

Improving the Accuracy and Usability of Iowa Falling Weight Deflectometer Data

**Final Report
May 2013**

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract This study aims to improve the accuracy and usability of Iowa Falling Weight Deflectometer (FWD) data by incorporating significant enhancements into the fully-automated software system for rapid processing of the FWD data. These enhancements include: (1) refined prediction of backcalculated pavement layer modulus through deflection basin matching/optimization, (2) temperature correction of backcalculated Hot-Mix Asphalt (HMA) layer modulus, (3) computation of 1993 AASHTO design guide related effective SN (SN_{eff}) and effective k-value (k_{eff}), (4) computation of Iowa DOT asphalt concrete (AC) overlay design related Structural Rating (SR) and k-value (k), and (5) enhancement of user-friendliness of input and output from the software tool. A high-quality, easy-to-use backcalculation software package, referred to as, <i>I-BACK: the Iowa Pavement Backcalculation Software</i> , was developed to achieve the project goals and requirements. This report presents theoretical background behind the incorporated enhancements as well as guidance on the use of I-BACK developed in this study. The developed tool, <i>I-BACK</i> , provides more fine-tuned ANN pavement backcalculation results by implementation of deflection basin matching optimizer for conventional flexible, full-depth, rigid, and composite pavements. Implementation of this tool within Iowa DOT will facilitate accurate pavement structural evaluation and rehabilitation designs for pavement/asset management purposes. This research has also set the framework for the development of a simplified FWD deflection based HMA overlay design procedure which is one of the recommended areas for future research.					
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IMPROVING THE ACCURACY AND USABILITY OF IOWA FALLING WEIGHT DEFLECTOMETER DATA

**Final Report
May 2013**

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EXECUTIVE SUMMARY

Highway agencies periodically evaluate the structural condition of roads as part of their routine maintenance and rehabilitation activities. The falling-weight deflectometer (FWD) test measures road surface deflections resulting from an applied impulse loading, simulative of a truck passing on the highway. The measured surface deflections are utilized to determine pavement layer stiffnesses through a backcalculation type structural analysis.

Although the Iowa Department of Transportation (DOT) has been collecting the FWD data on a regular basis, the pavement layer moduli backcalculation techniques used so far have been cumbersome and time consuming. More efficient and faster methods in FWD test data analysis were deemed necessary for routine analysis.

Previous Iowa DOT research projects focused on developing advanced pavement layer moduli backcalculation models using the artificial neural networks (ANN) methodology. The developed models were successfully validated using field data and incorporated into a Microsoft Excel spreadsheet-based backcalculation software toolbox with a user-friendly interface.

This study was undertaken with the objectives of improving the accuracy and usability of Iowa FWD data and the pavement inverse analysis tools. Based on the requirements by the technical advisory committee (TAC) members representing potential users of the developed backcalculation software system at the Iowa DOT, significant enhancements were incorporated into the fully-automated software system for rapid processing of the FWD data.

These enhancements include the following:

- Refined prediction of pavement layer modulus through deflection basin matching/optimization
- Temperature correction of HMA layer modulus
- Computation of 1993 AASHTO design guide-based effective structural number (SN_{eff}) and effective k-value (k_{eff})
- Computation of Iowa DOT asphalt concrete (AC) overlay design-based structural rating (SR) and k-value (k)
- Enhancement of user-friendliness of input and output from the software tool

A high-quality, easy-to-use, backcalculation software package called Iowa Pavement Backcalculation (I-BACK) software was developed to achieve the project goals and yielded the following highlighted benefits:

- Provides more-fine-tuned ANN pavement backcalculation results by implementation of deflection matching optimizer for conventional flexible, full-depth, rigid, and composite pavements

- Provides temperature normalized/corrected hot-mix asphalt (HMA) layer modulus at a standard reference temperature for conventional flexible, full-depth and composite pavements
- Provides effective SN_{eff} and the effective k-value (k_{eff}) as final outputs for pavement/asset management purposes
- Provides SR and k-value (k) as final outputs to make FWD deflection measurements suitable for use in the existing Iowa DOT AC overlay design procedure
- Produces separate smaller-sized output files from backcalculation analysis
- Produce separate smaller sized output files from backcalculation analysis

INTRODUCTION

Background

Evaluating the structural condition of existing, in-service pavements is 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 further estimate pavement remaining life. Although the Office of Special Investigations at Iowa Department of Transportation (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.

In a previous Iowa DOT project entitled, “Nondestructive Evaluation of Iowa Pavements-Phase I,” advanced backcalculation models were developed using the Artificial Neural Networks (ANN) methodology (Ceylan et al. 2007). These ANN models are capable of predicting pavement layer stiffnesses as well as pavement critical responses (forward modeling) fully based on FWD test results and pavement layer thickness information. 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 HMA/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.

A follow-up Phase II study of Iowa DOT Project (Ceylan et al. 2009) 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 DOTowns, 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.

Objective and Scope

The objective of this study is to incorporate significant enhancements into the developed fully-automated software system for rapid processing of the FWD data. Based on the requirements by the Technical Advisory Committee (TAC) members and engineers who will be using the program on a routine basis, the following enhancements were incorporated into the fully-automated software system, referred to as I-BACK: the Iowa Pavement Backcalculation Software:

- Deflection basin matching: After predicting the pavement layer modulus based on ANN models, adjust them to match the input deflection basin
- Temperature normalization/correction of HMA layer modulus
- Computation of overall pavement section effective Structural Number (SN_{eff}) and subgrade support (k_{eff}) following 1993 AASHTO design guide based procedures
- Computation of Structural Rating (SR) and soil support (k) following Iowa DOT Road Rater based AC Overlay Design Procedure
- Enhancement of user-friendliness of input and output from the software

I-BACK: ENHANCEMENT FEATURES AND MODULES

The I-BACK analysis flow charts are depicted in Figure 1 for flexible pavements (conventional HMA and full depth HMA pavements), Figure 2 for rigid pavements (PCC surface pavements), and Figure 3 for composite pavements (HMA overlaid PCC pavements).

As a first step in the I-BACK analysis, the pre-final pavement layer moduli are calculated from ANN backcalculation models (Ceylan et al. 2007, Ceylan et al. 2009). Then, the pre-final pavement layer moduli are adjusted through a deflection basin optimizer in I-BACK to match the actual measured FWD deflection basin. Note that the backcalculated moduli resulting from deflection basin optimization in I-BACK are moduli at pavement temperature at the time of FWD testing.

In the case of flexible pavement analysis, the temperature normalization routine is then invoked to correct the adjusted HMA moduli from optimizer to a standard reference temperature.

The SN_{eff} values are computed for conventional flexible and full-depth pavements in accordance with the AASHTO design procedure as follows. The temperature normalized HMA moduli are inputted into ANN forward models to produce FWD deflection basin at a standard reference temperature. The predicted FWD deflection basin at the standard reference temperature is then

utilized to compute the overall section SN_{eff} for flexible pavements in accordance with the 1993 AASHTO pavement design procedure (AASHTO 1993).

For rigid pavement analysis, the adjusted subgrade stiffness values from the deflection basin optimizer are utilized to compute effective subgrade support (k_{eff}) in accordance with the 1993 AASHTO design procedure (AASHTO 1993).

For composite pavement (HMA overlaid PCC pavements) analysis, the adjusted HMA moduli from the deflection basin optimizer are corrected to a standard reference temperature through temperature normalization routine similar to flexible pavement analysis. Similar to rigid pavement analysis, the adjusted subgrade stiffness values from the deflection basin optimizer are utilized to compute k_{eff} values in accordance with the 1993 AASHTO design procedure (AASHTO 1993).

The SR and k values are also computed for all three types of pavement in accordance with Iowa DOT Road Rater based AC overlay design procedure.

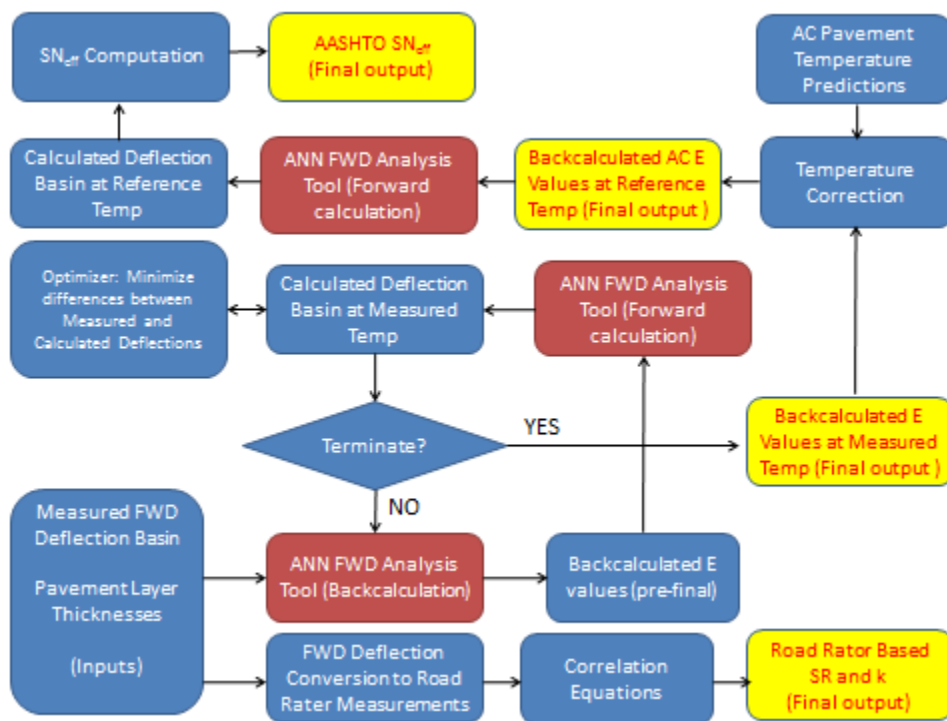


Figure 1. I-BACK analysis flow chart for flexible pavement

Deflection Basin Matching

Deflection basin matching provides a fool-proof method to validate the ANN-based backcalculation results since the predicted pavement layer moduli are optimized or fine-tuned to obtain a very close match between the actual FWD and predicted deflections. The pre final-pavement layer moduli from ANN backcalculation models are inputted into the ANN forward

models to predict the deflection basin and compare how closely the predicted deflection basin matches the measured deflection basin. The differences between the field measured and predicted deflection basins are minimized by adapting the in-built Excel Solver tool (employing evolutionary optimization or GRG Nonlinear optimization) in I-BACK. Thus, the robustness of I-BACK predictions has been greatly improved by incorporating the deflection basin matching/optimization routine.

