Development of an Overlay Design Procedure for Composite Pavements

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16. Abstract

The composite overlay design procedure currently used by ODOT sometimes produces very large overlay thicknesses that are deemed structurally unnecessary, especially for composite pavements already with thick asphalt overlays. This study was initiated to investigate the cause(s) and to develop a revised procedure. The current ODOT pavement overlay thickness design procedure is based on the structural deficiency approach recommended by the 1993 AASHTO Pavement Design Guide. The current procedure uses a simple, closed form procedure to back-calculate the subgrade modulus and the effective modulus of the existing pavement structure from the measured Falling Weight Deflectometer (FWD) surface deflections. The simplistic treatment of the AC and PCC layers as a combined layer in the back-calculation model was found to significantly underestimate the moduli of the existing pavement. A three-layer elastic model is adopted in lieu of the two-layer model used in the current procedure for back-calculation. The three-layer model allows the composite pavement structure to be modeled more accurately. The elastic moduli of the asphalt concrete layer and the underlying Portland cement concrete can both be back-calculated, instead of being combined as one. A revised overlay design procedure has been developed. A comparison of the revised procedure and the current procedure shows that the three-layer model produces higher effective thickness than the two-layer model for the same pavement structure. Therefore, the required overlay thickness is reduced. The revised design software has been implemented into a design software program, which also offers an optional feature that takes into consideration the temperature effects on the asphalt concrete moduli.

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EXECUTIVE SUMMARY

This final report documents the findings of the research study on development of an overlay thickness design procedure for composite pavements. The composite overlay design procedure currently used by ODOT sometimes produces very large overlay thicknesses that are sometimes deemed structurally unnecessary, especially for composite pavements that already have thick asphalt overlays. This study was initiated to investigate the cause(s) and to develop a revised procedure if necessary.

The ODOT pavement overlay thickness design procedure is based on the structural deficiency approach recommended by the 1993 AASHTO Pavement Design Guide. The structural capacity of the existing pavement is estimated using pavement surface deflections measured by Falling Weight Deflectometer (FWD), the most commonly used pavement non-destructive testing (NDT) device. The current procedure uses a simple, closed form procedure to back-calculate the subgrade modulus and the effective modulus of the existing pavement structure from the measured surface deflections. This procedure was designed for concrete pavement and has provided satisfactory overlay design on concrete pavements. However, when this procedure is adopted for composite pavements, the results are less than satisfactory. AASHTO does not have a composite overlay design procedure that relies solely on measured deflections to estimate the existing structural capacity. Instead, the AASHTO Guide suggests that the structural capacity of the existing pavement may be estimated based on engineering judgement.

The research team adopted a three-layer elastic model in lieu of the two-layer model used in the current procedure for back-calculation. The three-layer model allows the composite pavement structure to be modeled more accurately. The elastic moduli of the asphalt concrete layer and the underlying Portland cement concrete can both be back-calculated, instead of being combined as one. The back-calculation requires iterations, in which relaxation of error tolerance and moduli constraints are introduced to ensure that the back-calculated layer moduli are realistic. A revised overlay design procedure has been developed. A comparison of the revised procedure and the current procedure shows that the three-layer model produces higher effective thickness than the two-layer model for the same pavement structure. Therefore, the required overlay thickness is reduced. The revised design software has been implemented into a design software program, which also offers an optional feature that takes into consideration the temperature effects on the asphalt concrete moduli.

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SYMBOLS AND NOTATIONS

ESAL	Equivalent Single Axle Load
ODOT	Ohio Department of Transportation
FWD	Falling Weight Deflectometer
AC	Asphalt Concrete
PCC	Portland Cement Concrete
AASHTO	American Association of State Highway & Transportation Officials

CHAPTER 1

Introduction

1.1 Problem Statement

A majority of ODOT's 4-lane and interstate highways are composite pavements. Each year ODOT rehabilitates several hundred miles of the existing AC/PCC pavements by additional overlay. Therefore, it is important to have an effective means to evaluate the structural capacity of the existing AC/PCC pavements and to design the overlay thickness required to carry anticipated future traffic loading.

The pavement overlay thickness design procedure currently employed by ODOT works well for both flexible and rigid pavements, but it tends to produce very conservative design for composite pavements. For composite pavements with relatively thick existing asphalt overlays, the current design procedure consistently recommends very high overlay thicknesses that are often deemed structurally unnecessary. Research is needed to evaluate and verify the assumptions used for composite pavements in the current overlay design procedure and provide modifications as needed or to develop a new deflection based overlay design procedure for composite pavements.

ODOT's current overlay design procedure was developed by Chou (1996) based on the structural deficiency approach recommended by the 1993 AASHTO Design Guide for Design of Pavement. Several significant deviations from the 1993 AASHTO overlay design procedure were made, partly to accommodate the Dynaflect device used by ODOT at that time to measure pavement deflections instead of the Falling Weight Deflectometer (FWD) device recommended by AASHTO, and also to eliminate the subjective evaluation of the existing pavement's structural capacity as recommended in the 1993 AASHTO procedure. The current ODOT procedure has produced satisfactory designs for overlay on flexible or rigid pavements, but it often generates unrealistically thick overlays for composite (AC/PCC) pavements. A research study by Malella et al. (2008) recommended using deflections measured by the FWD device as input for the overlay design. This recommendation was subsequently adopted by ODOT and the overlay design software has been modified by Pan et al. (2012) to use FWD deflections as input. However, the problem of exceedingly high design overlay thickness for composite (AC/PCC) pavements now becomes even worse, likely due to the heavier FWD loading. Therefore, it is evident that the solution to this problem goes beyond simply replacing the Dynaflect deflections with the FWD deflections. Research is needed to investigate the possible cause(s) and find solution(s) to address the problem within the composite overlay design procedure and to validate the revised procedure through actual pavements.

1.2 Research Objectives and Goals

The primary goal of the proposed research is to develop and validate a FWD deflection-based overlay design procedure for composite pavements and incorporate it into the current version of ODOT's overall design software. In addition, a secondary goal is to provide ODOT with the ability to mechanistically determine the effective thickness of the Portland Cement Concrete (PCC) slab portion of a composite pavement for use in the U.S. Army Corps of Engineers' equation for the design of unbonded concrete overlays.

1.3 Research Approach

The principal methodology adopted in this study focuses on the evaluation of the current ODOT design procedure and identifies the limitations and potential errors, and the development of a new back-calculation model for improved estimation of pavement properties, which will become a core part of a new design procedure for the composite pavements.

The overlay design method currently adopted by ODOT is a deflection based design in which the deflection data from Falling Weight Deflectometer (FWD) are used to estimate the material properties of pavement layers needed for the overlay design via a structural deficiency approach. In this approach, the required overlay thickness is based on the difference between a newly designed pavement and the existing pavement. The difference in structure capacity represents the theoretical structural deficiency that must be met by the overlay. However, accurate determination of the effective thickness is a major challenge due to differences in performance and behavior among flexible, rigid and composite pavements, and due to lack of precise relationship between material characteristics, pavement deflections and performance. A major concern about the deflection based back-calculation model is the possibly simplistic modelling of a single effective modulus for the overall composite pavement. This two-layer (composite and subgrade) back-calculation model will be under intensive investigation in the context of current design procedure evaluation. Significant efforts will be devoted to the potential improvements of this back-calculation model for the new design procedure.

1.4 Outline of the Report

The report is divided into five chapters. Chapter 2 discusses the existing design procedure adopted by ODOT for composite pavements and evaluates it with recent field FWD data. Possible limitations and errors in the design are also discussed.

Chapter 3 presents the revised overlay design procedure for composite pavements. This procedure is centered around a back calculation model based on the multi-layer pavement analysis concept. A three-layer back-calculation model is presented with error tolerance relaxation and moduli constraints introduced with the intent to improve the performance of the revised procedure.

Chapter 4 presents the validation of the revised design procedure using both pre-construction and post-construction FWD data. Field coring for thickness verification and subsequent analysis with corrected thicknesses are also discussed.

Chapter 5 outlines the development of the software implementation for the revised design procedure.

Finally, Chapter 6 concludes this report with a summary of findings, conclusions and recommendations, followed by a number of appendices including examples and relevant data tables.

CHAPTER 2

Evaluation of the Existing Design Procedure

2.1 Introduction

Ohio Department of Transportation (ODOT) uses the overlay design method developed by Chou (1996) for the overlay of pavements. The method is based on structural deficiency approach recommended by 1993 AASHTO Design Guide with significant modifications made to eliminate the subjective evaluation of structural capacity of existing pavement and to accommodate the Dynaflect device used by ODOT at that time to measure deflections instead of Falling Weight Deflectometer (FWD) device recommended by AASHTO. At present ODOT uses FWD device for deflection measurement and the software was modified to use FWD data as input. The design method works well for flexible and rigid pavements; however, the design thickness often seems to be exceedingly high for the composite pavements.

A critical part of the design method is the use of the two-layer back-calculation model to obtain the subgrade modulus and the effective modulus of the existing pavement, based on a closed-form back-calculation procedure developed for rigid pavements by Ioannides et al. (1989). The effective modulus (E_{eff}) for a new pavement is computed based on the equal-rigidity concept. The effective PCC thickness of the new composite pavement is calculated with an AC-to-PCC factor of two. Based on all these parameters using empirical relationships, the effective thickness of existing pavement is computed. Required rigid pavement thickness for new pavement is computed based on 1993 AASHTO Design Guide. The overlay thickness is calculated based on the required thickness of pavement for new pavement and the effective thickness of existing pavement, and statistical corrections are applied based on the deviations obtained for each station.

In this chapter a brief summary of the existing overlay design procedure for composite pavements is provided. Evaluation of this procedure is done using the actual FWD data from 11 construction projects. Potential sources of error are also discussed.

2.2 Current Overlay Thickness Design Procedure for Composite Pavements

The existing ODOT overlay design procedure for composite pavements consists of the following steps.

a.) Obtain the road deflection data using the Falling weight deflectometer (FWD) device. FWD applies dynamic loads and the geophone sensors measure the deflection at seven different locations (-12, 0, 12, 24, 36, 48, and 60 inches). Out of all the deflections, only deflection from the four sensors: 0, 12, 24 and 36 inches are used for further computations.

b.) The area of the deflection basin and radius of relative stiffness are computed.

c.) Based on the relative stiffness, the non-dimensional deflection at first sensor is obtained.

d.) The effective modulus of the existing pavement, E_p is back-calculated with the input parameters of falling weight load, relative stiffness, Poisson's ratio, non-dimensional deflection, thickness of existing pavement and deflection at 0-inch sensor (deflection immediately below the load).

e.) Similarly, the modulus of subgrade reaction, k is computed with the input parameters of non-dimensional ratio, falling weight load, deflection at 0 inches sensor and relative stiffness.

f.) WithE_{ac}, E_{pcc} and Poisson's ratio for the new pavement, the effective modulus, E_{eff} is computed for a new pavement based on the equal-rigidity concept.

g.) The effective PCC thickness of new composite pavement, D_{new} is computed based on the thickness of asphalt and PCC layer.

h.) Based on E_{eff} computed in step (f) for the new pavement and back-calculated, E_p, effective thickness of the existing pavement, D_{eff} is calculated.

i.) The required thickness for new rigid pavement, D_{req} is calculated based on AASHTO 1993 pavement design guide.

j.) The required overlay thickness is calculated based on D_{req}, D_{eff}, and the statistical parameters.

