1,000,727	1,221,770	1,521,681
18	6.40	5.80	5.48	5.16	4.79	4.12	3.39	2.76	10.00	10.00				804,055	807,461	998,277	1,366,211
19	3.28	2.88	2.71	2.55	2.35	2.01	1.83	0.00	10.00	10.00				1,209,993	1,246,118	1,454,823	1,733,784
20	4.22	3.67	3.46	3.25	3.03	2.57	2.06	2.01	10.00	10.00				809,064	943,089	1,105,775	1,478,793
21	5.68	4.40	4.13	3.89	3.60	3.05	2.46	2.13	10.00	10.00				725,749	732,568	813,302	1,192,888
22	3.59	3.32	3.13	2.97	2.79	2.45	2.13	0.00	10.00	10.00				1,589,074	1,723,017	1,886,006	1,931,907
23	4.91	4.12	3.88	3.69	3.45	3.03	2.50	2.31	10.00	10.00				1,116,251	1,195,768	1,477,969	1,734,275
24	5.42	4.93	4.67	4.42	4.12	3.59	2.99	2.49	10.00	10.00				966,636	1,015,771	1,252,962	1,567,502
25	3.50	3.11	2.91	2.73	2.51	2.12	1.96	0.00	10.00	10.00				1,213,689	1,285,179	1,470,533	1,712,143
26	4.57	3.98	3.76	3.51	3.23	2.72	2.19	2.06	10.00	10.00				877,848	895,150	1,054,565	1,382,285
27	5.50	4.78	4.50	4.20	3.87	3.27	2.61	2.28	10.00	10.00				704,097	700,976	751,639	1,114,770
28	4.60	4.18	3.92	3.65	3.38	2.85	2.47	0.00	10.00	10.00				1,130,058	1,200,019	1,409,063	1,622,210

Figure 24. Composite pavement analysis menu

Location	Eac 4 Deflections- (psi) (D0-D12-D24-D36)				Epec 4 Deflections- (psi) (D0-D12-D24-D36)				ks 4 Deflections- (psi/in) (D0-D12-D24-D36)			
	6%	2%	5%	10%	6%	2%	5%	10%	6%	2%	5%	10%
4	1234,639	1265,899	1,519,102	1,836,437	9,499,322	9,147,167	7,792,633	7,546,496	202	203	216	222
5	891,216	913,423	1,029,944	1,530,668	7,592,611	7,316,779	6,347,208	6,670,237	161	163	166	172
6	736,423	737,415	837,433	1,267,516	6,556,046	6,322,297	5,875,011	5,209,243	132	137	139	143
7	1,352,596	1,449,436	1,693,213	1,819,741	6,640,353	6,161,698	5,603,228	5,720,321	192	190	195	192
8	1,105,947	1,174,549	1,406,344	1,668,527	4,863,962	4,565,452	4,171,684	4,222,728	158	156	157	156
9	896,930	913,876	1,121,740	1,398,118	3,955,277	3,847,150	3,549,299	3,210,390	136	135	136	133
10	788,556	785,320	787,003	1,231,608	7,535,960	7,621,437	6,794,030	6,905,758	224	222	229	238
11	618,524	630,006	612,382	950,001	5,874,340	5,792,261	5,562,333	4,893,209	186	183	186	185
12	510,503	520,648	468,596	772,525	4,839,293	4,876,478	4,723,546	4,086,396	153	151	150	152
13	868,732	884,403	1,017,604	1,687,890	11,212,355	10,343,529	8,756,121	7,517,044	133	136	158	161
14	699,010	704,099	816,814	1,299,901	8,395,041	8,233,398	7,226,994	6,521,882	111	112	126	129
15	589,797	582,923	617,571	1,041,449	7,019,359	7,006,064	6,377,420	4,795,449	94	92	99	105
16	1,320,104	1,445,332	1,691,148	1,775,915	5,101,984	4,773,213	4,430,351	4,192,110	138	139	141	132
17	954,938	1,000,727	1,221,770	1,521,681	4,133,066	4,026,434	3,722,162	2,998,709	116	120	121	110
18	804,055	807,461	998,277	1,366,211	3,347,803	3,396,332	3,077,044	2,582,748	100	104	103	93
19	1,209,993	1,246,118	1,454,823	1,733,784	6,703,043	6,368,631	5,743,087	5,995,298	218	217	222	222
20	909,064	943,089	1,105,775	1,478,793	5,374,990	5,096,446	4,533,829	4,456,015	169	167	169	169
21	725,749	732,568	813,302	1,192,898	4,423,493	4,315,517	3,873,046	3,591,367	144	143	144	145
22	1,589,074	1,733,017	1,866,006	1,931,907	7,366,460	6,922,938	6,353,703	6,471,687	148	150	156	152
23	1,118,251	1,195,768	1,477,969	1,734,275	6,075,579	5,604,080	5,148,606	4,333,281	119	123	129	118
24	966,616	1,015,771	1,252,962	1,567,502	4,488,521	4,417,099	4,034,015	3,103,407	106	111	111	99
25	1,213,689	1,265,179	1,470,533	1,712,143	5,548,079	5,269,105	4,743,724	4,858,034	218	216	219	215
26	877,848	895,150	1,054,565	1,382,285	4,208,145	4,031,352	3,700,352	3,838,214	173	170	174	168
27	704,097	700,976	751,639	1,114,770	3,654,947	3,629,093	3,277,411	3,212,183	141	139	141	138
28	1,130,058	1,200,019	1,409,063	1,622,218	3,775,932	3,456,469	3,376,836	3,671,105	163	159	162	157
29	822,980	828,926	974,988	1,250,888	3,011,004	2,960,112	2,794,933	2,649,789	126	125	127	119
30	662,059	614,149	788,781	1,077,938	2,955,561	2,404,246	2,368,640	1,696,826	106	108	111	99
31	830,329	848,417	1,013,213	1,507,917	7,812,279	7,512,331	6,454,643	6,659,213	129	134	143	144