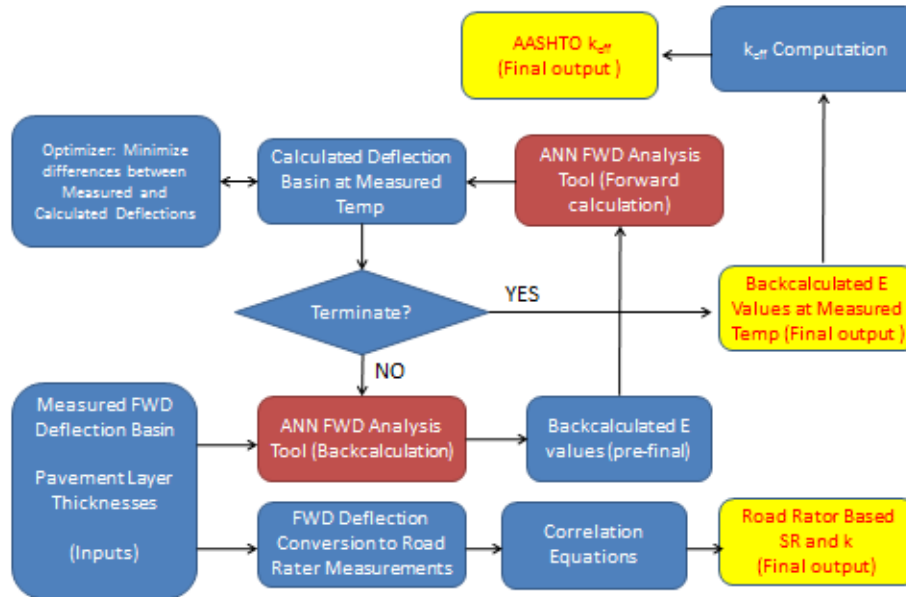


Figure 2. I-BACK analysis flow chart for rigid pavement

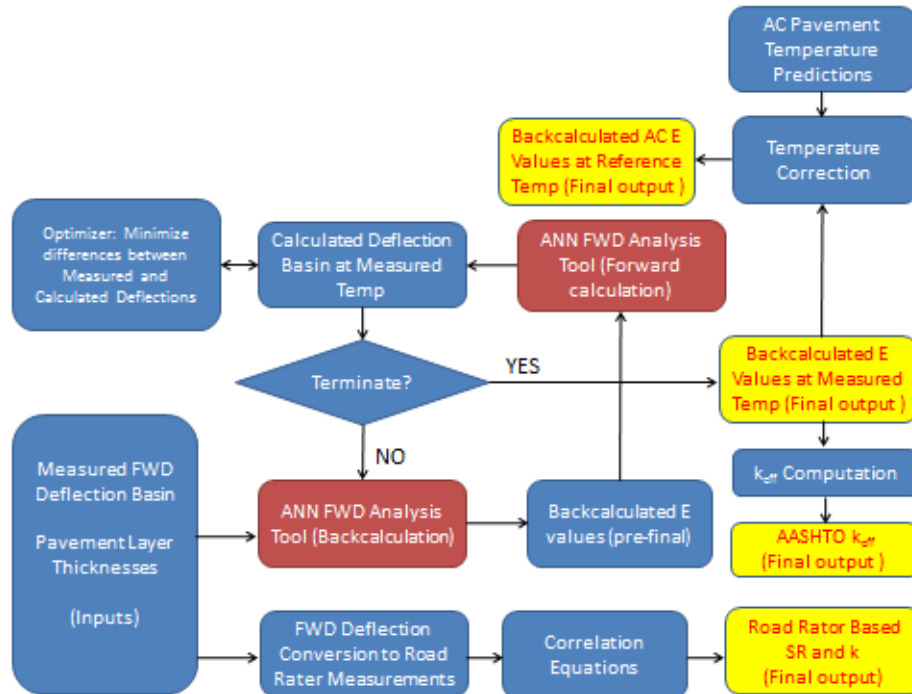


Figure 3. I-BACK analysis flow chart for composite pavement (HMA overlaid PCC pavement)

Temperature Normalization for HMA Modulus

The stiffness, or modulus, of HMA is very temperature-sensitive. The temperature normalization routine was incorporated into I-BACK in close consultation with the TAC in order to correct the backcalculated HMA moduli to a standard reference temperature for the section being analyzed. The incorporated temperature normalization routine consists of: (1) HMA pavement temperature estimation and (2) temperature correction algorithm for HMA modulus.

Prediction of HMA Pavement Temperature

Before correction of the backcalculated HMA moduli to a standard reference temperature, the mid-depth pavement temperature at which FWD deflections were taken should be identified. The direct measurement of this temperature requires the time-consuming process of installation of temperature probe in depth of pavement. Alternatively, this temperature may be estimated from approximate methods based on air and surface temperatures measured at the time of FWD testing. Lukanen et al. (2000) developed a set of equations called as BELLS models for predicting in-depth pavement temperatures in LTPP testing based on empirical data. Among these equations, the BELLS3 model accounts for shaded condition of pavement surface under routine testing conducted by most highway agencies. The BELLS3 model employed in temperature normalization routine is expressed as follows:

$$T_d = 0.95 + 0.892 \times IR + \{\log(d) - 1.25\}\{-0.448 \times IR + 0.621 * (1 - day) + 1.83 \times \sin(hr_{18} - 15.5)\} + 0.042 \times IR \times \sin(hr_{18} - 13.5) \quad (1)$$

Where:

T_d = Pavement temperature at depth d in °C

IR = Infrared surface temperature measured at the time of FWD testing in °C

Log = Base 10 logarithm

d = Depth at which mat temperature is to be predicted, mm

1-day = Average air temperature the day before testing

sin = Sine function on an 18-hr clock system, with 2 radians equal to one 18-hr cycle

hr_{18} = Time of day, in 24-hr clock system, but calculated using an 18-hr asphalt concrete (AC) temperature rise and fall time cycle

Temperature Correction for HMA Modulus

Several equations (Ullidtz 1987, Baltzer and Jansen 1994, Deacon et al. 1994, Noureldin 1994, Kim et al. 1995, Ali and Lopez 1996, Lukanen et al. 2000, Chen et al., 2000) have been proposed relating the HMA modulus to a standard reference temperature. However, different values of standard reference temperature are found in literature for HMA modulus characterization. The commonly used standard reference temperatures are 68°F in AASHTO 1993 design procedure (AASHTO 1993), 70 °F in AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO 2008) and Pavement ME (formerly, DARWin-ME) (AASHTO 2012), 77 °F in some previous studies (Noureldin 1994). Among them, the temperature correction equation developed by Chen et al (2000) using Texas Mobile Load Simulator (MLS) data is the only available model with the flexibility to normalize to any reference temperature with good accuracy. Considering this advantage, it was incorporated into the temperature normalization routine in I-BACK:

$$E_{T_w} = E_{T_c} / [(1.8T_w + 32)^{2.4462} * (1.8T_c + 32)^{-2.4462}] \quad (2)$$

Where:

E_{T_w} = the adjusted modulus of elasticity at T_w , MPa

E_{T_c} = the adjusted modulus of elasticity at T_c , MPa

T_w = the temperature to which the modulus of elasticity is adjusted, °C

T_c = the mid-depth temperature at the time of FWD data collection, °C

Although a standard reference temperature of 68°F is utilized in the current implementation of I-BACK, the temperature correction equation proposed by Chen et al. (2000) could be easily adapted later for any reference temperature, should a need arise.

Computation of Effective Structural Number (SN) and Subgrade Support (k-value): AASHTO Pre ME-Design Approach

The concept of SN_{eff} is typically used for evaluating the overall structural condition of flexible pavements. Similarly, the k_{eff} is used for determining the subgrade support for PCC rigid pavement and composite pavement analysis. Typically, when the ratio of SN_{eff} to as-built SN based on in-place pavement structure falls below 90%, the evaluated section is recommended for structural improvement. The AASHTO 1993 design procedure (AASHTO 1993) outlines a method for calculation of SN_{eff} and the k_{eff} using the measured deflection data. The SN_{eff} and the k_{eff} equations in the AASHTO 1993 design procedure (AASHTO 1993) are expressed as follows:

$$SN_{eff} = 0.0045D^3\sqrt{E_p} \quad (3)$$

$$k_{eff} = k_{dynamic}/2 \quad (4)$$

Where:

D = total pavement thickness, inch

E_p = effective modulus of pavement layers, psi

$k_{dynamic}$ = effective dynamic modulus of pavement layers calculated from deflection basin, psi

Following the AASHTO 1993 design procedure, the pseudo-codes and algorithms for implementing the computation of these two parameters (SN_{eff} and k_{eff}) in I-BACK were developed. First, the deflection basin at the reference temperature is computed using the temperature normalized AC modulus and the ANN forward models. Next, the computed deflection at the center of the load plate (d_0) is related to the effective modulus of pavement layers (E_p), subgrade resilient modulus (M_R) and other parameters as shown in the following equation:

$$d_0 = 1.5pa \left\{ \frac{1}{M_R \sqrt{1 + \left(\frac{D^3 \sqrt{E_p}}{a \sqrt{M_R}} \right)^2}} + \frac{\left[1 - \frac{1}{\sqrt{1 + \left(\frac{D}{a} \right)^2}} \right]}{E_p} \right\} \quad (5)$$

Where:

d_0 = deflection measured at the center of the load plate (inch) at the reference temperature (68°F)

p = load pressure, psi

a = load plate radius, inch

The unknown E_p value required in the SN_{eff} computation (See equation 3) is determined in I-BACK by again employing the in-built Excel Solver Tool. Unlike SN_{eff} computation for AC surfaced pavements, the k_{eff} computation for rigid pavements and composite pavements is quite

straightforward. The backcalculated k-values ($k_{dynamic}$) are inputted into equation 4 to obtain k_{eff} values.

Computation of Structural Rating (SR) and Soil Support (k-value): Iowa DOT AC Overlay Design Procedure Using Road Rater Deflection Measurements

The Iowa DOT has developed an AC overlay design procedure for existing flexible, rigid and composite pavements using the Road Rater measurements (Heins 1979, Marks 1983, Potter and Dirks 1986, Potter and Dirks 1989). This overlay design procedure was patterned closely after the 1993 AASHTO design procedures. For the Iowa DOT AC overlay design procedure, the concept of SR as the estimated AASHTO SN was developed to characterize present structural condition of existing pavement. The SR was graphically related to average Road Rater sensor No. 1 deflection (d_0) value to determine SR from Road Rater deflection measurement.

In addition to SR, the Iowa DOT AC overlay design procedure also adapted soil support k-value to estimate existing subgrade soil support condition. The base relationship chart for soil support k-value for flexible, rigid and composite pavements was developed by relating soil support k-values with Road Rater deflection measurements.