The design procedure in detail with the equations and charts is presented in Appendix A which also includes an example for illustration.

2.3 Evaluation of Existing Design Procedure Using the FWD Data

The results obtained from the existing design procedure used by ODOT have been presented in Table 2.1. The overlay actually constructed in the field is also presented in the "as constructed" column of the table for comparison.

Table 2.1. Design of overlay thickness with the existing design procedure

County-Route	Thickness (in.)		Added Overlay (in.)	Existing Design (in.)			
	AC	PCC		# of stations*	Avg.	Std. Dev.	Design Overlay
ASD 42	6.00	9.00	1.50	63	-0.73	2.83	2.90
ATH 50	5.25	9.00	0.00	68	2.14	2.90	5.14
CUY 422	4.00	9.00	1.25	55	-1.28	2.19	1.53
FRA 71	6.75	10.00	1.50	54	6.48	1.41	8.29
GUE 70	7.00	9.00	1.50	65	6.44	2.07	9.10
HUR 20	5.75	9.00	0.00	38	1.52	3.12	5.52
LUC 475	6.50	9.00	1.00	39	5.70	1.26	7.32
MIA 75	8.25	9.00	0.00	38	7.85	0.91	8.79
TUS 250	4.50	9.00	0.00	34	2.30	2.01	4.89
UNI 33	6.00	9.00	0.00	47	2.15	1.39	3.93
WAS 50	4.25	9.00	0.00	34	3.63	1.71	5.41

* Note that (1) only mid-slab deflection data are used in the calculations; (2) though the existing software provides FWD data from three load levels, FWD data from one single load level (approximately 9000 lbs) are used in each design, for consistency in the comparison with the results from the revised design method.

Although the actual thickness as constructed in the field was primarily an empirically based practical decision, it is clear that the existing overlay thickness design procedure for composite pavements tends to produce excessively large thicknesses which are most likely structurally unnecessary.

Details of step-by-step analysis of the existing procedure are illustrated in Appendix A. The back-calculated effective moduli by the existing procedure are generally underestimated (an example is provided graphically later in Chapter 3 which also includes a comparison with the revised design procedure), and as such it produces underestimated effective thickness, and consequently overly conservative overlay thickness.

2.4 Possible Sources of Error

The possible sources of error associated with the existing design procedure can be summarized as follows.

1) The core of the existing procedure is the two-layer back calculation for the estimation of the layer modulus for the existing pavements, with the assumption that the asphalt layer and PCC layer behave as one, and only one effective modulus (E_p) is back-calculated. In essence, because the behavior of these layers is very much different, treating them as one layer can be too simplistic and may result in significant errors. The most significant modification of the existing design procedure would be to improve the back calculation model to obtain the individual modulus of each layer.

2) During the calculation of the modulus of subgrade reaction (*k*), only the non-dimensional deflection (d_0) for deflection at 0 inch, i.e., right below load is used. However, it is well-known that, the deflections at locations farther away from the loading are influenced by the material properties of lower layers and the deflections nearer to the loading are influenced by the material properties of upper layers. Therefore, use of only one single deflection value (which is exactly under the load) may have caused errors in the computation of *k*. A suggestion is made to compute the modulus of elasticity for the subgrade based on the measured six deflections and then compute the modulus of the subgrade reaction with the following equation,

$$\boldsymbol{k} = \left(\frac{\boldsymbol{E_f}}{\boldsymbol{E}}\right)^{\frac{1}{3}} \times \left(\frac{\boldsymbol{E_f}}{\boldsymbol{1-v_f^2}}\right) \times \frac{\boldsymbol{1}}{\boldsymbol{h}} \qquad (2.1)$$

where E_f = E_3 = elasticity of subgrade;
E = E_p =back calculated E based on E_1 and E_2;
v_f = Poisson's ratio of subgrade (= 0.45);
$h = h_1 + h_2$ =Total thickness of pavement.

3) Temperature correction may need to be considered to address the influence of the AC layer temperature measured during FWD testing.

2.5 Summary

Design examples using the actual FWD data are examined. The primary cause for the overly conservative design of the existing procedure originates from the simplistic treatment of the AC and PCC layers as a combined layer in the back-calculation model. As a result, this back-calculated modulus of the existing pavement is considerably underestimated. Other sources of error may also contribute, but improving the back-calculation model would most likely make the biggest difference. It is concluded that a three-layer model should be used in the revised design procedure.

CHAPTER 3

A Revised Overlay Design Procedure for Composite Pavements

3.1 Introduction

The existing overlay design procedure for composite pavements must be revised to improve the back-calculation model and offer better estimation of layer moduli. It is proposed that the two-layer (pavement and subgrade) back-calculation model be replaced by a three-layer (AC, PCC and subgrade) back-calculation model.

In the new method, a layered elastic back-calculation method is used in place of the closed form back-calculation procedure in the existing procedure. Three different moduli of elasticity for AC layer, PCC layer and subgrade as back-calculated from FWD data are subsequently converted into the modulus of subgrade reaction and the equivalent modulus of the existing pavement. The conversion to equivalent modulus follows the equal-rigidity concept in which the subgrade reaction is computed with the relationship developed by Vesic and Saxena (1974). The values of equivalent modulus and subgrade modulus are used in a similar way as the effective modulus and subgrade modulus in the existing design. Subsequently the effective thickness of the existing pavement is obtained based on the equal-rigidity concept and the overlay design thickness.

The back-calculation adopted for the revised overlay design method is based on the linear elastic method. For axisymmetric problems in elasticity, a convenient method is to assume a stress function that satisfies the governing differential equations and the boundary and continuity conditions. After the stress function is found, the stresses and displacements can be determined (Timoshenko and Goodier, 1951). A back-calculation program developed by Federal Aviation Administration (FAA), namely BAKFAA is used. The back-calculation program is dynamically linked to a forward calculation program called LEAF. LEAF is a layered elastic analysis computer program developed as part of FAA airport pavement design and analysis programs (Hayhoe, 2002). The back-calculation program calls the forward calculation program to calculate the deflection, the measured deflection (from FWD) and calculated deflection (from LEAF) are then compared and feedbacks are returned to the forward calculation to again calculate the deflection; this iterative process is continued until the acceptable precision is achieved and the moduli of the three different layers, AC, PCC and subgrade are finally determined.

It should be noted that when the number of layers increases in the layered elastic analysis, the possibility of non-unique solution also rises. In other words, multiple combinations of the three moduli may produce similar surface deflection basins that all match with the measured deflection basin, depending on the specified inaccuracy/error tolerance. This possibility may be especially strong when the deflection data are inconsistent or questionable. As a consequence, the back-calculated modulus for AC or PCC layers can be sometimes well outside its commonly acceptable range. Hence the present study also explores some strategies to improve the quality of the back-calculation process.

In this chapter the details of the revised overlay design procedure are presented. Comparison of the overlay design with the existing design procedure using the actual FWD data is also included.

3.2 Overview of the Revised Design Procedure

3.2.1. General framework of the revised design procedure

A general description on the procedure for the revised overlay design of the composite pavements can be summarized as follows. It is noted that the new pavement refers to the pavement after overlay.

a.) FWD data are taken to back-calculate the three layer moduli. The thicknesses of layers are provided as input and seed value (initial "guess" values as leading to starting the back-calculation process) for layer moduli are also specified and the back-calculation process is performed to obtain modulus values for E_1 (AC layer), E_2 (PCC layer) and E_3 (subgrade).
b.) Based on these E_1 and E_2, and Poisson's ratio of two layers, E_p is calculated based on the equal-rigidity concept.
c.) The subgrade reaction, k is calculated.
d.) With E_{ac}, E_{pcc} and Poisson's ratio specified for the new pavement, the effective modulus, E_{eff} is computed for a new pavement based on the equal-rigidity concept.
e.) D_{new} is computed based on the thickness of AC and PCC layer.
f.) Based on E_{eff} computed in step (d) for the new pavement, back calculated E_p and $D_{new}$of existing pavement, D_{eff} of the existing pavement is calculated.
g.) The required thickness of the new pavement, D_{req} is calculated using 1993 AASHTO Guide's rigid pavement design equation.
h.) The required overlay thickness is calculated based on D_{req}, D_{eff} and statistical parameters.

The details of the calculations with relevant equations are included in Appendix B and an example of calculations is presented using FWD data from ASD-42 (Ashland County).

3.2.2 Improving the back-calculation model

A flow chart for this implementation is presented in Figure 3.1. It includes two important strategies to improve the back-calculation.

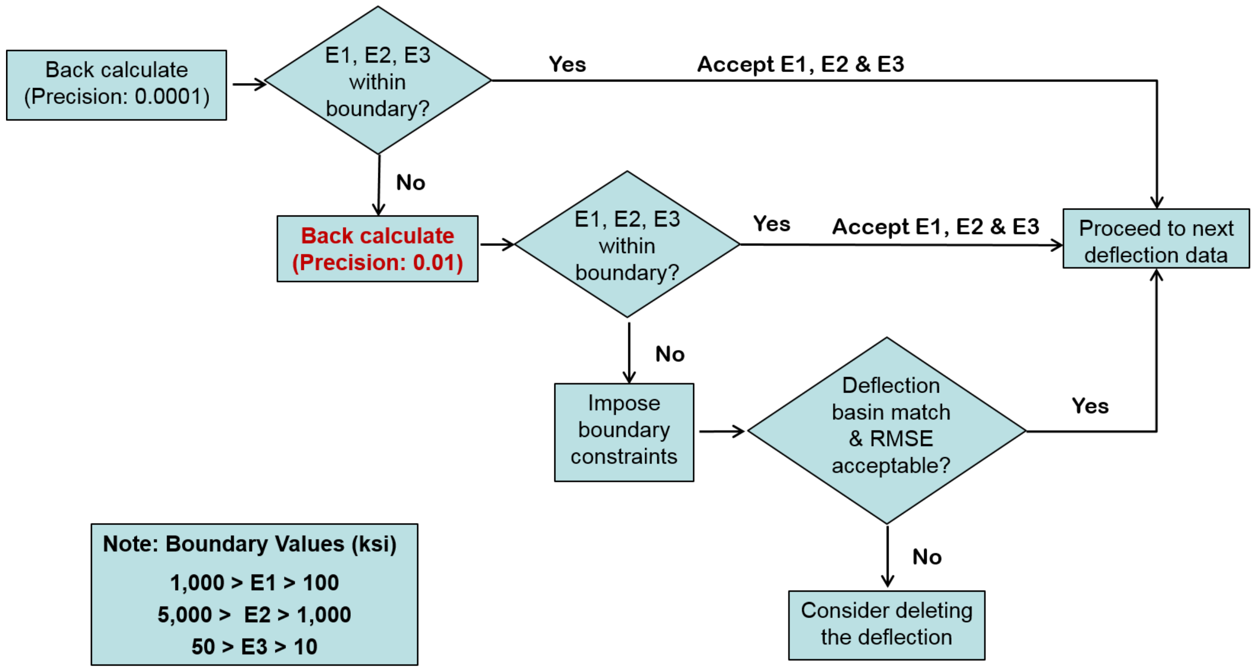


Figure 3.1. Flowchart of the back-calculation process. E_1, E_2 and E_3 are the modulus of AC, PCC and subgrade layer, respectively

When the number of layers increases in the layered elastic analysis, the possibility of non-unique solution also rises. Multiple combinations of the three moduli may produce similar surface deflection basins that all match with the measured deflection basins within the specified error tolerance. As a result, the moduli for AC and PCC layers can sometimes end up outside the generally considered acceptable ranges for these moduli values. In particular, an excessively high demand of accuracy (i.e., an exceedingly low error tolerance) may often lead to "best deflection-matching" moduli which however may be very high or low, outside the commonly acceptable ranges of the materials. Therefore, it is possible to produce reasonable estimates of moduli if the computational error tolerance can be increased, instead of invariably seeking the combination of moduli to best match the deflections. This is the first strategy explored in the present study, as shown in Figure 3.1. An initially high precision convergence (e.g., 0.0001 mil) is used in the back-calculation, if the results are unrealistic, a low precision convergence (e.g., 0.01 mil) is then used for re-backcalculation.