Composite Pavement Analysis /

Figure 25. Sample Excel sheet outputs of composite pavement analysis

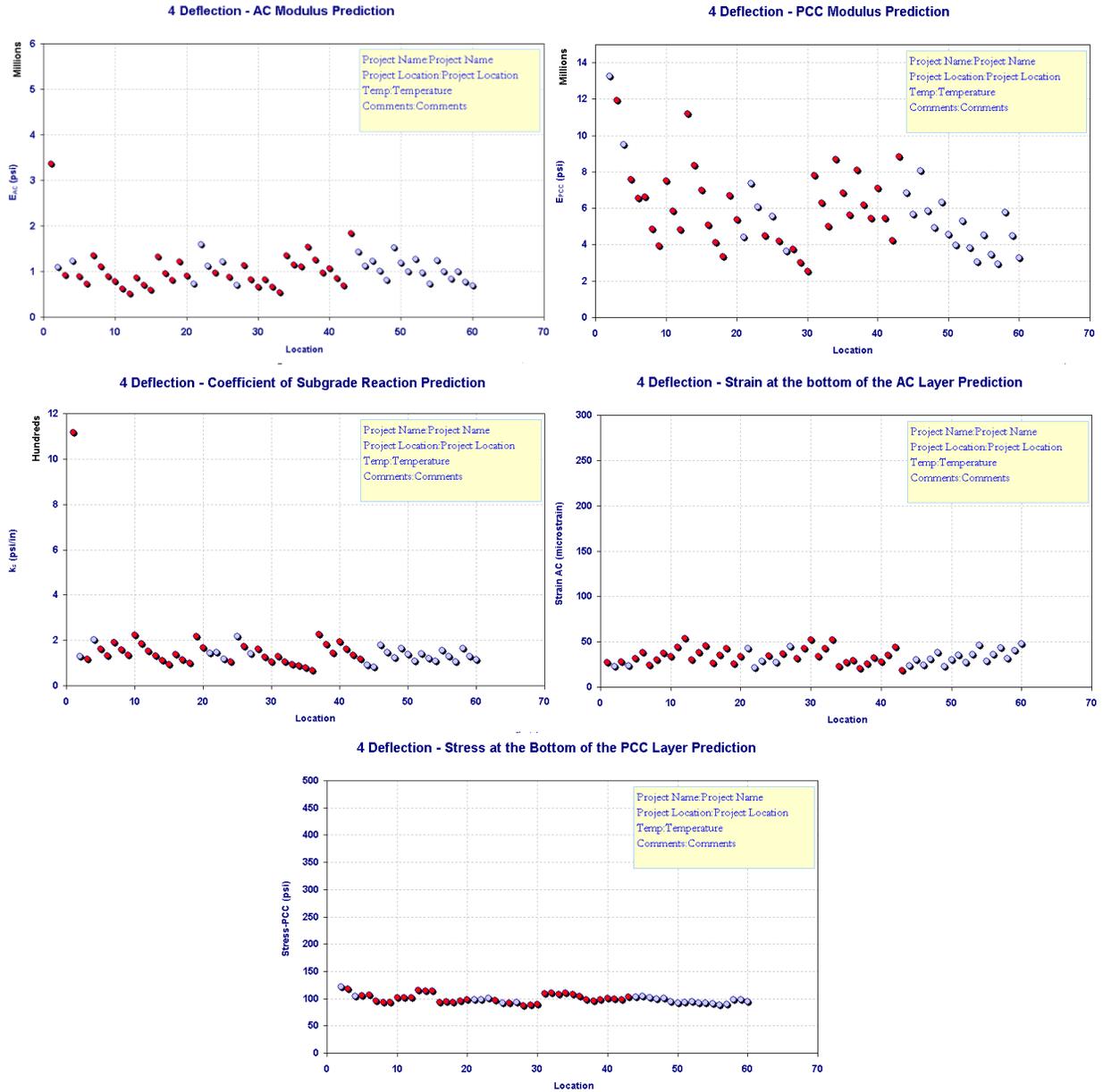


Figure 26. Sample Excel sheet charts of composite pavement analysis

Prediction	Statistic			Details		
	Average (psi)	Std Dev (psi)	CV	Model	Deflection	Moire
Eac	1,038,278	414,020	40%	CPDR-4	4	0
	1,033,033	444,615	43%	CPDR-4	4	2
	1,257,428	456,117	36%	CPDR-4	4	5
	1,522,626	283,506	18%	CPDR-4	4	10
	1,115,212	551,508	50%	CPDR-6	6	0
	1,408,963	371,373	26%	CPDR-6	6	2
	1,882,929	655,874	35%	CPDR-6	6	5
	1,354,267	402,321	30%	CPDR-6	6	10
	1,258,102	648,019	52%	CPDR-7	7	0
	1,471,269	945,284	64%	CPDR-7	7	2
	1,376,167	624,481	45%	CPDR-7	7	5
	1,495,759	361,232	24%	CPDR-7	7	10
	1,108,669	514,662	46%	CPDR-8	8	0
	1,400,777	662,400	47%	CPDR-8	8	2
	1,460,520	731,657	50%	CPDR-8	8	5
1,550,613	406,559	26%	CPDR-8	8	10	

Note: Eac predictor are limited to range between 1,000,000 and 3,000,000 psi.

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Prediction	Statistic			Details		
	Average (psi)	Std Dev (psi)	CV	Model	Deflection	Moire
Eacc	5,700,655	2,337,869	41%	CPDR-4	4	0
	5,541,671	2,069,289	37%	CPDR-4	4	2
	4,977,317	1,756,488	35%	CPDR-4	4	5
	4,604,157	1,703,022	37%	CPDR-4	4	10
	4,110,025	3,345,769	81%	CPDR-6	6	0
	4,582,784	3,613,504	79%	CPDR-6	6	2
	4,554,526	3,258,023	72%	CPDR-6	6	5
	4,052,316	3,034,113	75%	CPDR-6	6	10
	4,010,109	3,600,751	90%	CPDR-7	7	0
	4,438,591	3,744,457	84%	CPDR-7	7	2
	4,608,601	3,723,943	80%	CPDR-7	7	5
	4,106,721	3,067,744	74%	CPDR-7	7	10
	4,176,696	2,900,627	69%	CPDR-8	8	0
	4,106,327	3,155,405	76%	CPDR-8	8	2
	3,938,022	2,688,639	68%	CPDR-8	8	5
4,212,302	2,833,110	67%	CPDR-8	8	10	

Note: Eacc predictor are limited to range between 1,000,000 and 12,000,000 psi.

Prediction	Statistic			Details		
	Average (griffin)	Std Dev (griffin)	CV	Model	Deflection	Moire
k _v	156	132	84%	CPDR-4	4	0
	156	128	82%	CPDR-4	4	2
	161	125	78%	CPDR-4	4	5
	159	123	78%	CPDR-4	4	10
	205	176	86%	CPDR-6	6	0
	239	216	90%	CPDR-6	6	2