Correlation of Road Rater Deflection Measurements to FWD Deflection Measurements

In the past, the Iowa DOT used the Road Rater based measurements for AC overlay design procedures, pavement management system, and research evaluations. However, with the acquisition of FWD by the Iowa DOT Office of Special Investigations, the use of Road Rater was abandoned. Consequently, the FWD deflection measurements were correlated to Road Rater deflection measurements to continue the use of AC overlay design procedure (Jones and Hanson 1991). Figure 4 displays the developed linear correlation equations between FWD and Road Rater deflection measurements along with the model coefficients. These correlation equations (Figure 4) were incorporated into the I-BACK computation algorithms to convert the measured FWD deflection measurements into Road Rater deflection measurements.

$$\text{FWD} = x \times (\text{R.R.}) + C$$

	PCC Sections				Composite Sections				AC Sections			
	X	C	r ²	Std. Error	X	C	r ²	Std. Error	X	C	r ²	Std. Error
Sensor 1	3.745	0.83	0.92	0.62	4.890	0.83	0.96	1.11	11.830	-3.89	0.92	4.23
Sensor 2	3.822	0.67	0.91	0.60	4.034	0.64	0.99	0.35	8.918	-1.30	0.96	1.07
Sensor 3	3.850	0.63	0.90	0.53	3.803	0.86	0.98	0.41	7.622	-0.51	0.96	0.52
Sensor 4	4.056	0.48	0.91	0.39	3.816	0.86	0.96	0.41	6.116	0.189	0.92	0.35

Figure 4. Generalized linear correlation equation with coefficients between FWD and Road Rater deflection measurements; Note. sensor 1 deflection (d₀), sensor 2 deflection (d₁₂), sensor 3 deflection (d₂₄), and sensor 4 deflection (d₃₆) (adapted from Jones and Hanson 1991)

Determination of SR for Flexible Pavement

Figure 5 presents flexible pavement base relationship chart to determine SR from Road Rater d₀ corrected to 80°F. The Road Rater d₀ at testing temperature were corrected to 80°F. A nomograph, as shown in Figure 6, was developed to correct the Road Rater d₀ at testing temperature to 80°F and then use it to compute SR.

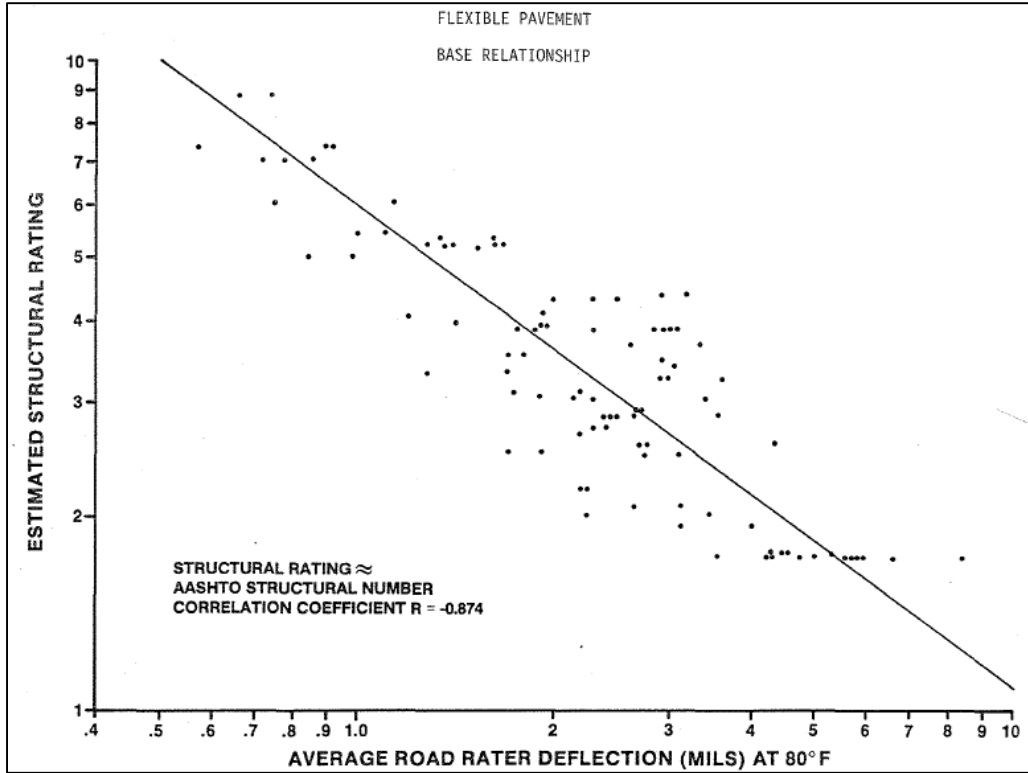


Figure 5. Flexible pavement base relationship between SR and Road Rater D_0 at 80°F (adapted from Potter and Dirks 1989)

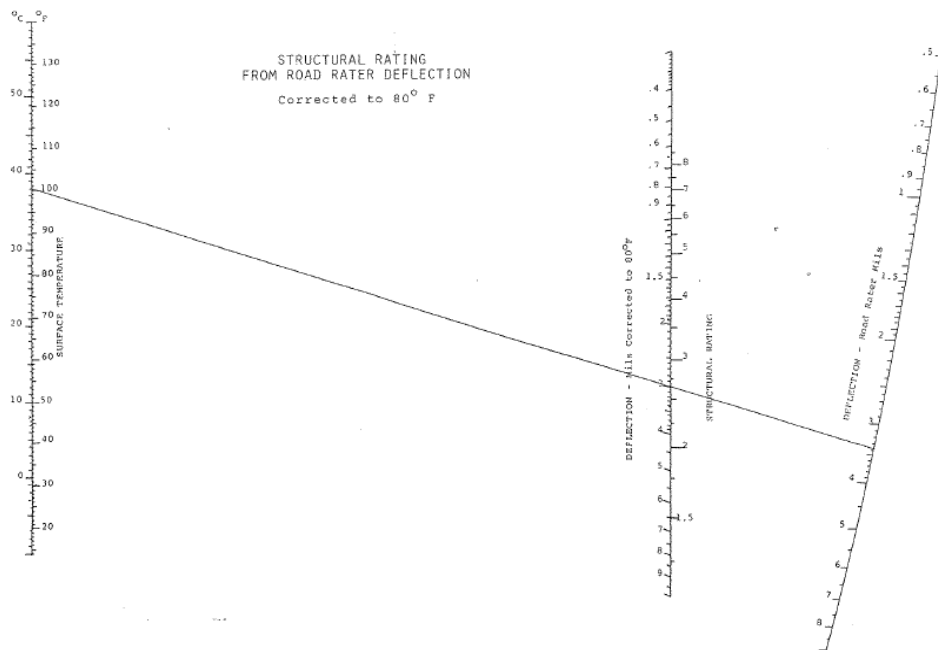


Figure 6. Flexible pavement SR determination nomograph (adapted from Potter and Dirks 1989)

To incorporate flexible pavement SR determination from nomograph and chart into I-BACK computation algorithms, a synthetic database was developed from chart in Figure 5 and nomograph from Figure 6. By using this synthetic database, two correlation equations were developed. These equations are Road Rater d_0 temperature correction equation and SR determination equation expressed as follows

$$y = (1.3804 - 0.0046T)x + 1.2592 - 0.296 \times \ln(T) \quad (6)$$

Where:

- y = Road Rater d_0 corrected to 80°F, mils
- x = Road Rater d_0 at testing temperature, mils
- T = Temperature, °F

$$\log_{10}y = -0.74171 \times \log_{10}x + 0.7831 \quad (7)$$

Where:

- y = SR at 80°F
- x = Road Rater d_0 corrected to 80°F, mils

Figure 7 and Figure 8 compare Road Rater D_0 at 80°F and SR determined from the nomograph (see Figure 6) and the developed equations. The data not used in equation development were randomly selected and used in these comparisons. As seen in these figures, the developed equations provide good estimations of both Road Rater D_0 at 80°F and SR determined from nomograph.

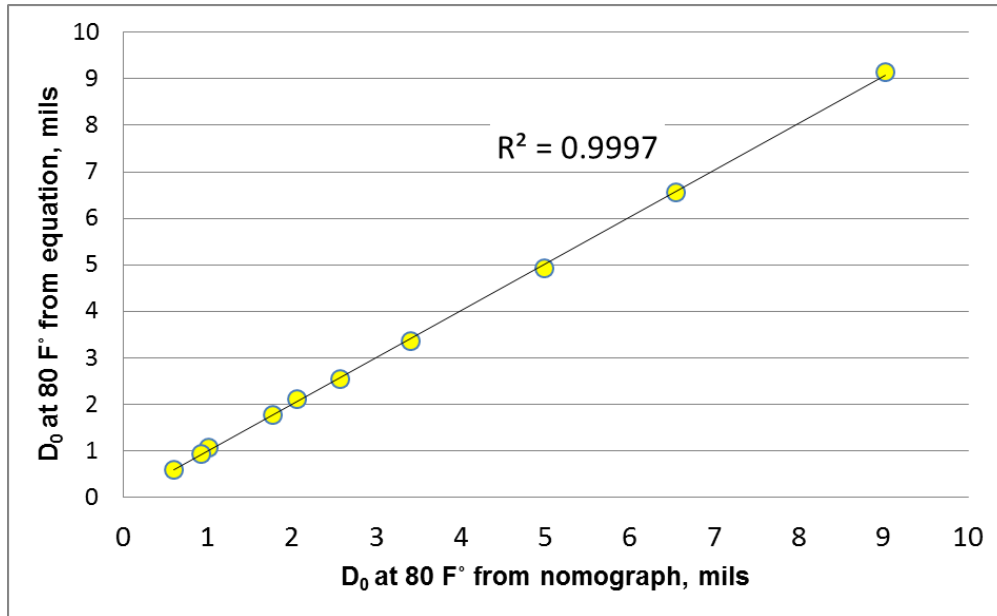


Figure 7. Road Rater D_0 temperature correction for flexible pavement: nomograph versus equation

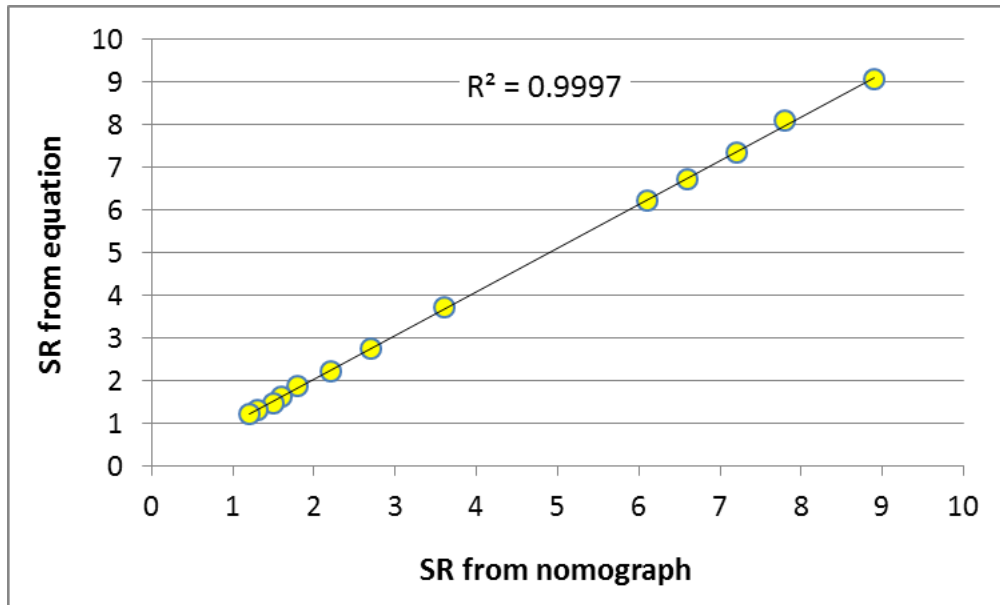


Figure 8. SR determination for flexible pavement: nomograph versus equation

Determination of SR for Rigid and Composite Pavements

Figure 9 presents the rigid and composite base relationship chart to determine SR from Road Rater d_0 in Iowa DOT AC overlay design procedure. No temperature correction is applied to d_0 for both of rigid and composite pavements. However, for composite pavement, temperature correction to 70°F is applied to SR at testing temperature. Similar to the development of SR prediction equation for flexible pavement, a correlation equation between SR and Road Rater d_0 was developed using synthetic database derived from chart in Figure 9. The chart based rigid and composite pavement SR determination procedures were then incorporated into the I-BACK computation algorithms. The developed correlation equation is expressed as follows:

$$\log_{10}y = -0.81779 \times \log_{10}x + 0.72032 \tag{8}$$

Where:

y = SR at testing temperature

x = Road Rater d_0 at testing temperature, mils

Figure 10 compares SR determined from the rigid and composite pavement base relationship chart (see Figure 9) and the developed equations using randomly selected data not used in equation development. As seen in this figure, the developed equation provides good SR estimations for rigid and composite pavements.