The second strategy is to impose (boundary) constraints on the moduli range for each layer, forcing layer moduli to be within conventionally acceptable range of values (see Figure 3.1). Of course, the resulting deflections may not match very well; the error is then assessed to determine whether the back-calculated moduli should be discarded. The difference between the calculated deflections and the measured FWD deflections can be quantified by the Root-Mean-Square-Error (RMSE) as described in the following, since each set of FWD deflections used for back-calculation consists of six deflection measurements:

$$RMSE = \sqrt{\frac{(w_{0(cal)}-w_{0(mes)})^2+(w_{12(cal)}-w_{12(mes)})^2+\ \dots\ +(w_{60(cal)}-w_{60(mes)})^2}{6}} \tag{3.1}$$

w represents the deflection at the specific FWD location, from 0, 12, 24, 36, 48 and 60 inches away from the center of the falling weight; the number in the subscript indicates this distance. Subscript “cal” indicates the calculated deflection and “mes” the measured. During the back-calculation the progress of the RMSE is monitored, comparing the updated $RMSE_n$ with the last $RMSE_{n-1}$:

$$\Delta_n = |RMSE_n - RMSE_{n-1}| \tag{3.2}$$

When the difference Δ_n diminishes below the given tolerance, $\Delta_n < tolerance$, it signals the convergence of the back-calculation and the end of the iteration.

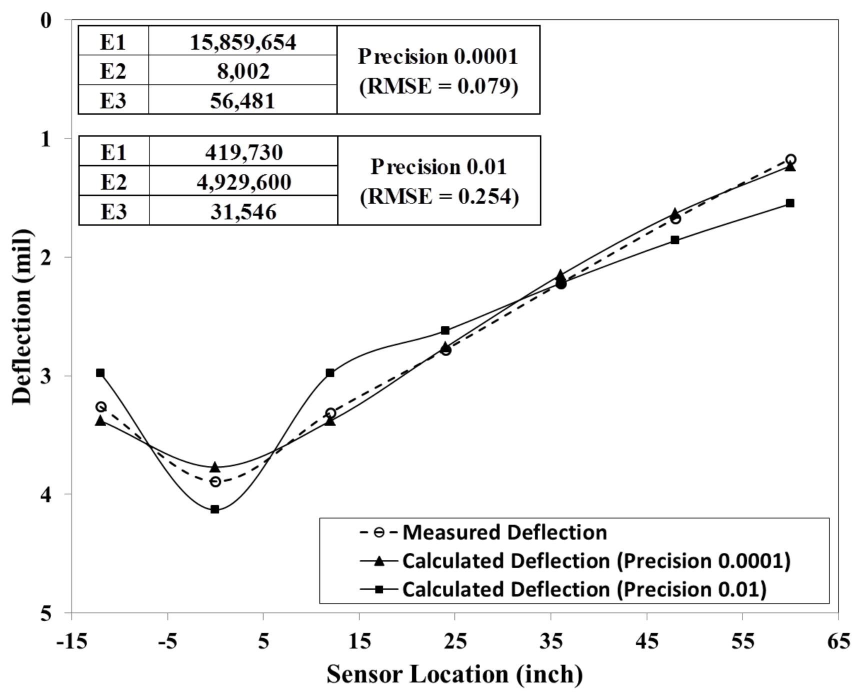


Figure 3.2. Deflection matching with different levels of precision

Figure 3.2 shows an example of the precision convergence and RMSEs with different tolerances. With an initial high level of precision convergence, i.e., a small error tolerance of 0.0001 (mil), the deflections match very well with the measurements (RMSE=0.079 mil). But the back-calculated moduli for both AC and PCC defy the conventional wisdom of material properties; they are way outside their normal ranges and AC is much stiffer than PCC. This is a typical example of the potential drawbacks of seeking the best match; but it is possible to produce reasonable estimates of moduli if the computational error tolerance can relaxed (increased). When a low level of precision convergence, i.e., a larger error tolerance of 0.01 (mil) is used, the back-calculated moduli are much more reasonable and the deflections still match reasonably, but obviously with a larger difference (RMSE=0.254 mil).

3.2.3 Computation of equivalent modulus, effective thickness and overlay thickness

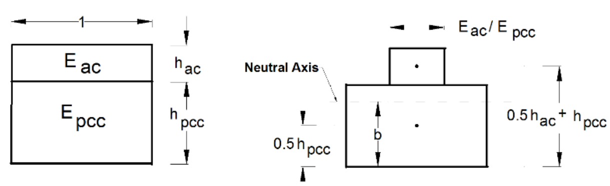
Once the moduli of all three layers are obtained after the back-calculation, they are converted into equivalent modulus (E_p) using equal-rigidity concept. In the similar way, an effective modulus of subgrade reaction (k) is computed using the modulus of elasticity of the subgrade. For a bonded two-layer system, the rigidity of each layer can be calculated according to Huang (1993):

$$R_1 = \frac{E_{ac}[\frac{h_{ac}^3}{12} + h_{ac}\left(0.5 * h_{ac} + h_{pcc} - b\right)^2]}{1 - v_{ac}^2} \tag{3.3}$$

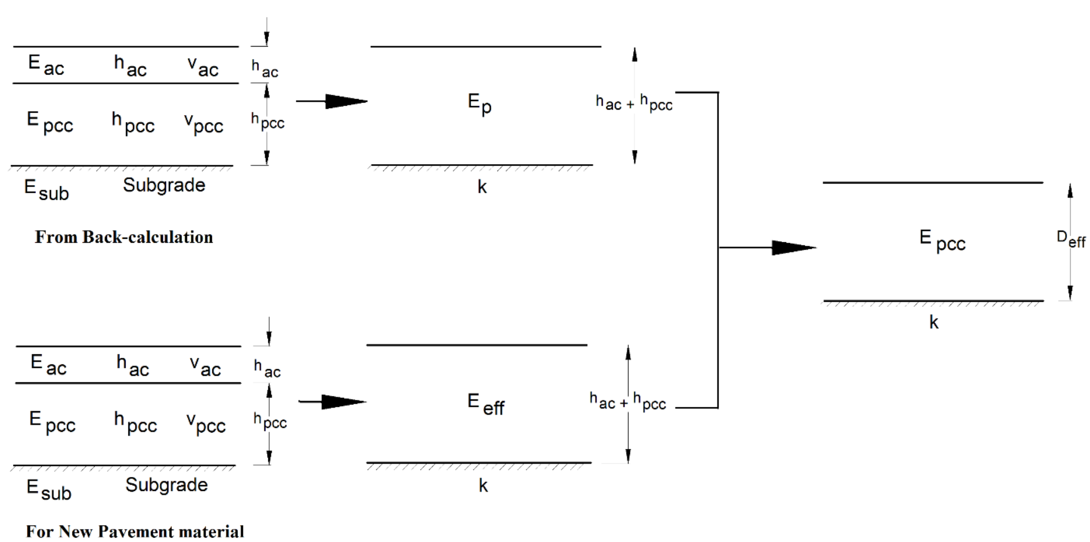
$$R_2 = \frac{E_{pcc}[\frac{h_{pcc}^3}{12} + h_{pcc}\left(b - 0.5 * h_{pcc}\right)^2]}{1 - v_{pcc}^2} \tag{3.4}$$

$$b = \frac{\left(\frac{E_{ac}}{E_{pcc}}\right) * h_{ac} * \left(0.5 * h_{ac} + h_{pcc}\right) + 0.5 * h_{pcc}^2}{\left(\frac{E_{ac}}{E_{pcc}}\right) * h_{ac} + h_{pcc}} \tag{3.5}$$

where R_1 and R_2 are the rigidity of the AC layer and the PCC layer, respectively. h_{ac} and h_{pcc} are the thickness of AC and PCC layer, respectively. E_{ac} and E_{pcc} are the back-calculated modulus of AC and PCC layer, respectively. v_{ac} is the Poisson's ratio of AC and v_{pcc} is the Poisson's ratio of PCC.



a) Original versus Equivalent Section (4)



b) Determination of Effective Slab Thickness

Figure 3.3. Schematic representation of the conversion of E_1, E_2 and E_3 to equivalent modulus (E_p) and computation of D_{eff}

Figure 3.3 shows the schematic representation of the equal-rigidity concept about the conversion of E_1, E_2 and E_3 to the equivalent modulus (E_p) and the subgrade reaction (k). Existing AC layer is converted to an equivalent PCC layer with an AC-to-PCC factor of 2.0, as recommended by 1993 AASHTO Guide and the centroid is computed for the equivalent PCC layer.

Subsequently the equivalent modulus can be calculated with the following relationships (Chou, 1996),

$$E_p = \frac{12*(1-\upsilon^2)(R_1+R_2)}{h^3} \tag{3.6}$$

$$\upsilon = \frac{\upsilon_{ac}h_{ac}+\upsilon_{pcc}h_{pcc}}{h_{ac}+h_{pcc}} \tag{3.7}$$

$$h = h_{ac} + h_{pcc} \tag{3.8}$$

Subgrade reaction (dynamic) can be calculated according to relationship developed by Vesic and Saxena (1970).

$$k_{dyn} = \left(\frac{E_{sub}}{E_p}\right)^{\frac{1}{3}} \times \left(\frac{E_{sub}}{1-\upsilon_{sub}^2}\right) \times \frac{1}{h} \tag{3.9}$$

where E_{sub} is the elastic modulus of subgrade calculated from back-calculation and υ_{sub} is Poisson's ratio of subgrade. According to the recommendation by AASHTO (1993), a factor of 0.5 should be multiplied to the dynamic value to obtain the static modulus of subgrade reaction.

$$k_s = 0.5\, k_{dyn} \tag{3.10}$$

Subsequently the effective thickness of the existing pavement can be calculated (Chou, 1996),

$$D_{eff} = \frac{D_{new}}{[E_{eff}\ /\ E_p]^{0.333}} \tag{3.11}$$

where D_{new} is the effective PCC thickness of new composite pavement, $D_{new} = \frac{h_{ac}}{2} + h_{pcc}$. E_{eff} is the effective modulus of the new composite pavement, calculated via Eqs. (3.3~3.8) with the values of the new pavement (AC and PCC) material properties. In the present study E_{ac} and E_{pcc} for the new pavement are taken to be 450 ksi and 5,000 ksi. The value of effective thickness of the existing pavement (D_{eff}) shall be no greater than effective PCC thickness of new composite pavement (D_{new}). In case that computed D_{eff} is greater than D_{new}, D_{eff} should be set up to be equal to D_{new}.