	255	229	90%	CPDR-6	6	5
	256	224	87%	CPDR-6	6	10
	245	215	88%	CPDR-7	7	0
	312	307	98%	CPDR-7	7	2
	322	316	98%	CPDR-7	7	5
	331	319	96%	CPDR-7	7	10
	170	170	94%	CPDR-8	8	0
	235	212	90%	CPDR-8	8	2
	252	233	93%	CPDR-8	8	5
250	229	92%	CPDR-8	8	10	

Note: kv predictor are limited to range between 50 and 1,000 griffin.

Prediction	Statistic			Details		
	Average	Std Dev	CV	Model	Deflection	Moire
Eac	34	9	26%	CPDR-4	4	
	34	8	23%	CPDR-6	6	
	33	8	24%	CPDR-7	7	
	33	8	26%	CPDR-8	8	
	37	10	28%	CPDR-4	4	
Eacc	38	10	26%	CPDR-6	6	
	34	10	29%	CPDR-7	7	
	30	25	83%	CPDR-8	8	

Note: Strain AC predictor are limited to range between 5 and 200 microstrain.
Note: PCC Strain predictor are limited to range between 10 and 320 psi.

Figure 27. Output statistics summary sheet for composite pavement analysis

SUMMARY

In summary, the following are some of the significant features of the fully-automated ANN-based, user-friendly pavement structural analysis software system:

- A comprehensive pavement structural analysis tool incorporating all three common pavement types (flexible, rigid, and composite)
- Capability of automatically reading the FWD raw data collected by the JILS-20 type FWD machine that Iowa DOT owns
- Integration of all the ANN models developed as part of Phase I research into a comprehensive unified framework
- Rapid backcalculation of pavement layer moduli and prediction of critical pavement responses from FWD data (100,000 deflection basins analyzed in less than a second)
- Useful for both project-level and network-level pavement structural evaluation
- Visualization of results through automatic plotting capability
- Commonly used Import/Export options for transporting data
- Automatic generation of output statistics

REFERENCES

Ceylan, H., Guclu, A., Bayrak, M. B., and Gopalakrishnan, K. 2007. *Nondestructive Evaluation of Iowa Pavements-Phase I*. CTRE Project 04-177, Center for Transportation Research and Education, Iowa State University, Ames, Iowa.