of SR (Potter and Dirks 1989) for composite pavement expressed below has been incorporated into I-BACK computation algorithm.

$$\text{Temp. Corrected SR} = \text{Non - Temp Corrected SR} + (70 \text{ }^\circ\text{F} - \text{Pave .Temp}) \times (-0.0145) \quad (9)$$

Determination of k-value for Flexible, Rigid and Composite Pavements

Figure 11 presents soil support k-value relationship charts for flexible pavement and Figure 12 presents soil support k-value relationship charts for rigid and composite pavements. The base relationship charts for soil support k-value used in Iowa DOT AC overlay design procedure graphically relate soil support k-values with average Road Rater d_0 values and the ratio of Surface Curvature Index (SCI) values to Road Rater d_0 values (SCI/ d_0). SCI is defined as the difference in mils between Road Rater Sensor No. 1 (d_0) and Sensor No. 2 (d_{12}).

Similar to the development of SR determination equations described previously, the correlation equations for subgrade support k-values were developed using synthetic database derived from charts shown in Figure 11 and Figure 12. The developed equations were then incorporated into I-BACK computation algorithms. The developed correlation equations are expressed as follows:

$$k = 456.52y^2 - 68.295xy + 2.554x^2 + 421.04y - 31.494x + 80.628 \quad (10)$$

Where:

- k = modulus of subgrade reaction for flexible pavement, psi/inch
- y = SCI/Road Rater d_0
- x = Road Rater d_0 , mils

$$k = -2967.2y^2 + 561.988xy - 26.61x^2 + 751.01y - 71.271x + 176.76 \quad (11)$$

Where:

- k = modulus of subgrade reaction for rigid and composite pavements, psi/inch
- y = SCI/Road Rater d_0
- x = Road Rater d_0 , mils

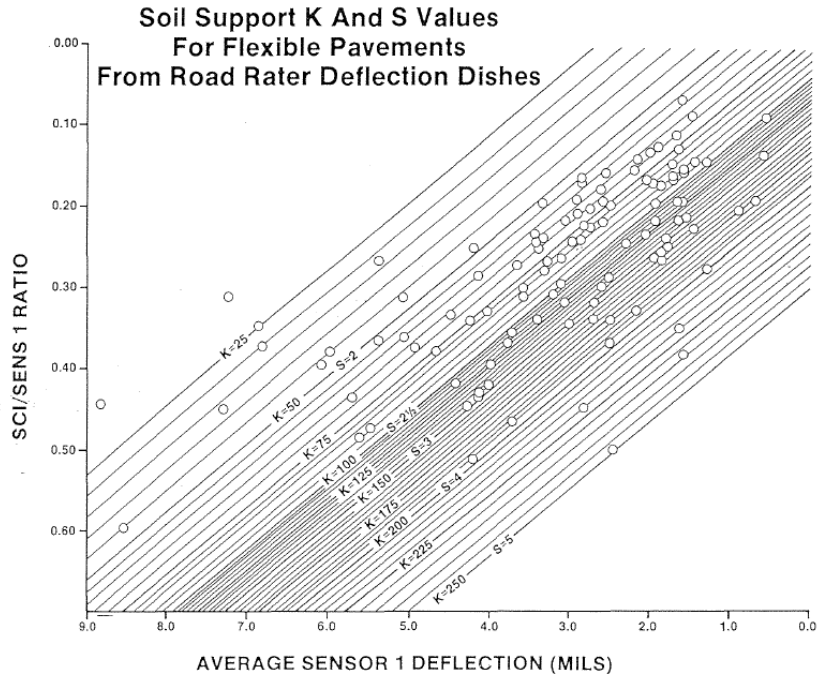


Figure 11. Flexible pavement base relationship for soil support k-value determination (adapted from Potter and Dirks 1989)

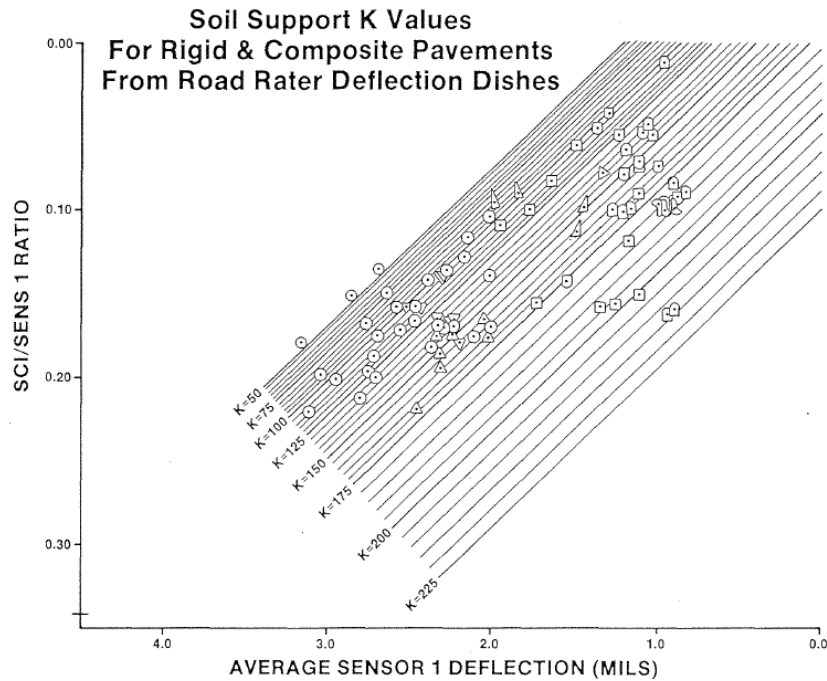


Figure 12. Rigid and composite pavement base relationship for soil support k-value determination (adapted from Potter and Dirks 1989)

Figure 13 compares k-values determined from the flexible pavement k-value base relationship chart and the developed equations using randomly selected data not used in equation

development. Figure 14 displays similar comparison for rigid and composite pavements. As seen in these figures, the developed equations provide good k-value estimates for both the flexible and rigid/composite pavements.

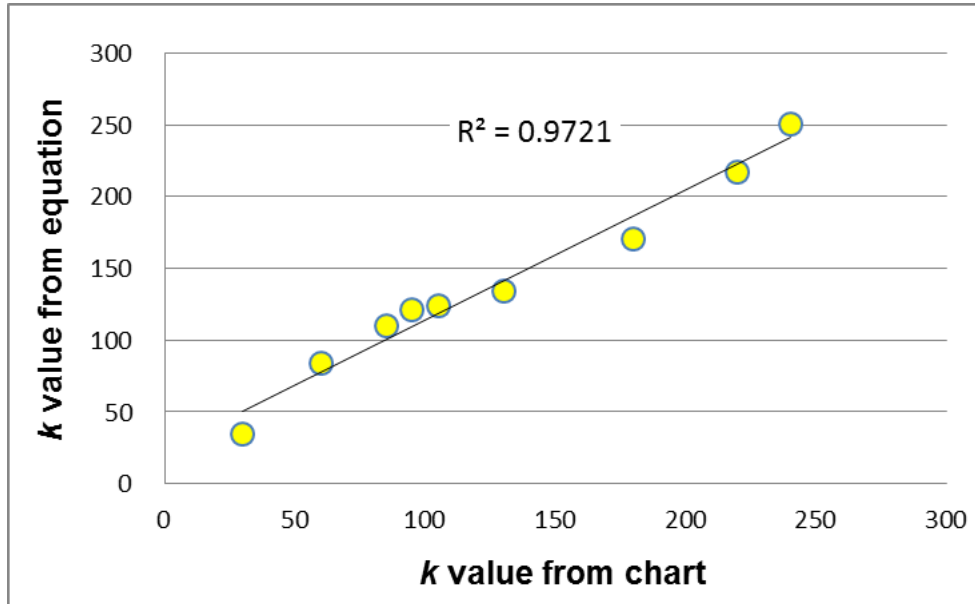


Figure 13. k-value determination for flexible pavement: chart versus equation

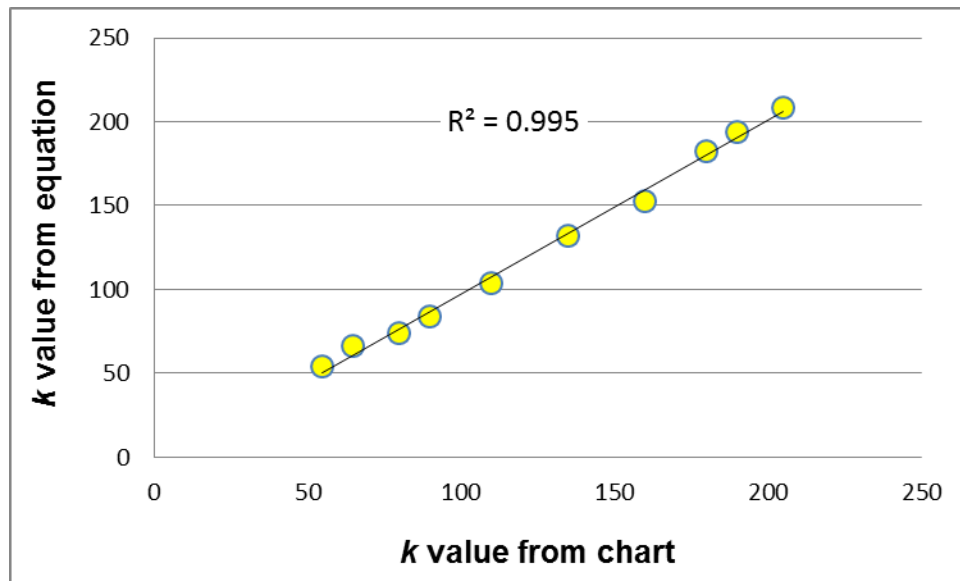


Figure 14. k-value determination for rigid and composite pavements: chart versus equation

I-BACK USER MANUAL

The password-protected, Excel Spreadsheet based I-BACK was developed by writing Macros using Microsoft's Visual Basic for Applications (VBA) programming language. In case of troubleshooting, the user is requested to change the macro security (Tools → Macro → Security) to the “medium” or “low” level to allow the macros to run. I-BACK provides user interaction for data editing and pasting, and all other functionalities available in Excel. The Excel sheets in I-BACK include a main menu and analysis menu (for each pavement type) for recording inputs and displaying the results of analysis. The input and output space is divided by a control button with command buttons in each of the analysis spreadsheets. I-BACK also generates an output file in CSV format at the completion of analysis in the same folder where the software tool is saved.