The parameter obtained as subgrade reaction is used to compute the required thickness of rigid pavement, D_{req} under provided traffic and other parameters based on 1993 AASHTO Guide (1993). Finally, the required overlay thickness is calculated as,

$$H_{over} = A(D_{req} - D_{eff}) \tag{3.12}$$

where the coefficient, A is the AC-to-PCC factor and can be determined as,

$$A = 2.2233 + 0.0099\,(D_{req} - D_{eff})^2 - 0.1534(D_{req} - D_{eff}) \tag{3.13}$$

It should be noted that the entire calculation process is conducted at all FWD deflection stations for any given pavement section which may consist of 30~60 stations. Therefore, statistical considerations are accounted for in order to produce a single overlay design thickness, H_{over}^{D}. The mean, $\overline{H}_{over}$, and the standard deviation, S_{over}, of the overlay thickness are computed, the design overlay can be computed as,

$$H_{over}^{D} = \overline{H}_{over} + Z_R S_{over} \tag{3.14}$$

Z_R represents a reliability coefficient, determined based on the reliability level R.

To illustrate the application of the revised design method as described, the detailed calculation performed with the FWD data from ASH-42 (Ashland County) is presented in Appendix B.

3.3 A Design Example with the Revised Design Procedures

In this section a design example is illustrated with the details of the intermediate results during the design process. WAS-50 is a composite pavement section located in Washington County Route 50 and is examined for the overlay design.

WAS-50 is used as an illustrative example with the details of the intermediate results during the design process (Figures 3.4~3.9). Figure 3.4 presents the measured FWD deflection data across the entire section which consists of 34 stations. At each station seven deflections were measured. For clarity only the deflection under the center of the falling weight, the deflections at 36 in. and 60 in. away from the center are plotted here; their patterns of distribution are quite consistent. The FWD deflection data were then used for back-calculation for the layer moduli. Subsequently in Figures 3.5~3.9, the results from the existing procedure based on the two-layer model and those from the revised procedure based on the three-layer model are presented together for comparison.

Figure 3.5 shows the back-calculated AC modulus (E_1), PCC modulus (E_2) and subgrade modulus (E_3). It can be seen that the moduli of different layers are well separated. The AC and PCC layer moduli were then converted to the equivalent modulus according to Eqs. (3.3~3.8) and the results are shown in Figure 3.6, which evidently shows that the three-layer model now produced significant larger equivalent moduli of the composite pavement than the two-layer back-calculation model. The subgrade reactions from different back-calculation models are also compared in Figure 3.7; the differences in subgrade reaction are much more modest than those in pavement moduli.

With the relevant moduli determined, the effective thickness of the existing pavement can be determined and is presented in Figure 3.8. The results show that the two-layer back-calculation model clearly underestimated the structural capacity compared with the three-layer back-calculation model. As a consequence, the overlay design thickness with the three-layer model is now much more reasonable than the existing procedure, as shown in Figure 3.9, which presents the distribution at all stations, mean and final design thickness. Originally a 5.15-in overlay thickness resulted from the two-layer model based design; with the three-layer model the overlay thickness becomes less than zero, meaning that no overlay is needed.

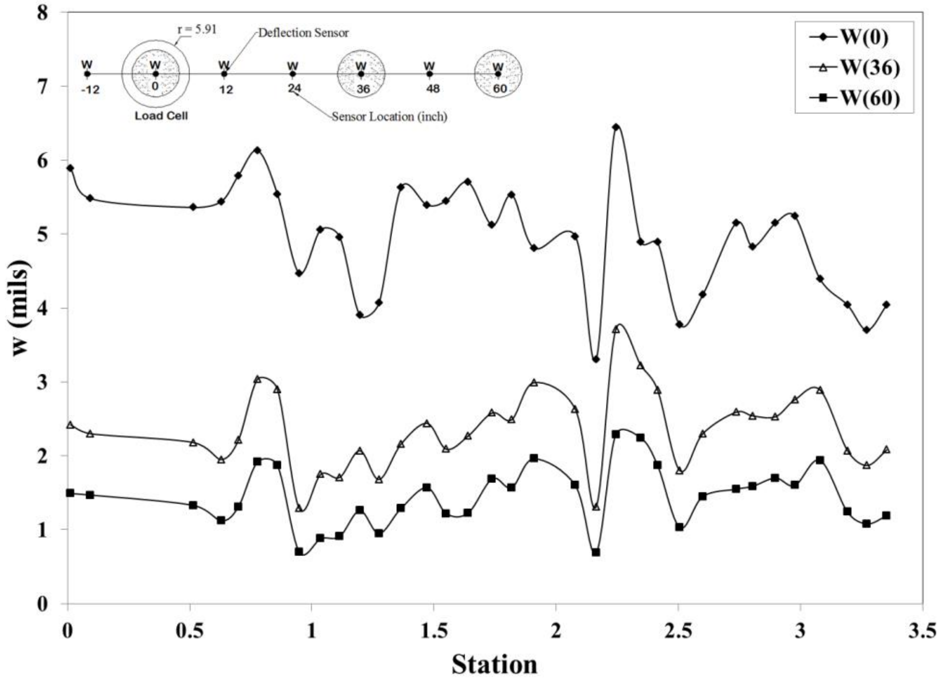


Figure 3.4. WAS-50: deflections at three sensor locations for FWD measurement across the entire pavement section.

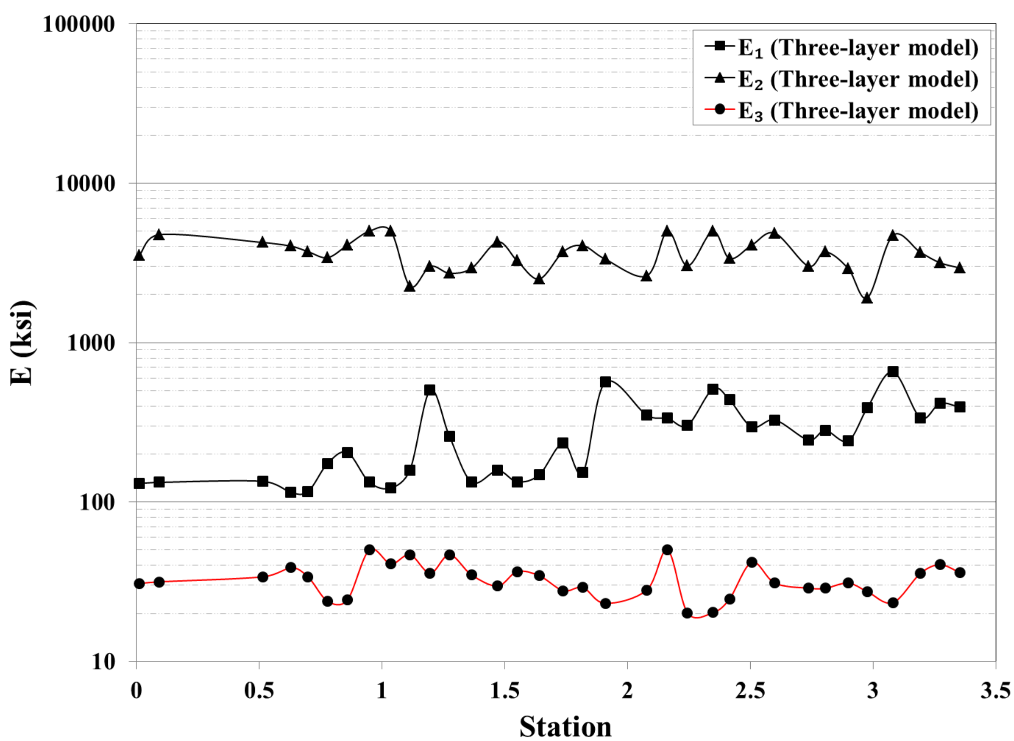


Figure 3.5. WAS-50: back-calculated moduli based on a three-layer model.

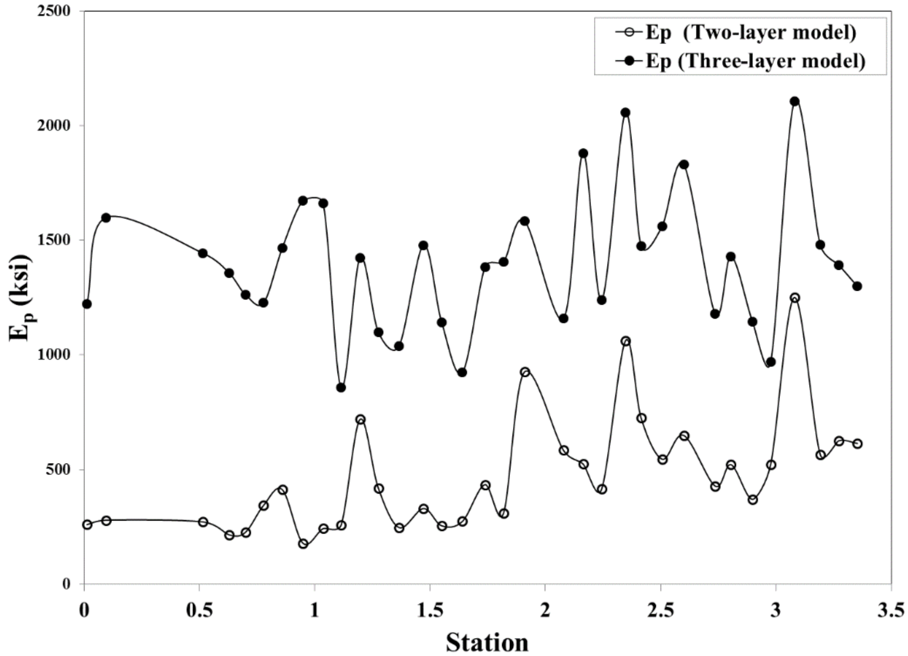


Figure 3.6. WAS-50: the equivalent moduli of the combined pavement layer based on two-layer and three-layer model.