Program Main Menus

I-BACK starts by displaying the main menu (Figure 15). As a first step, users are expected to select the pavement type (conventional, full-depth flexible, rigid or composite 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 loadings. The software toolbox is programmed to give warning messages if the user the 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.

The ANN information illustrated in Figure 16 provides the user the general information on ANN models employed. By clicking “ANN info show” button as shown in Figure 16(a), six Excel sheets as shown in Figure 16(b) are created. Each of Excel sheets as shown in Figure 16(c) contains the ANN model information such as the ranges of the data used for ANN model development. These Excel sheets can be hidden by choosing “ANN info hide”.

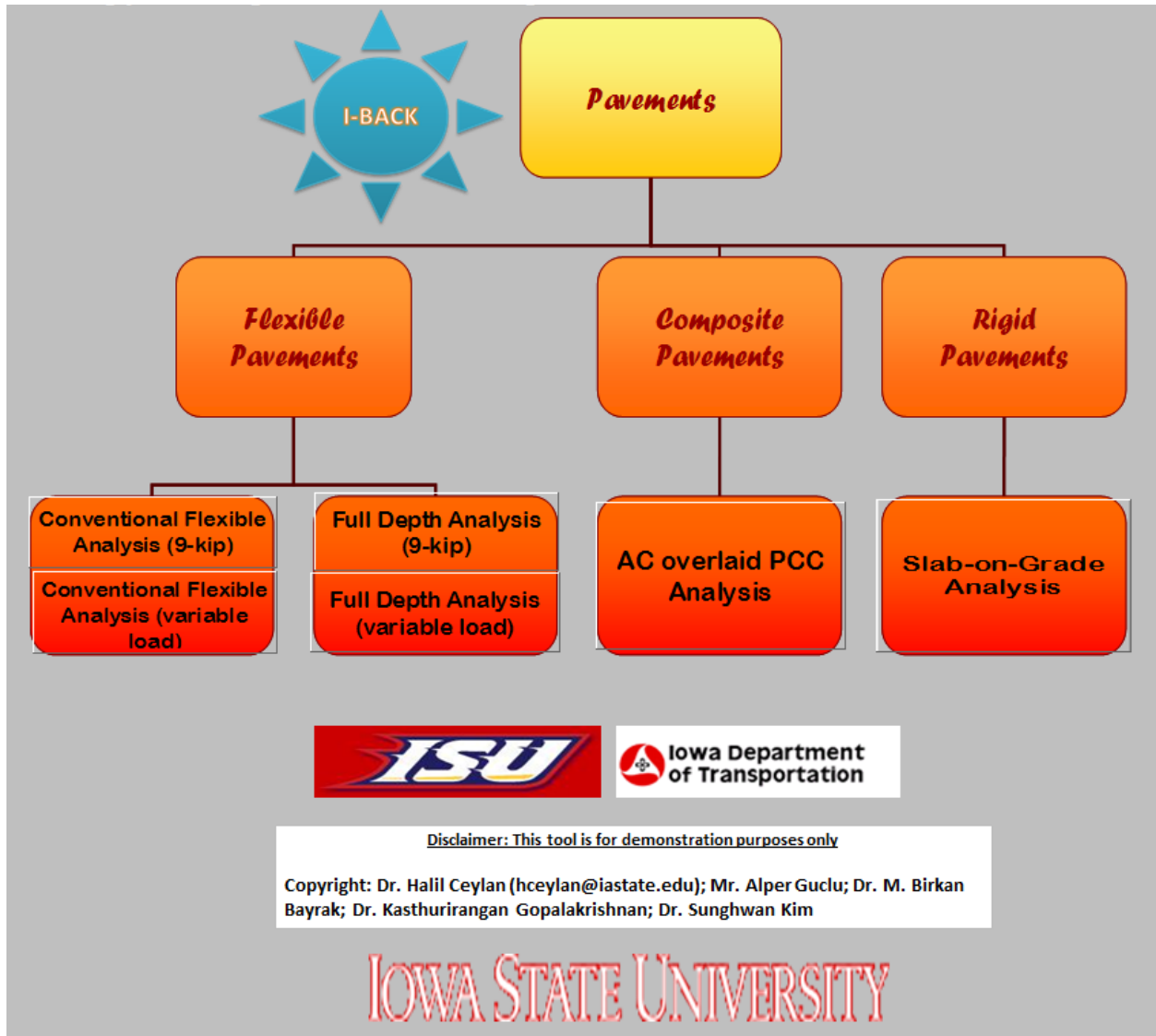
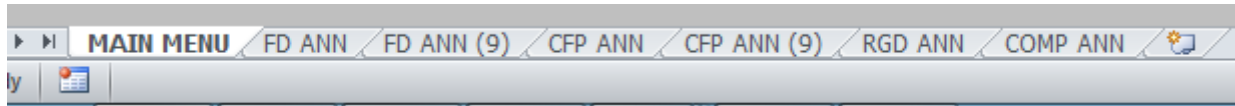


Figure 15. I-BACK program main menu



(a)



(b)

	8 Deflections-Eac	8 Deflections-Eri	FC -eac-esg-sd	FC -eac-esg-sd	FC -eac-esg-sd
Deflection	8	8	8	8	8
Def-Min	0.2726414	0.2726414	0.2726414	0.4353061	0.4353061
Def-Max	116.2279	116.2279	116.2279	66.97756	66.97756
Hac-Min	3	3	3	3	3
Hac-Max	28	28	28	28	28
Load-Min	44	44	44	44	44
Load-Max	186	186	186	186	186
E-Min	100000	1000	1.195304	3.645302	0.315
E-Max	6000000	15000	1675.833	6035.573	45.2
WeightFile	4381	4381	4503	4503	4503
	0%	0%	8 def	8 def	8 def
1	9.38E-02	3.47E-01	-1.65E-01	-1.65E-01	-1.65E-01
2	-1.674708	-4.21E-01	1.73E-01	1.73E-01	1.73E-01
3	-1.461965	-1.043324	-7.69E-01	-7.69E-01	-7.69E-01
4	-1.522861	-1.307949	-1.06E+00	-1.06E+00	-1.06E+00
5	-1.01715	-1.022498	-6.69E-01	-6.69E-01	-6.69E-01
6	-6.56E-01	-9.21E-01	-4.13E-01	-4.13E-01	-4.13E-01
7	1.118753	2.40E-01	9.72E-01	9.72E-01	9.72E-01
8	1.503013	1.35E-02	8.73E-01	8.73E-01	8.73E-01
9	1.060284	-9.88E-01	-5.07E-02	-5.07E-02	-5.07E-02
10	-8.58E-01	-7.17E-01	-3.87E-01	-3.87E-01	-3.87E-01
11	2.711796	5.81E-01	7.73E-01	7.73E-01	7.73E-01
12	7.708158	60.88257	1.15E+00	1.15E+00	1.15E+00
13	-2.646723	-28.36716	-5.30E-01	-5.30E-01	-5.30E-01
14	1.50E-01	-9.888139	-4.42E-02	-4.42E-02	-4.42E-02
15	1.120319	-3.309855	1.95E-01	1.95E-01	1.95E-01
16	2.319184	3.983927	8.38E-01	8.38E-01	8.38E-01
17	1.77153	8.486038	6.29E-02	6.29E-02	6.29E-02
18	1.810938	16.54343	2.38E-01	2.38E-01	2.38E-01
19	1.567331	21.72925	6.65E-01	6.65E-01	6.65E-01

(c)

Figure 16. ANN Information: (a) ANN Information button in main menu, (b) Screenshot of main menu on choosing ANN info show option, (c) Sample Excel sheet for ANN model information

Pavement Analysis Menus

Pavement analysis menu consist of three main parts: inputs, analysis tool, and outputs. The user can provides the software with the information required for analysis in the inputs part of

pavement analysis menu. The analysis tool allows user processing data and executing analysis with several functions. The results of analysis are provided in the output part of pavement analysis menu.

Figure 17 illustrates the conventional flexible pavement analysis menu of I-BACK as a typical layout example. The analysis tool for all pavement types has four button functions, “Run”, “Filter”, “Open FWD data file” and “Main Menu”. The analysis tool for rigid pavements has additional submenus of “Equation.” The detail descriptions of these button functions are presented in the following subsection. Table 1 summarizes key inputs required and outputs produced through I-BACK.

Location	Pav. Surfaces (in.)								Asphalt Concrete (AC) Thickness (in.)	Gravel Base Thickness (in.)	Pav. Load (kip)	I-BACK	AC Modulus, Eac (ksi) - Actual Temp	Subgrade Modulus, Es (ksi) - Actual Temp	Gravel Base Modulus, Eb (ksi) - Actual Temp	Depth (in) @ Top of AC	Depth (in) @ Top of Subgrade - Actual Temp	Interface Stress (ksi) @ Top of Subgrade - Actual Temp
	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Sub 8										
1	4.32	4.33	4.43	4.43	4.78	3.78	3.07	2.50	9.00	9.00	9.00	0	5,281.93	1,029	3,000	9	19	0
2	4.37	3.98	3.62	3.69	3.92	3.27	2.80	2.42	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
3	3.97	3.74	3.62	3.49	3.22				9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
4	3.90	3.98	3.70	3.63	3.33				9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
5	3.70	3.62	3.49	3.18	3.18				9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
6	3.92	3.43	3.32	3.18	3.00				9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
7	4.28	4.18	3.97	3.78	3.52	3.28	2.47	2.04	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
8	4.18	4.02	3.94	3.94	3.42	2.97	2.41	1.90	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
9	3.98	3.94	3.67	3.48	3.25	2.82	2.29	1.84	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
10	3.98	3.97	3.40	3.20	2.99	2.64	2.23	1.91	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
11	3.98	3.98	3.37	3.17	2.94	2.58	2.18	1.80	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
12	3.42	3.19	2.89	2.78	2.58	2.22	1.89	1.60	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
13	4.17	4.17	3.90	3.73	3.52	3.08	2.57	2.02	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
14	3.97	3.98	3.69	3.52	3.28	2.84	2.38	1.92	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
15	3.72	3.94	3.48	3.32	3.11	2.71	2.22	1.87	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	23	0
16	3.27	3.28	3.17	3.07	2.98	2.71	2.38	2.02	9.00	9.00	9.00	0	6,000.000	1,000	3,000	7	7	0
17	3.12	3.10	3.09	2.92	2.81	2.58	2.22	1.83	9.00	9.00	9.00	0	6,000.000	1,000	3,000	7	9	0
18	2.98	2.98	2.87	2.79	2.67	2.44	2.12	1.83	9.00	9.00	9.00	0	6,000.000	1,000	3,000	7	10	0
19	3.97	3.78	3.62	3.46	3.28	2.92	2.47	2.08	9.00	9.00	9.00	0	6,000.000	1,000	3,000	12	28	0
20	3.94	3.93	3.41	3.25	3.07	2.74	2.32	1.92	9.00	9.00	9.00	0	6,000.000	1,000	3,000	12	28	0
21	3.94	3.43	3.30	3.18	2.98	2.67	2.28	1.88	9.00	9.00	9.00	0	6,000.000	1,000	3,000	12	28	0
22	3.25	3.18	3.09	2.97	2.88	2.67	2.30	2.0	9.00	9.00	9.00	0	6,000.000	1,000	3,000	8	34	0
23	3.17	3.08	2.97	2.88	2.78	2.57	2.22	1.94	9.00	9.00	9.00	0	6,000.000	1,000	3,000	7	16	0
24	3.07	2.94	2.85	2.74	2.63	2.47	2.13	1.84	9.00	9.00	9.00	0	6,000.000	1,000	3,000	8	23	0
25	4.30	4.21	4.04	3.82	3.60	3.18	2.68	2.18	9.00	9.00	9.00	0	6,362.278	3,729	3,000	9	23	1
26	4.18	4.07	3.90	3.72	3.49	3.07	2.52	2.07	9.00	9.00	9.00	0	6,662.718	2,428	3,000	14	23	1
27	4.04	3.94	3.78	3.60	3.38	2.98	2.45	2.00	9.00	9.00	9.00	0	5,764.478	2,048	3,000	14	23	1
28	4.32	4.03	4.03	4.43	4.78	3.78	3.07	2.50	9.00	9.00	9.00	0	5,281.93	1,029	3,000	9	19	0
29	4.08	4.00	4.41	4.31	3.98	3.50	2.98	2.38	9.00	9.00	9.00	0	5,334.452	1,477	3,000	9	20	0
30	4.00	4.29	4.20	4.01	3.78	3.32	2.75	2.23	9.00	9.00	9.00	0	5,334.452	1,477	3,000	9	20	0
31	3.93	3.44	3.32	3.14	3.00	2.67	2.25	1.89	9.00	9.00	9.00	0	6,000.000	1,000	3,000	9	24	1
32	3.98	3.28	3.18	3.02	2.84	2.58	2.18	1.80	9.00	9.00	9.00	0	6,000.000	2,760	3,000	9	27	1
33	3.12	3.18	3.03	2.89	2.73	2.40	2.07	1.70	9.00	9.00	9.00	0	6,000.000	2,229	3,000	9	28	1
34	3.92	3.98	3.27	3.08	2.90	2.61	2.28	2.00	9.00	9.00	9.00	0	6,000.000	1,000	3,000	10	13	1
35	3.43	3.28	3.17	2.94	2.80	2.52	2.18	1.80	9.00	9.00	9.00	0	6,000.000	1,000	3,000	10	11	1
36	3.30	3.12	2.98	2.80	2.60	2.40	2.08	1.80	9.00	9.00	9.00	0	6,000.000	1,200	3,000	12	17	1
37	4.08	4.00	4.44	4.28	4.03	3.71	3.18	2.71	9.00	9.00	9.00	0	6,000.000	1,000	3,000	12	17	0

Figure 17. I-BACK pavement analyses menu for conventional flexible pavement analysis

Table 1. Key required inputs and outputs produced by I-BACK

Type	Inputs	Outputs
Flexible (conventional /full depth)	<ul style="list-style-type: none"> • FWD loads applied and deflection measurements • Pavement layer thicknesses 	<ul style="list-style-type: none"> • E_{AC}-modulus of HMA or AC, K_b-base modulus parameter, and E_{Ri}-subgrade resilient modulus at actual FWD testing temperature • E_{AC} at reference temperature • SN_{eff} - effective SN • Road Rater based SR and k
Rigid	<ul style="list-style-type: none"> • FWD loads applied and deflection measurements • Pavement layer thicknesses 	<ul style="list-style-type: none"> • E_{PCC}-modulus of PCC and k_s-coefficient of subgrade reaction • k_{eff} - effective k-value • Road Rater based SR and k
Composite	<ul style="list-style-type: none"> • FWD loads applied and deflection measurements • Pavement layer thicknesses 	<ul style="list-style-type: none"> • E_{AC}, E_{PCC}, and k_s at actual FWD testing temperature • E_{AC} at reference temperature • k_{eff} • Road Rater based SR and k

General Information Inputs

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 18). The information required in this window are project name, project location, FWD testing date, time, and temperature conditions of air and pavement surface. The user is required to fill in the information to continue with pavement analysis. Note that the Time, Infrared (IR) temperature at the time of FWD testing and previous day air temperature are required inputs for carrying out temperature correction of AC modulus and subsequent SN_{eff} computations.

The screenshot shows a 'General Information' dialog box with an orange background. It contains the following fields and their placeholder text:

- Project Name: Project Name
- Project Location: Project Location
- Date: Date
- Comments: Comments
- Time (HH.MM): Time (ex. 9.50, 14.30, 15.26)
- IR Temperature (F): Pavement Surface Temperature
- Prev. Day Air Temperature (F): Prev. Day Air Temperature

A 'Continue' button is located at the bottom center of the dialog box.

Figure 18. General information window

FWD Deflection Database and Inputs

At the next step, users are expected to enter the FWD deflection database and inputs for the I-BACK program. Required analysis parameters are deflection data, pavement layer information (layer thicknesses), and FWD load (for variable FWD load analysis). Depending on pavement type, the number of layers can be changed. If any of the required parameter is missing, the program will display an error message “No Data” in the results section. Clicking the “Main Menu” button allows the user to go back to I-BACK program main menu for selection of the pavement type.

The input requirements for conducting conventional flexible pavement analyses are FWD deflection data, asphalt concrete thicknesses, granular base thickness, and FWD load. The input requirements for conducting full depth asphalt pavement analyses are same as conventional flexible pavement analyses except not requiring granular base thickness.

Required input parameters for rigid pavement analysis are deflection data, PCC layer thickness, granular base thickness, degree of bonding, and estimated moduli ratio (E_{base}/E_{PCC}), and FWD load. To simplify the ANN-based backcalculation methodology, PCC layer and base layer thickness are adjusted into only one thickness value, effective PCC thickness, in the program

(Ceylan et al, 2007). During analysis, the effective PCC thickness is automatically calculated from pavement layer information (PCC layer thickness, granular base thickness, degree of bonding, and estimated moduli ratio) and used in backcalculation analysis. The clicking “Equation” button in rigid pavement analysis tool menu provides the equations sheet as shown in Figure 19. This equations sheet summarized the equations used for calculation of effective PCC thickness for fully bonded PCC layers, unbonded PCC layers and partially bonded PCC layers.

Effective thickness for fully bonded PCC layers as:

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

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

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:

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

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

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_{we} = 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

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

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

Figure 19. Screen shot of effective PCC thickness equations sheet

Required input parameters for composite pavement analysis are deflection data, pavement layer information (layer thicknesses, estimated PCC modulus, estimated coefficient of subgrade reaction), and FWD load.

The default units used in the program are based on 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 these input parameters are not in the desired ranges. The user is requested to refer to the report for the appropriate ranges of these parameters.

Users can enter the FWD deflection database manually or obtain those directly from the JILS-20 type FWD raw data files clicking “obtain FWD file data file”. The “obtain FWD file data file” allows the user load the FWD raw data files and extract the FWD deflections required into the program as shown in Figure 20. Based on FWD loads of deflections, the program allows two types of flexible pavement analysis; 9-kip-constant FWD load analysis and variable FWD load analysis. The 9-kip-constant FWD load analysis uses the FWD deflection data normalized to 9

kip-constant FWD load. The variable FWD load analysis uses the raw FWD deflection data corresponding to the raw FWD loads.

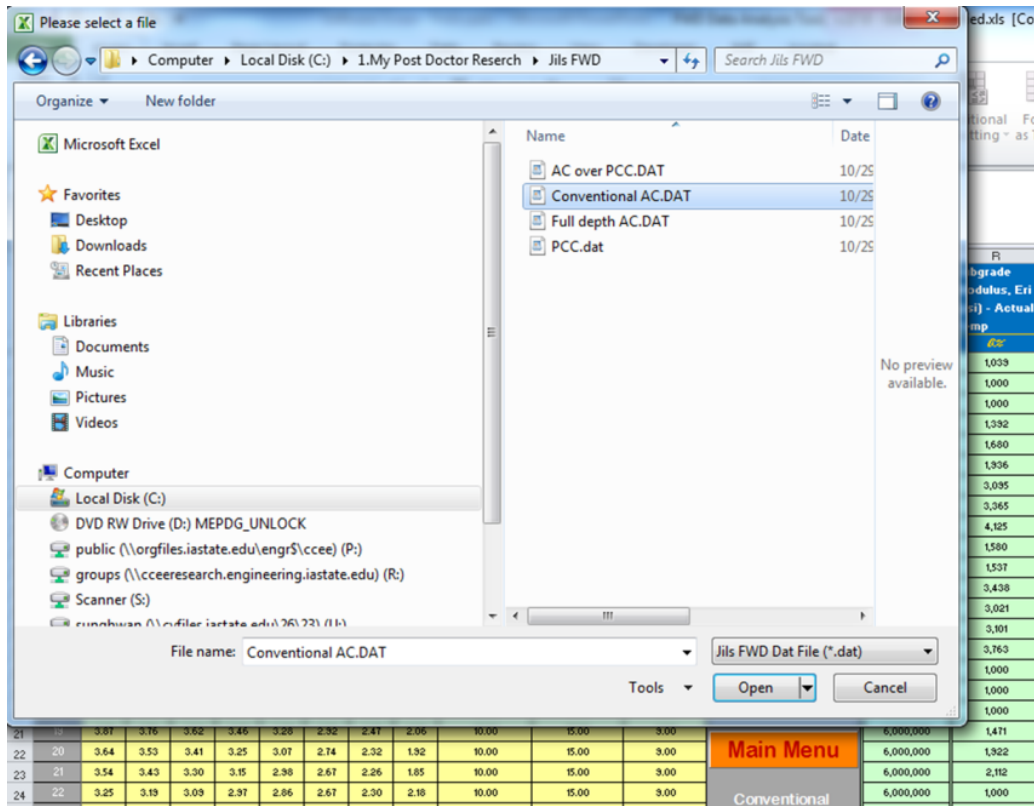


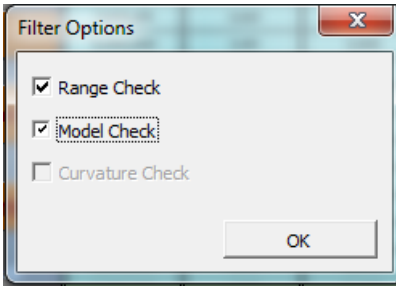
Figure 20. Screen shot of FWD data extraction through open FWD data file button

Filtering Menu

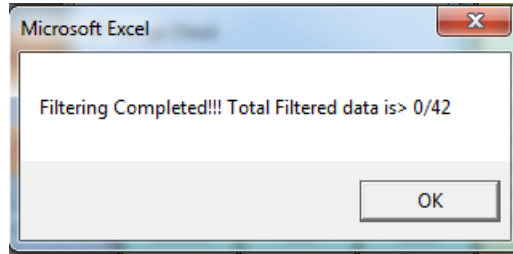
After entering the FWD data required, there is a data preprocessing unit for filtering the data. It is optional to use the filtering window. Figure 21 shows the available options for filtering. The two options are:

- 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. Therefore, results for these parameters are also calculated. With this approach, engineers will have a better understanding of the sources of errors.