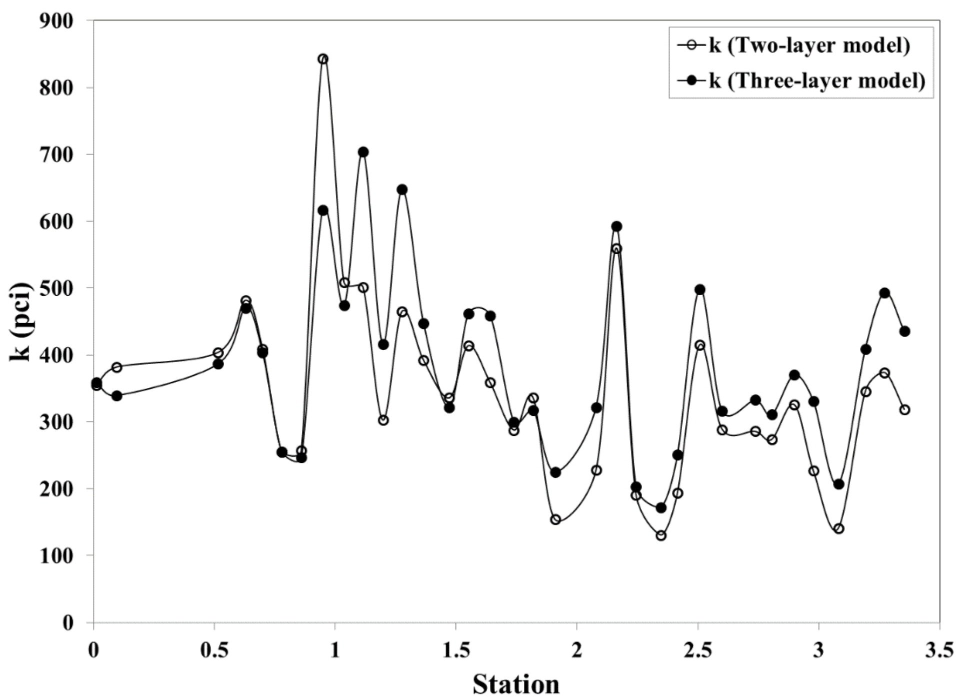


Figure 3.7. WAS-50: the subgrade reactions of the subgrade layer based on the two-layer and three-layer model.

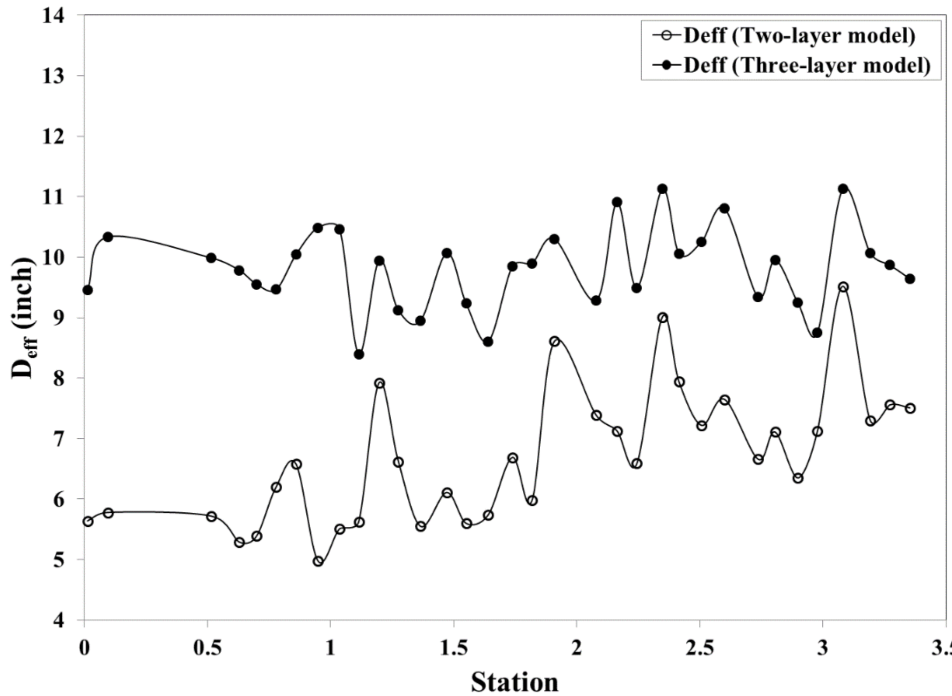


Figure 3.8. WAS-50: the effective thicknesses of composite pavements based on the two-layer and three-layer model.

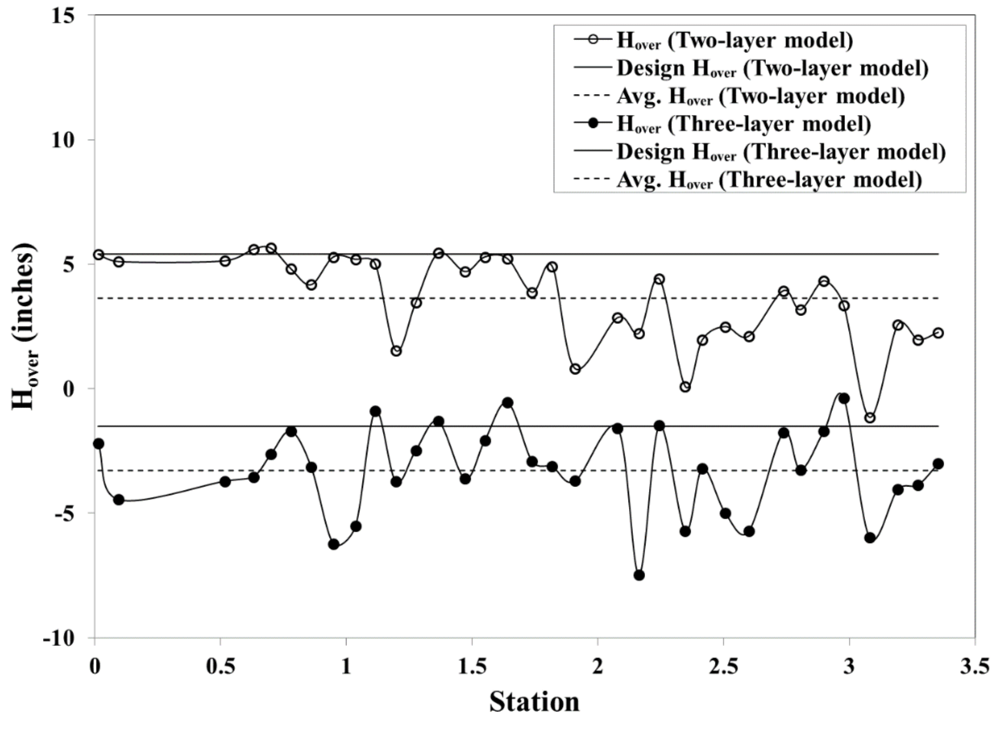


Figure 3.9. WAS-50: the overlay design thicknesses of composite pavements based on the two-layer and three-layer model.

3.4 Effective Thickness of PCC Slab Portion in Composite Pavements

A secondary goal of this research is to provide ODOT with the ability to mechanistically determine the effective thickness of the Portland Cement Concrete (PCC) slab portion of a composite pavement for use in the U.S. Army Corps of Engineers' equation for the design of unbonded concrete overlays. Once the back-calculated layer moduli are obtained, this thickness is readily available, via the following equation which is similar to Eq. (3.11) discussed earlier,

$$D_{eff(pcc)} = \frac{D_{pcc}}{[\,E_{new\,(pcc)}/E_{pcc}\,]^{0.333}} \tag{3.15}$$

Where, $E_{new\,(pcc)}$ is the modulus of new PCC (its default value is set to be 5,000,000 psi in the revised procedure), E_{pcc} is the back-calculated moduli for PCC layer and D_{pcc} is the PCC thickness of existing pavement.

An example is illustrated here in Table 3.1 using 3 stations in ATH-50. The pavement consists of 5.25 inches of AC and 9 inches of PCC. Back-calculated moduli are presented in Columns 3 ~ 5, evidently the 4th Column, E2, represents the moduli for PCC layer, E_{pcc}. In this case D_{pcc} is 9 in., Equation (3.15) provides the calculation for the effective of PCC layer, as shown in the last column.

Table 3.1. Calculation results for the effective thickness of PCC

Station	Load (lbf)	Modulus (psi)			Effective PCC thickness
		E1	E2	E3	
2.278	10681	320,355	2,798,722	48,940	7.42
2.374	10451	213,737	3,982,706	40,862	8.34
2.452	10089	765,149	5,000,000	24,106	9.00

It is noteworthy that the PCC modulus of existing pavement is imposed to be no greater than the modulus of new PCC, 5,000,000 psi, hence the effective thickness of PCC cannot be greater than its original thickness (Station 2.452).

Here is an important note about using the developed software for this computation: back-calculated rmoduli can be obtained from a file named “ReCalculateFWD.csv” inside a temporary folder named “BAKTemp” in C:\ drive. If the record of the back-calculated moduli is wanted, this file should be copied and saved in different location ***immediately*** after the design is completed. The data in this folder will be cleared and replaced in the next design.

3.5 Temperature Correction of Back-calculated AC Layer Moduli

The moduli of the asphalt concrete (AC) layer depend on the temperature and the pavement deflections are often measured under a wide range of temperature at different construction sections. Therefore, it may be necessary to correct the back-calculated AC layer moduli to a standard reference temperature.

In general, there are two approaches for temperature correction on asphalt layer moduli. Moduli of asphalt concrete at different temperatures can be converted to moduli at a reference temperature by applying temperature correction factors. The other approach is to modify deflections to those at a reference temperature; the corrected deflections are then used for back-calculation of asphalt concrete moduli. There have been a variety of methods developed in the literature (Akbarzadeh et al., 2012). The current study explores a few such methods compares the two approaches: deflection correction and moduli correction.

For the moduli correction approach, two representative methods are explored: a method developed by Chen et al. (2000), hereafter referred to as Chen's method, and a recommendation from Asphalt Institute (1982), hereafter referred to as AI's method.

For the deflection correction approach, two methods are investigated. The first correction method examined was proposed by Park et al. (2002) based on temperature correction procedure developed by Kim et al. (1995). The second method explored in the present study was developed by SHRP (1993).

The details of this investigation are documented in Appendix C. It is concluded that, overall the moduli correction approach is more consistent compared to deflection correction approach; in particular, Chen's method offers a simple and straightforward means for moduli corrections for the composite pavements. Therefore, in this section only the details of Chen's moduli correction method are offered.

Chen et al. (2000) developed a correction equation based on the FWD data from several projects in Texas and the results of back-calculation program MODULUS. The following equation is used in the present study,

$$E_{Tr} = E_T \left(\frac{1.8\,T+32}{1.8\,T_r+32}\right)^{2.4462} \tag{3.16}$$

where E_{Tr} is the modulus corrected to the reference temperature of T_r (20°C) and E_T is the modulus determined at temperature of T (°C).

The reference temperature used in this study is 68°F (20°C), since in AASHTO pavement design, the structural number is computed at a standard temperature of 68°F. Most of the research studies (e.g., Johnson and Baus, 1992; Baltzer and Jansen, 1994; Chen et al., 2000; Park et al., 2002) have chosen a reference temperature in the range of 68~77°F (20~25°C).

One important temperature needed for correction is the average temperature at the mid-depth of AC layer; it is usually selected as the representative value for the effective temperature of the AC layer where temperature typically varies through its depth. In the present study, the BELLS2 equation (Stubstad et al., 1998) is employed for predicting the mid-depth temperature,

$$T_d = \beta_0 + \beta_1 IR + [log_{10}(d) - 1.25][\beta_2 IR + \beta_3 T_{(1-day)} + \beta_4 \sin(hr_{18} - 15.5)] + \beta_5 IR \sin(hr_{18} - 13.5) \quad (3.17)$$

where T_d is the pavement temperature (°C) at depth *d* within the asphalt layer; IR is the surface temperature (°C) measured with infrared gauge; *d* is the depth (mm) at which the temperature is to be predicted; $T_{(1-day)}$ is the average of the previous day's high and low air temperatures (°C); hr_{18} is the time of day in a 24-hour system and calculated using an 18-hour asphalt temperature rise and fall function (Stubstad et al., 1998). The coefficients used in Eq. (3.17) can be found in Stubstad et al. (1998): β_0 = 2.780; β_1 = 0.912; β_2 = –0.428; β_3 = 0.553; β_4 = 2.630; β_5 = 0.027.

This temperature correction is later featured in the design software, offered as an option for the user to take into account the effect of the temperature on the AC moduli. As shown in the Chen' method discussed above as well as in Appendix C, all the methods we explored invariably involve certain empirical parameters/coefficients that were calibrated based on specific experiments and locations; these parameters may need to be recalibrated when applied to new locations or conditions. However, as shown in Appendix C, the layer moduli of several county routes were significantly improved after temperature correction (using the recommended values of parameters reported in the literature); hence it is generally recommended that the design engineer should consider the temperature correction, but the design software does provide the user with the flexibility of skipping this step.

3.6 Summary

A revised overlay design procedure for composite pavements is developed. It is based on a layered elastic approach adopted for the back-calculation process. A three-layer back calculation model implemented within the BAKFAA program is used to calculate the modulus of AC, PCC and subgrade. Moduli constraints and precision relaxation are applied to improve the quality of the back-calculation and intended to ensure that the back-calculated values of moduli are realistic. The results have shown that the revised procedure produces much more efficient designs. The evaluation and validation of the revised design procedure will be discussed in Chapter 4.

The present study also investigates suitable methods for temperature correction for pavement design in the state of Ohio. It is found that overall moduli correction approach is more consistent compared to deflection correction approach; Chen's method can be recommended as a simple and straightforward means for moduli corrections, and it is eventually included in the design software as an optional feature.

CHAPTER 4

Validation of the Proposed Revised Design Procedure

4.1 Introduction

A major part of the validation process is to examine the performance of the revised procedure using FWD data after overlay was constructed to assess the consistency of the design. It should be noted that, the research communities have generally recognized the fact that there are usually significant differences between moduli determined from back-calculation and those obtained through laboratory testing, and unfortunately, a well-defined relationship between laboratory and back-calculated moduli could not be established yet (Akram et al., 1994; Nazarian et al., 1995; Mikhail et al., 1999; Huang, 2003) Hence, it is important to focus on the consistency of the design procedure as far as its validation is concerned.

In this chapter, overlay design is first performed on FWD data before the overlay construction (hereafter referred to as pre-construction FWD data). After the overlay was done in the field, the FWD data (hereafter referred to as post-construction FWD data) obtained on the “new” overlay composite pavement are used for design to determine if and how much additional overlay thickness is still needed.

During this validation process it was found that in several projects the percentage of back-calculated moduli that are outside their conventional ranges appears to be excessively high; hence it is necessary to identify the reason why some FWD data lead to “outrageous” back-calculated layer moduli and thus large variation in design thickness. It was necessary to verify the layer thickness of composite pavements used for back-calculation. A number of station locations with FWD data that resulted in questionable back-calculated of layer moduli were identified. Field coring on these locations was carried out and the results are analyzed in this chapter.

4.2 Overlay designs with Pre and Post FWD data

Examples of 11 composite pavement sections in Ohio are summarized in Table 4.1 (with pre-construction FWD data) and Table 4.2 (with post-construction FWD data); and they were examined for the overlay design in the present study. Each section is denoted by the abbreviation of the county followed by the route number.

Table 4.1. Summary of overlay design results from the current (two-layer based) design and revised (three-layer based) design procedure using the pre-construction FWD data. Note that the temperature effects are not considered.

County	Thickness (in.)		Added Overlay (in.)	# of Stations	Existing Design (in.)			Revised Design (in.)		
	AC	PCC			Avg.	Std. Dev.	Design	Avg.	Std. Dev.	Design
ASD 42	6.00	9.00	1.5	63	-0.73	2.83	**2.90**	-10.65	4.75	**-4.56**
ATH 50	5.25	9.00	0	68	2.14	2.90	**5.14**	-6.65	2.61	**-3.95**
CUY 422	4.00	9.00	1.25	53	-1.28	2.19	**1.53**	-2.75	1.69	**-0.58**
FRA 71	6.75	10.00	1.5	54	6.48	1.41	**8.29**	-2.06	2.84	**2.62**
GUE 70	7.00	9.00	1.5	65	6.44	2.07	**9.10**	-1.06	2.66	**2.35**
HUR 20	5.75	9.00	0	38	1.52	3.12	**5.52**	-3.95	2.99	**-0.13**
LUC 475	6.50	9.00	1	39	5.70	1.26	**7.32**	-1.15	1.92	**1.30**
MIA 75	8.25	9.00	0	38	7.85	0.91	**8.79**	-0.80	2.28	**2.13**
TUS 250	4.50	9.00	0	34	2.30	2.01	**4.89**	-5.45	1.64	**-3.75**
UNI 33	6.00	9.00	0	47	2.15	1.39	**3.93**	-3.80	2.17	**-1.01**
WAS 50	4.25	9.00	0	34	3.63	1.71	**5.41**	-3.28	1.71	**-1.51**

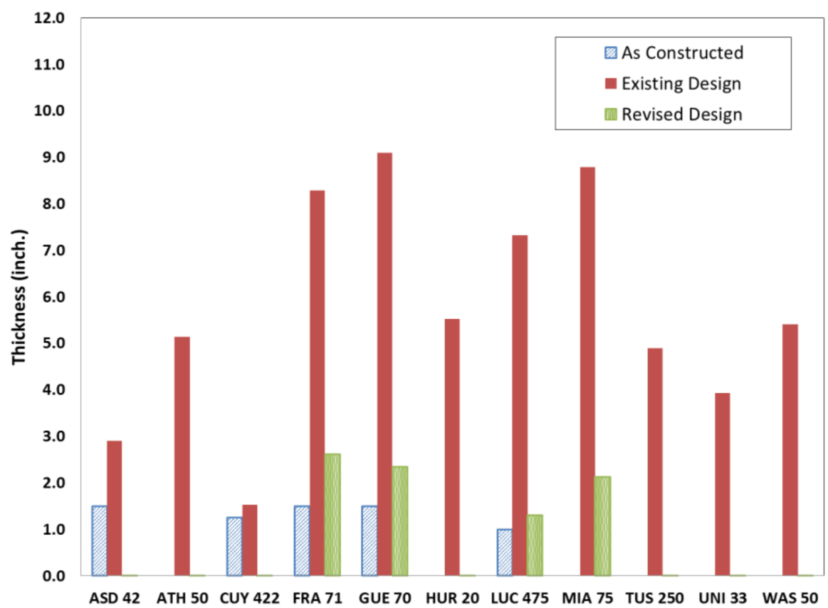


Figure 4.1. Overlay design thickness using the pre-construction FWD data for 11 composite pavement projects.

Table 4.2. Summary of overlay design results from the current (two-layer based) design and revised (three-layer based) design procedure using the post-construction FWD data. Note that the temperature effects are not considered.

County	Thickness (in.)		Added Overlay (in.)	No# Stations	Existing Design (in.)			Revised Design (in.)		
	AC	PCC			Avg.	Std. Dev.	Design	Avg.	Std. Dev.	Design
ASD 42	7.50	9.00	1.5	58	-2.22	3.64	**2.45**	-15.80	4.52	**-10.00**
ATH 50	5.25	9.00	0	62	-5.06	3.78	**-1.14**	-9.09	2.25	**-6.75**
CUY 422	5.25	9.00	1.25	51	-1.91	2.93	**1.53**	-4.92	1.49	**-3.01**
FRA 71	8.25	10.00	1.5	41	4.27	1.24	**6.31**	-6.97	1.58	**-4.36**
GUE 70	8.50	9.00	1.5	62	3.89	1.84	**6.25**	-6.13	1.55	**-4.14**
HUR 20	5.75	9.00	0	29	-1.07	5.21	**5.61**	-6.89	2.95	**-3.10**
LUC 475	7.50	9.00	1	26	2.68	1.30	**4.34**	-3.94	1.88	**-1.53**
MIA 75	8.25	9.00	0	32	1.87	2.61	**5.22**	-5.27	0.54	**-4.58**
TUS 250	4.50	9.00	0	25	2.97	1.80	**5.28**	-4.48	1.78	**-2.63**
UNI 33	6.00	9.00	0	45	2.26	1.60	**4.31**	-2.84	2.47	**0.32**
WAS 50	4.25	9.00	0	36	-1.70	3.12	**1.53**	-5.87	1.49	**-4.32**

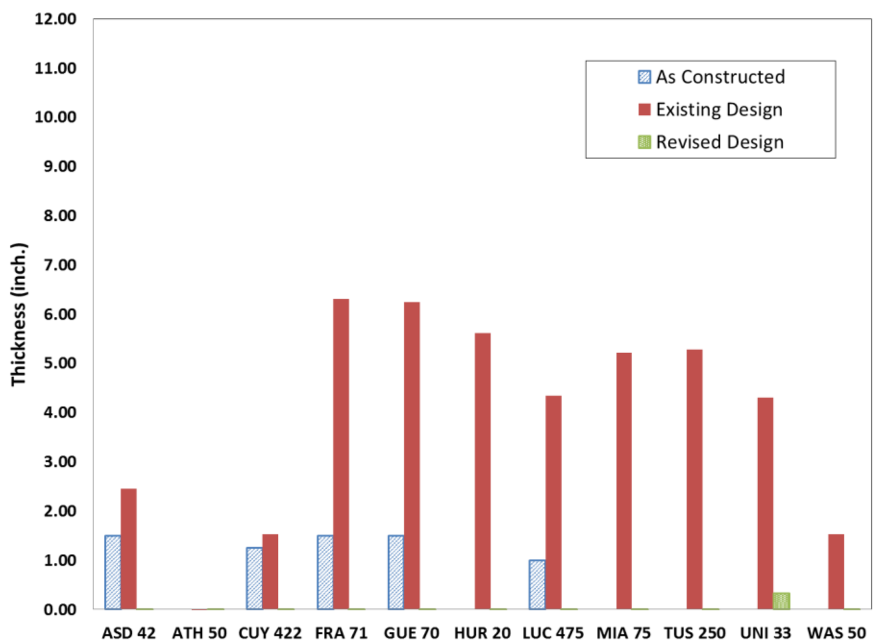


Figure 4.2. Overlay design thickness with post-construction FWD data for 11 composite pavement projects.