(a)



(b)

Figure 21. Filtering the FWD data: (a) Filter options menu, (b) Filtering results (no filtered data in this example)

ANN Based Preliminary Backcalculation Result Outputs

After preprocessing the data, clicking the “Run” button will activate a neural network-based analysis of pavements. The program will analyze the employed ANN model for the pavement properties. 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. The default units used in the program are based on US customary units. Reported results are modulus values, strains, and stresses. Modulus and stress values are reported in psi and strains are reported in micro-strains ($\times 10^6$).

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.

The rigid pavement analysis results include 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).

The composite pavement analysis results include 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.

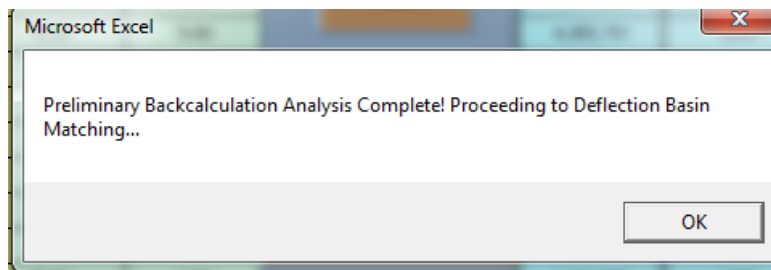
Figure 22(a) illustrates the sample analysis results of a conventional flexible pavement. Failure to

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 D₄₈ is missing in the input data, then output columns will display the error message of “No Data.” At the end of each column, a statistical summary (i.e., mean, standard deviation, and coefficient of variation) of the results is presented.

After completing ANN based preliminary backcalculation, a progress report window appears as shown in Figure 22(a). Its purpose is to give user the notice of completion of ANN based preliminary backcalculation and its intention to proceed to deflection basin matching analysis to determine final backcalculation results.

AC Modulus, Eac (psi) - Actual Temp	Subgrade Modulus, Esi (psi) - Actual Temp	Granular Base Modulus Param., K (psi) - Actual Temp	Strain (μϵ) @ Bottom of AC	Strain (μϵ) @ Top of Subgrade - Actual Temp	Deviator Stress (psi) @ Top of Subgrade - Actual Temp
0%	0%	0%	B def	B def	B def
5,261,155	1,039	3,000	16	19	0
6,000,000	1,000	11,285	10	23	0
6,000,000	1,000	12,000	10	26	0
6,000,000	1,392	4,072	12	19	0
6,000,000	1,680	8,669	11	20	0
6,000,000	1,936	12,000	11	22	1
4,982,169	3,095	3,000	16	30	1
5,179,578	3,365	3,000	16	27	1
5,266,160	4,125	3,000	15	26	1
5,091,562	1,580	12,000	17	79	1
4,955,751	1,537	12,000	17	85	1
5,113,697	3,438	12,000	17	74	1
5,606,415	3,021	3,000	14	15	1
6,000,000	3,101	3,000	13	15	1
6,000,000	3,763	3,000	13	18	1
6,000,000	1,000	12,000	7	7	0
6,000,000	1,000	12,000	7	9	0
6,000,000	1,000	12,000	7	10	0

(a)



(b)

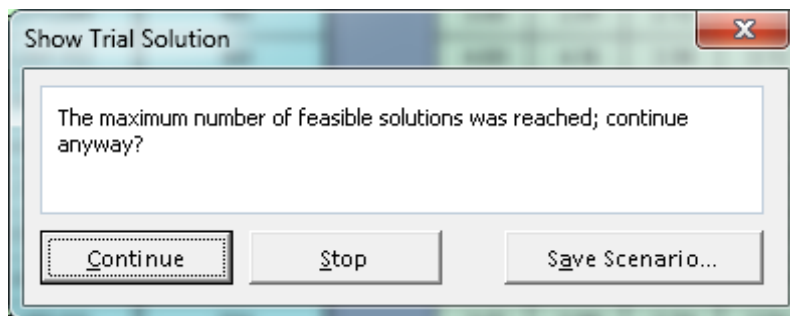
Figure 22. ANN based preliminary backcalculation analysis: (a) Preliminary backcalculation analysis result outputs, (b) Progress report window after completing ANN based preliminary backcalculation analysis

Deflection Basin Matching/Optimization of Backcalculation Analysis Result Outputs

Clicking the “OK” button in progress report window (see Figure 22 (b)) will activate deflection basin matching/optimization based backcalculation analysis. Figure 23 (a) illustrates the sample analysis results of a conventional flexible pavement. The analysis results will be displayed on the right side of ANN based preliminary backcalculation analysis result columns in the screen. The user should scroll right to see all results. If user have a trial solution checking screen shown in Figure 23 (b) during deflection basin matching analysis, user can hit “Stop” button (See Figure 23 (b)) to proceed with analysis since the solutions do not generally improve beyond this point.

AC Modulus, Eac (psi) - Actual Temp	Subgrade Modulus, Eri (psi) - Actual Temp	Granular Base Modulus Param., K (psi) - Actual Temp	Computed FWD Deflections after Deflection Basin Matching (mils)									Mean Abs. Error bet. Meas and Comp. FWD Deflections
After Deflection Basin Matching			D-0	D-8	D-12	D-18	D-24	D-36	D-48	D-60	MAE	
4,488,319	1,040	3,000	5.01	4.83	4.68	4.43	4.15	3.57	3.03	2.53	0.0477	
5,757,290	1,000	11,260	4.14	3.99	3.87	3.68	3.47	3.03	2.61	2.21	0.1104	
6,000,000	1,364	12,000	3.95	3.80	3.68	3.50	3.30	2.88	2.47	2.09	0.0989	
6,000,000	1,716	4,596	4.00	3.85	3.73	3.54	3.33	2.90	2.49	2.10	0.0343	
6,000,000	2,125	9,167	3.81	3.66	3.55	3.35	3.15	2.74	2.34	1.96	0.0458	
6,000,000	2,808	11,999	3.63	3.48	3.36	3.18	2.98	2.58	2.18	1.82	0.0579	
4,843,995	3,074	3,000	4.30	4.12	3.99	3.75	3.50	2.99	2.50	2.06	0.0254	
4,988,833	3,342	3,000	4.18	4.00	3.87	3.64	3.40	2.90	2.43	2.00	0.0276	
5,090,039	4,089	3,000	4.01	3.83	3.70	3.48	3.24	2.76	2.30	1.89	0.0232	
5,999,994	2,504	12,000	3.69	3.54	3.42	3.24	3.04	2.63	2.24	1.87	0.0512	
5,995,312	2,786	11,998	3.63	3.48	3.37	3.18	2.99	2.58	2.19	1.82	0.0538	
5,999,994	5,256	12,000	3.25	3.10	2.99	2.81	2.62	2.23	1.86	1.52	0.0567	
4,993,991	2,876	3,000	4.27	4.09	3.96	3.73	3.48	2.98	2.50	2.07	0.0372	
5,482,614	3,025	3,000	4.02	3.85	3.73	3.52	3.29	2.83	2.39	1.98	0.0343	
5,738,201	3,716	3,000	3.80	3.64	3.52	3.31	3.10	2.66	2.24	1.86	0.0303	
6,000,000	3,431	11,999	3.51	3.36	3.25	3.07	2.87	2.47	2.08	1.73	0.1635	
6,000,000	4,374	12,000	3.36	3.22	3.11	2.92	2.73	2.34	1.96	1.61	0.1682	

(a)



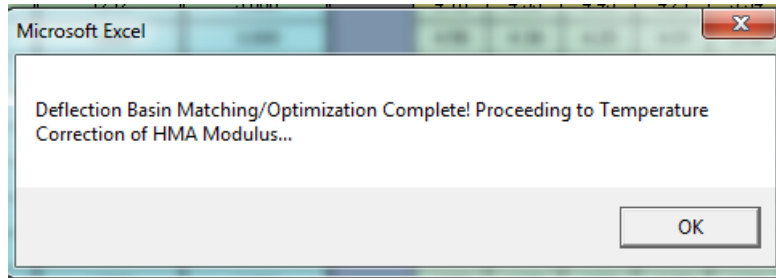
(b)

Figure 23. Deflection basin matching/optimization of backcalculation analysis: (a) Optimized backcalculation analysis result outputs, (b) Trial solution check message box

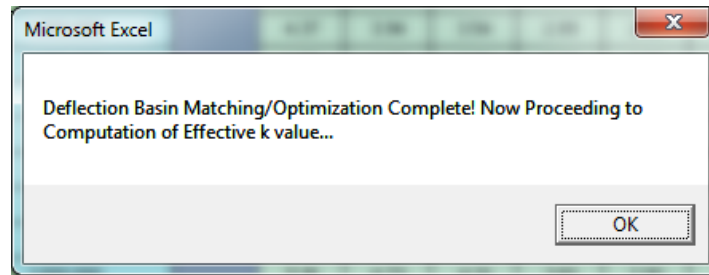
The deflection basin matching/optimization based backcalculation analysis refines ANN-based backcalculation results for each pavement type to obtain a very close match between the actual FWD and predicted deflections. Reported results are refined/optimized modulus for each

pavement type, FWD deflection predictions, and Mean Absolute Error (MAE) between measured and predicted FWD deflections for assessment of the accuracy of refined/optimized modulus.

After completing the deflection basin matching/optimization based backcalculation analysis, progress report window appears as shown in Figure 24(a) for flexible and composite pavements and Figure 24(b) for rigid pavement. Its purpose is to give user the notice of completion of analysis and its intention to proceed to HMA modulus temperature correction for flexible and composite pavements or computation of effective k-value (k_{eff}) for rigid pavement.