A summary of the final design thickness for all projects is also presented in Fig. 4.1 which also includes the actual thicknesses as constructed in the field. The results from the revised design with the three-layer back-calculation model are evidently significantly more efficient, no thicknesses are larger than 3 inches. The thickness “as constructed” in Figure 4.1 shows the actual constructed overlay thickness in the field, at the time it was believed that the existing procedure did not produce reasonable results for these pavement sections, so practical decisions were made largely based on field observations and engineering experience on these pavement conditions. A thickness indicated as zero meant that no overlay was constructed; only some milling and filling was done. Of course, these practical decisions do not necessarily justify the revised three-layer based design procedure, but it is clearly shown that the three-layer back-calculation model made some significant improvement on evaluating the structural capacity of the pavement conditions.

Five pavement sections (ATH-50, HUR-20, TUS-250, UNI-33, WAS-50) with no overlay done in the field but requiring significant overlay based on the existing design, now no longer require any overlay according to the revised design. Three sections (FRA-71, GUE-70, LUC-475) now have the design thicknesses that are very close to the field decisions. Two sections (ASD-42, CUY-422) with very modest overlay demand from the existing design now have overlay thicknesses to be reduced to zero. Only one section, MIA-75, remains with a (much reduced) demand of about 2-inch overlay. This is likely attributed to the temperature effects; FWD deflections were taken under a very high temperature (82.9 ~ 96.2°F at the surface) at this section, and therefore probably substantially overestimated, leading to the underestimation of AC moduli. Indeed, after the moduli corrections based on the temperature effects are applied, the overlay thickness for MIA-75 is reduced to -1.05 in. (i.e., no overlay needed).

It is of interest to examine the designs in the context of the combination of pre-construction and post-construction. After the actual overlay was constructed in the field, the so-called post-construction new FWD data became available and were used for the design calculations. The results are summarized in Table 4.2 and the final overlay thickness is graphically presented in Figure 4.2.

Comparing the design between pre-construction and post-construction, all sections have reduced overlay design than pre-construction, after milling or overlay. All except one (UNI-33) do not need additional overlay. UNI-33 (Union County) is a rare exception; it requires a small overlay thickness (0.32 in.), while in pre-construction design no overlay is required (note that this also happened with the existing design procedure: design thickness increases after post-construction). A close examination shows that the post-construction FWD data contain quite a few sets of large deflections, leading to large variations in the back-calculated moduli and the resulting effective thickness.

It should be noted that in all the design results presented thus far, the temperature effects have not been taken into account; the reason is that the existing procedure does not have this feature. For a fair comparison, the above examples did not consider these effects in the revised design. Details of moduli correction based on temperature effects are documented in Appendix C, which is focused on four pavement sections where the temperatures at FWD tests differed considerably from the standard temperature of 68°F and thus their effects could be very significant. Here, we offer a brief summary of the design outcomes for all sections when the temperature effects are considered in the revised design, as shown in Table 4.3. Overall consideration of temperature effects on AC moduli may further slightly reduce the overlay design thickness for the majority of the pavement sections whose FWD tests were done under temperatures above the reference temperature (68°F), while for the rest, the design thickness is increased slightly because their FWD tests were done below the reference temperature (68°F).

Table 4.3. Summary of overlay design results using the pre-construction FWD data, focusing on the comparison between temperature correction neglected vs. temperature correction considered

County Route	Thickness (in.)		Added overlay (in.)	No. of stations	Revised Design (in.) [Temp. Corr. Neglected]			Revised Design (in.) [Temp. Corr. Considered]		
	AC	PCC			Avg.	Std. Dev.	Design	Avg.	Std. Dev.	Design
ASD 42	6.00	9.00	1.5	63	-10.65	4.75	**-4.56**	-11.54	4.29	**-6.04**
ATH 50	5.25	9.00	0	68	-6.65	2.61	**-3.95**	-7.90	2.16	**-5.65**
CUY 422	4.00	9.00	1.25	53	-2.75	1.69	**-0.58**	-2.57	1.96	**-0.06**
FRA 71	6.75	10.00	1.5	54	-2.06	2.84	**2.62**	-2.53	2.63	**1.80**
GUE 70	7.00	9.00	1.5	65	-1.06	2.66	**2.35**	-1.15	3.91	**3.86**
HUR 20	5.75	9.00	0	38	-3.95	2.99	**-0.13**	-3.14	2.92	**0.61**
LUC 475	6.50	9.00	1	39	-1.15	1.92	**1.30**	-3.24	1.41	**-1.44**
MIA 75	8.25	9.00	0	38	-0.80	2.28	**2.13**	-3.49	2.14	**-0.74**
TUS 250	4.50	9.00	0	34	-5.45	1.64	**-3.75**	-6.44	0.93	**-5.47**
UNI 33	6.00	9.00	0	47	-3.80	2.17	**-1.01**	-2.53	2.34	**0.47**
WAS 50	4.25	9.00	0	34	-3.28	1.71	**-1.51**	-4.79	1.65	**-3.08**

The revised overlay composite design procedure produces much efficient and reasonable design thickness and overall it is consistent. It should be noted that large variations in FWD deflection data are a major issue for any deflection based overlay design. The main challenge has been to address the large variation as a result of questionable or inconsistent FWD data. It is important to understand the cause(s) of questionable FWD data and resulting large variation. The layer thickness affects the deflections and its accuracy impacts the design results. Hence, it is necessary to verify the layer thickness of composite pavements used for back-calculation.

4.3 Field Coring at Selected County Routes

Field coring was conducted to verify the thickness of AC and PCC layer at select stations in four construction projects based on a careful examination of FWD data. At each route, several station locations with FWD data that resulted in questionable back-calculated layer moduli were identified. Field coring on these locations was carried out and the results are analyzed in this section.

Coring was done in four different county routes, ASD-42 (Ashland), CUY-422 (Cuyahoga), HUR-20 (Huron) and UNI-33 (Union). On each route, in total 12 specimens were cored at selected (FWD) stations in a span of approximately 2~4 miles; 3 adjacent specimens separated by no more than a few feet were cored near the same location.

4.3.1 Summary of field coring results

It has been found that at some locations there are considerable variations in the thickness of the AC and/or PCC layers. For example, at several locations only flexible pavement was observed in place of supposed composite pavement. Using the corrected layer thicknesses, back-calculations are performed to evaluate the sensitivity of back-calculated moduli as affected by layer thicknesses. Relevant analysis is also included along with the coring results for each route. The details of the coring results and analysis can be found in Appendix D. In what follows the key findings are summarized in Table 4.3.

Table 4.4. Summarized coring results and analysis for 4 routes.

Route	Date	Expected Thickness (in.)		Measurements and Observations	Comments
		AC	PCC		
ASD-42	04/29/2015	7.5	9	5 out of 12 stations contain no PCC layer at all; AC thickness varies from 7 to 12 inches.	Two of these five identified stations are associated with very high deflections, which can be explained by the absence of PCC layer as previously unknown.
CUY-422	05/14/2015	5.25	9	Only 1 station appears to be without PCC. AC thickness varies from 5 to 11.5 inches	The deflection is normal for the station without PCC; One station has very high deflection, correction of layer thickness does not have a significant impact;

					Correction of thicknesses improves the back-calculation for the other 6 stations.
HUR-20	06/10/2015	5.75	9	1 station contains no PCC layer but 18 inches of AC. For the rest AC varies from 3.5 to 11 inches	The station with no PCC has very high deflections; Three stations have very high deflection and low back-calculated moduli for PCC layer. Coring indicates slightly different thicknesses, which do not change much about the back-calculated moduli.
UNI-33	06/30/2015	6	9	Thicknesses of all stations are close to provided ones.	Two stations have very high deflection; Correction of thicknesses does not improve. Correction of thicknesses improves the back-calculation of one station.

4.3.3 Evaluation of the field coring results

As shown in the preceding section on the field coring and subsequent analysis, despite the discovery of significantly different layer thicknesses at some locations, overall the difference between the actual thickness and the provided thickness at the majority of the examined locations is quite modest and its effect seems also limited in regards to the back-calculated moduli. Some locations without PCC layer are identified and their large deflections can now be explained by the absence of PCC as discovered. However, large deflections still persist in composite pavements, even with thickness correction from coring results, would still result in unreasonably small moduli and effective thickness of existing pavement, thus requiring very large overlay thickness.

An effort has been made to examine the pattern of the deflection before and after overlay construction in order to understand why some deflections are so high. Figs.4.3-4.6 show the deflection under the falling load (i.e. W(0), where the FWD load is dropped) at the pre and post- construction for each routes. There is no clear pattern that may offer some explanations for the high deflections.