(a)



(b)

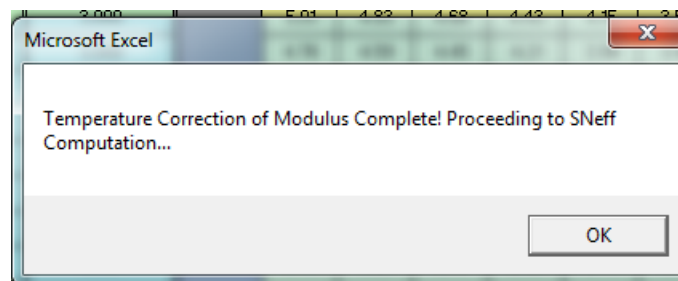
Figure 24. Progress report window after completing optimization of backcalculation analysis: (a) flexible and composite pavements, (b) rigid pavement

HMA Modulus Normalization Result Outputs

Clicking the “OK” button in progress report window (see Figure 24 (a)) will activate HMA modulus temperature normalization routine for flexible and composite pavements. The HMA modulus temperature normalization routine in I-BACK corrects the backcalculated HMA moduli to a standard reference temperature (68°F) by using HMA pavement temperature estimation and HMA modulus temperature correction algorithm. Reported results are temperature corrected modulus at a standard reference temperature (68°F) for flexible and composite pavements. Figure 25(a) illustrates the sample analysis results of a conventional flexible pavement. The analysis results will be displayed on the right side of the deflection basin matching/optimization based backcalculation analysis result columns in the screen. The user should scroll right to see all results.

AC Modulus, E _{ac} (psi)	Subgrade Modulus, E ₁ (psi)	Granular Base Modulus Param., K (psi)
<i>After Temperature Correction</i>		
2,902,909	1,040	3,000
3,723,641	1,000	11,260
3,880,619	1,364	12,000
3,880,619	1,716	4,596
3,880,619	2,125	9,167
3,880,619	2,808	11,999
3,132,949	3,074	3,000
3,226,626	3,342	3,000
3,292,083	4,089	3,000
3,880,614	2,504	12,000
3,877,587	2,786	11,998
3,880,615	5,256	12,000
3,229,963	2,876	3,000
3,545,989	3,025	3,000
3,711,295	3,716	3,000
3,880,619	3,431	11,999
3,880,619	4,374	12,000
3,880,619	5,378	11,818
3,880,619	1,494	12,000

(a)



(b)

Figure 25. HMA modulus temperature correction: (a) Temperature corrected HMA modulus result outputs, (b) Progress report window after completing HMA modulus temperature correction

After completing HMA modulus temperature normalization procedure, progress report window appears as shown in Figure 25(b). Its purpose is to give user the notice of completion of procedure and its intention to proceed to the computation of effective SN (SN_{eff}) for flexible pavement and effective k-value (k_{eff}) for composite pavement.

Output Results of the Effective SN (SN_{eff}) for Flexible Pavement and the Effective k-value (k_{eff}) of Rigid and Composite Pavements

Clicking the “OK” button in progress report windows shown in Figure 24(b) will activate computation of effective k-value (k_{eff}) for rigid pavement. Similar to this, clicking the “OK” button in progress report windows shown in Figure 25(b) will activate computation of effective SN (SN_{eff}) for flexible pavement and effective k-value (k_{eff}) for composite pavement.

Figure 26 illustrates the sample analysis results of rigid pavement. Reported results for rigid and composite pavements is effective k-value (k_{eff}). Figure 27 illustrates the sample analysis results of a conventional flexible pavement. Reported results for flexible pavement are effective modulus of pavement layer (E_p) and effective SN (SN_{eff}). The user should scroll right to see all results.

k_{eff}
Effective k-value
pci
87
90
88
89
57
58
76
77
73
77
64
66
71
72
62
62
73
74
49

Figure 26. Effective k-value (k_{eff}) for rigid and composite pavements

Effective Pavement Modulus, E_p (psi)	Effective Structural Number, S_{Neff}
<i>S_{Neff} Computation</i>	<i>S_{Neff} Computation</i>
87,950	5.0030
106,688	5.3357
111,839	5.4202
110,689	5.4016
116,238	5.4904
121,173	5.5670
102,200	5.2598
105,200	5.3108
109,746	5.3862
119,389	5.5395
120,969	5.5639
134,994	5.7711
103,136	5.2758
109,631	5.3843
116,014	5.4869
124,956	5.6243
130,268	5.7029
135,632	5.7802
112,693	5.4340

Figure 27. Effective SN (S_{Neff}) with effective modulus of pavement layer (E_p) for flexible pavement

Output Results of the Road Rater Based SR and k

Figure 28 illustrates the sample analysis results of Road Rater Based SR and k-value computation for a conventional flexible pavement. The analysis results will be displayed on the farthest to the right side on the screen. The user should scroll right to see all results.

Iowa DOT Structural Rating (SR)	Iowa DOT k (psi/in.)	
<i>Iowa DOT SR and k</i>		
6.53	184.8	
6.60	184.1	
6.74	173.6	
6.81	170.8	
6.40	177.7	
6.47	175.1	
6.19	174.0	
6.29	173.1	
6.53	153.7	
6.59	153.4	
6.52	172	AVERAGE
0.19	11	STDEV
3%	6%	CV

Figure 28. Road Rater Based SR and k for flexible pavement

After completing computation of Road Rater Based SR and k-value, the final progress report window appears as shown in Figure 29. Its purpose is to inform the user about the completion of all analysis and to proceed with the generation of a summary result file which is a separate end result file.

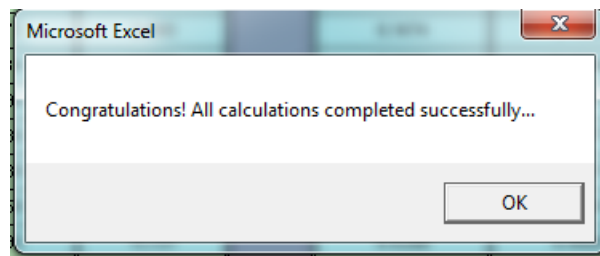


Figure 29. Final Progress report window after completion of analysis

Summary Result File

After the successful completion of full backcalculation analysis, both the inputs and outputs are written onto a separate output file in CSV format. This eliminates the need to re-save the Excel tool with all the macros for the sake of retaining the outputs from the analysis. Through this enhancement in I-BACK, the Excel tool will always serve as a separate analysis tool and the output files (less than 100 kbs) can be saved for future reference.

SUMMARY

The objective of this study is to incorporate significant enhancements into the fully-automated software system for rapid processing of the FWD data with the goal of improving the accuracy and usability of collected Iowa FWD data. These enhancements included: (1) deflection basin matching/optimization, (2) temperature normalization of HMA layer modulus, (3) computation of 1993 AASHTO design guide based effective SN (SN_{eff}) and effective k-value (k_{eff}), (4) computation of Iowa DOT AC overlay design based Structural Rating (SR) and k-value (k), and (5) enhancement of user-friendliness of input and output from the software.

A high-quality, easy-to-use backcalculation software package referred to as, I-BACK: the Iowa Pavement Backcalculation Software, was developed to achieve goals with the following highlighted benefits:

- Provide more fine-tuned ANN pavement backcalculation results by implementation of deflection matching optimizer for conventional flexible, full-depth, rigid, and composite pavements
- Provide temperature normalized/corrected HMA layer modulus at a standard reference temperature for conventional flexible, full-depth and composite pavements
- Provide effective Structural Number (SN_{eff}) and the effective k-value (k_{eff}) as final outputs for pavement/asset management purposes
- Provide Structural Rating (SR) and k-value (k) as final outputs to make FWD deflection measurements suitable for use in existing Iowa DOT AC overlay design procedure
- Produce separate smaller sized output files from backcalculation analysis

REFERENCES

- AASHTO. 1993. *AASHTO Guide for Design of Pavement Structures*. Washington, DC.
- AASHTO. 2008. *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice*. Washington, DC.
- AASHTO. 2012. *AASHTOWare Pavement ME Design*. Washington, DC.
<<http://www.darwinme.org/MEDesign/Index.html>> (February 22, 2013).
- Ali, H. and Lopez, A., 1996. Statistical analysis of temperature and moisture effects on pavement structural properties based on seasonal monitoring data. *Transportation Research Record 1540*: 48-55. Washington DC: Transportation Research Board, National Research Council.
- Baltzer, S. and Jansen, J. M. 1994. Temperature correction of asphalt moduli for FWD measurements. *Proceedings of the 4th International Conference on Bearing Capacity of Roads and Airfields*, Volume 1, Minneapolis, MN.
- Ceylan, H., Guclu, A., Bayrak, M. B. and Gopalakrishnan, K. 2007. *Nondestructive Evaluation of Iowa Pavements-Phase I*. Final Report, CTRE Project 04-177, Ames, IA: Center for Transportation Research and Education (CTRE), Iowa State University.
- Ceylan, H., Gopalakrishnan, K., Kim, S., Guclu, A., and Bayrak, M. B. 2009. *Nondestructive Evaluation of Iowa Pavements-Phase II: Development of a Fully Automated Software System for Rapid Analysis/Processing of the Falling Weight Deflectometer Data*. Final Report, CTRE Project 04-177Phase 2, Ames, IA: Center for Transportation Research and Education (CTRE), Iowa State University.
- Chen, D., Bilyeu, J., Lin, H. H., and Murphy, M. 2000. Temperature correction on falling weight deflectometer measurements. *Transportation Research Record 1716*: 30-39. Washington DC: Transportation Research Board, National Research Council.
- Deacon, J. A., Coplantz, J. S., Tayebali, A. A., and Monismith, C. L. 1994. Temperature considerations in asphalt-aggregate mixture analysis and design. *Presented at the Annual 73th Meeting of the Transportation Research Board*. Washington, DC: Transportation Research Board.
- Heins, D. 1979. *Road Rater Dynamic Deflections for Determine Structural Rating of Flexible Pavements*. Final Report for IHRB 178, Ames, IA: Office of Materials, Iowa Department of Transportation.
- Jones, K., and Hanson, T. 1991. *Correlation of the Road Rater and the Dynatest Falling Weight Deflectometer*. Final Report for MLR-91-4, Ames, IA: Office of Materials, Iowa Department of Transportation.
- Kim, Y. R., Hibbs, B. O., and Lee, Y. C. 1995. Temperature correction of deflections and backcalculated moduli. *Transportation Research Record 1473*: 55-62. Washington DC: Transportation Research Board, National Research Council.
- Lukanen, E. O., Stubstad, R., and Briggs, R. 2000. *Temperature Predictions and Adjustment Factors for Asphalt Pavement*. FHWA-RD-98-085, Mclean, VA: Federal Highway Administration.
- Marks, V. J. 1983. *Dynamic Deflections to Determine Roadway Support Ratings*. Final Report for IHRB 245, Ames, IA: Office of Materials, Iowa Department of Transportation.
- Noureldin, A.S. 1994. Temperature gradient in a full depth asphalt and its effect on modulus and shear Gradients. *The Proceedings of 6th Conference on Asphalt Pavements for Southern Africa (CAPSA)*.

- Potter, C. J., and Dirks, K. L. 1986. *Structural Analysis and Overlay Design of Pavements Using the Road Rater*. Final Report for MLR-84-3, Ames, IA: Highway Division, Iowa Department of Transportation.
- Potter, C. J., and Dirks, K. L. 1989. *Pavement Evaluation Using the Road Rater Deflection Dish*. Final Report for MLR-89-2, Ames, IA: Highway Division, Iowa Department of Transportation.
- Ullidtz, P.1987. *Pavement Analysis*. The Technical University of Denmark.