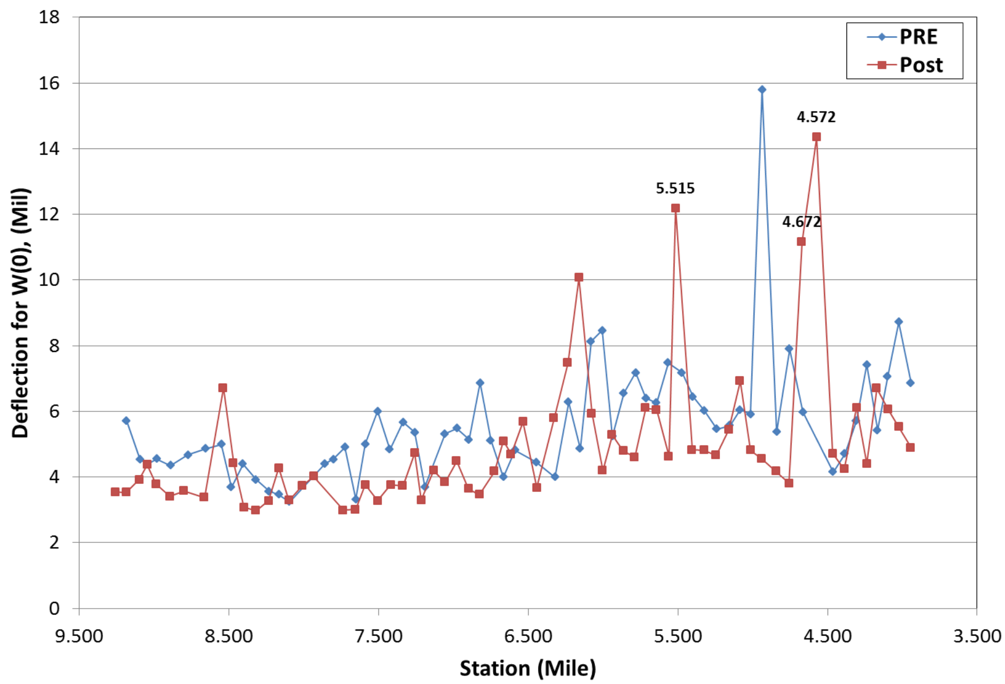


Figure 4.3. Comparison of deflections for ASD County

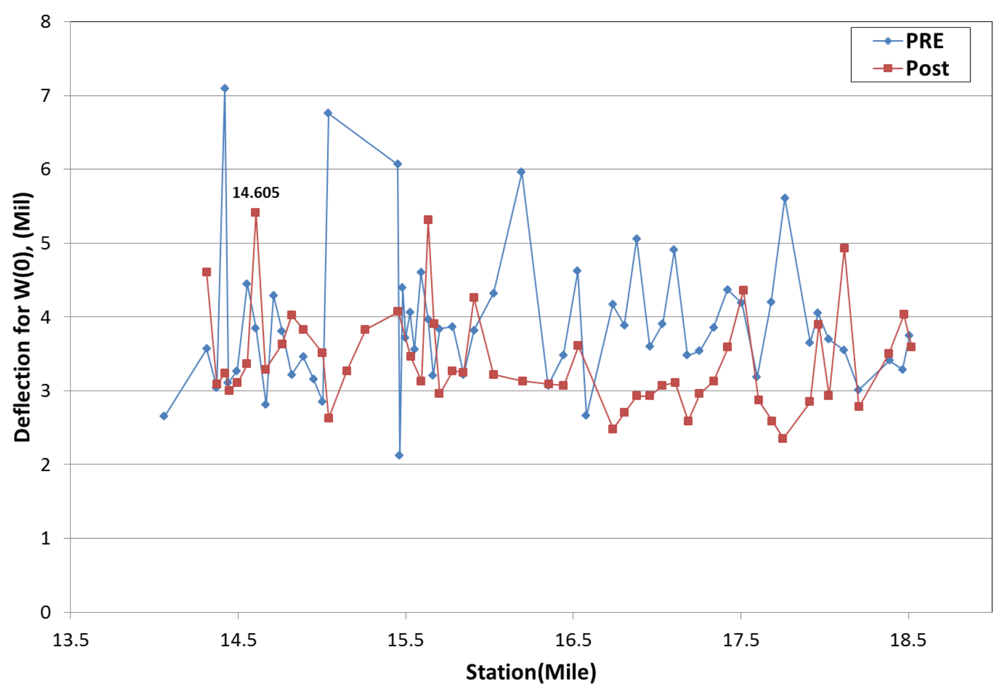


Figure 4.4. Comparison of deflections for CUY County

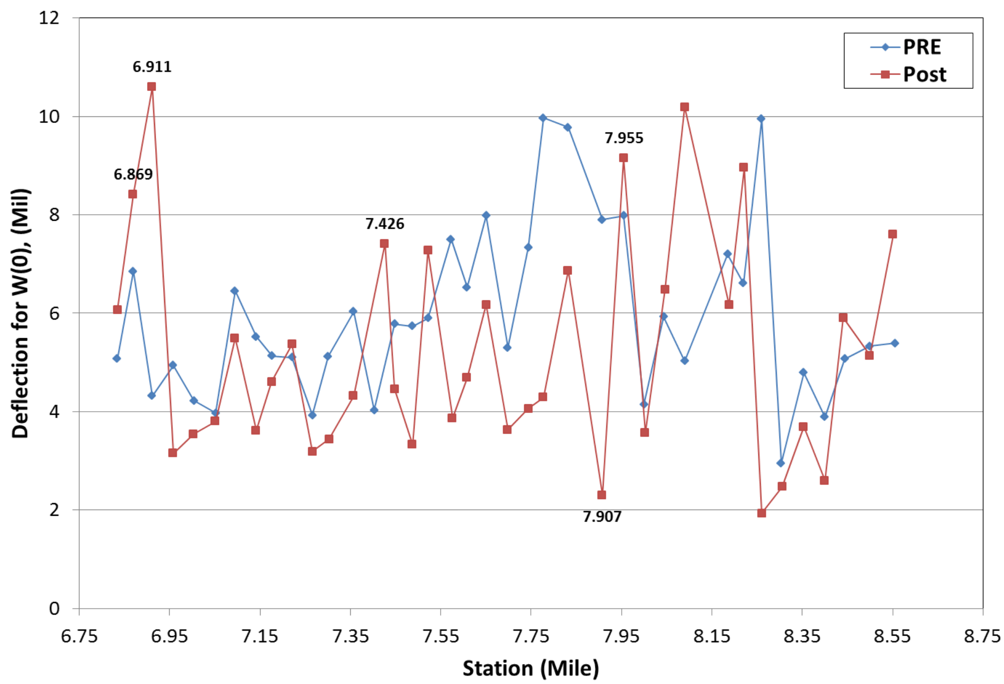


Figure 4.5. Comparison of deflections for HUR County

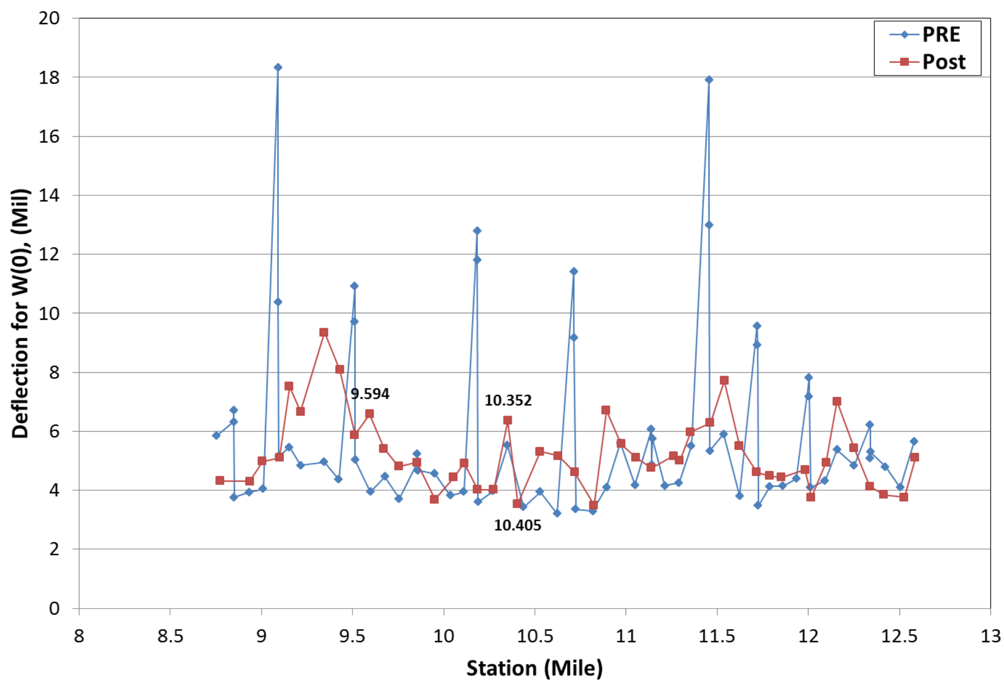


Figure 4.6. Comparison of deflections for UNI County

4.4 Summary

Evaluation using pre-construction and post-construction FWD data shows that overall the revised overlay design procedure for composite pavements is consistent and produces much more efficient overlay thickness design than the existing design procedure. The main concern is the large variations as a result of questionable FWD data, especially those apparently excessively high deflections.

Presently the revised design procedure imposes certain constraints on moduli ranges, and as a consequence, removes the “outrageous” back-calculated layer moduli and thus reduces the large variations of design thickness. However, in some projects, the percentage of discarded data which fail to meet the moduli constraints appears to be excessively high, it is necessary to identify the underlying reason. The research team conducted field coring to verify the layer thickness of composite pavements used for back-calculation, because incorrect or inaccurate layer thickness can lead to erroneous back-calculated layer moduli.

Based on the calculation results using the FWD data, 4 county routes, each with 12 locations were selected for coring to examine the layer thicknesses. Results of field coring reveal that there have been significant variations in layer thickness at some locations. It should be noted that the calculations excluded deflections from locations other than the mid-slab, hence the large variations cannot be attributed to the effects of joints/cracks. Analysis shows that the influence of the layer thickness difference (between the provided and the measured in the field) is quite modest, and cannot solely explain the large variations in the measured FWD deflections and the back-calculated moduli. The cause of the large variations in the deflection data remains a subject worthy of further investigations.

CHAPTER 5

Implementation of the Overlay Composite Design Software

5.1 Introduction

The software for design of composite pavement overlay is also implemented using VBA excel and Visual Basic (.net framework) on which the currently used design software was built, providing certain continuity for users who are already familiar with the existing software. A streamlined step-by-step design process is implemented in this new software: reading FWD data, selecting data (at different load level), back-calculation for layer moduli, adjusting temperature effect (optional); and calculation of overlay thickness.

5.2 Overview of the software

An instructional manual is provided in Appendix E, detailing the software installation and user guidelines. Verification of the software implementation is demonstrated in Appendix F.

In this chapter a brief overview of the design process in the process is offered. Five major steps are involved in a typical process; and the progress of the design is normally indicated in the left pane on the window as shown in Figure 5.1.

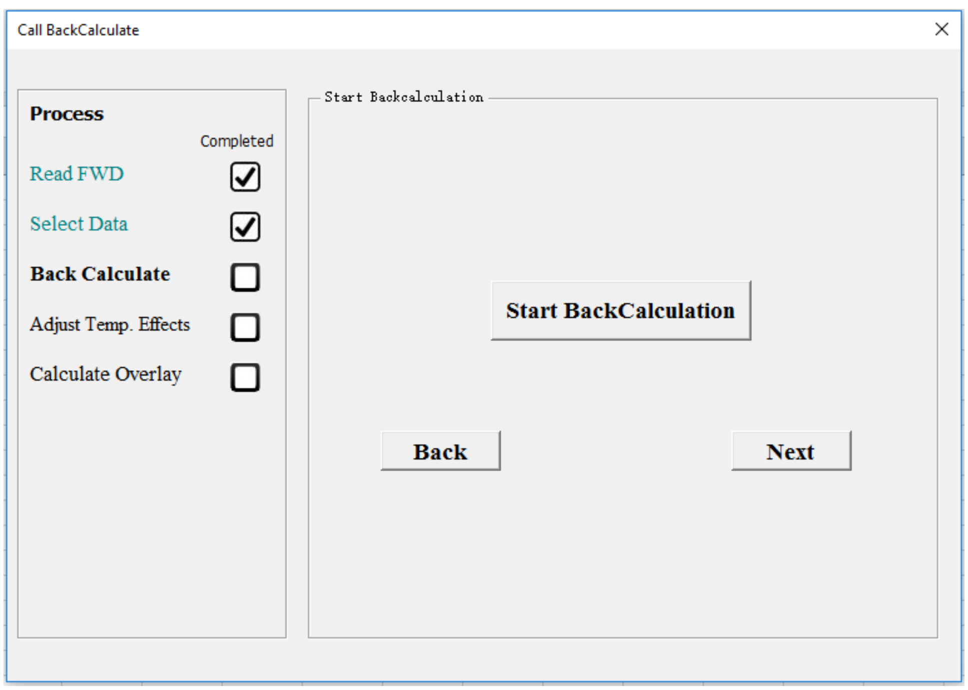


Figure 5.1. A typical window showing the progress of the design process: the first two steps completed, ready to start back-calculation.

1. Read FWD: select the FWD file (from windows browser) for the overlay design.
2. Select Data: each FWD files typically consists FWD deflections under 3 different levels of load/falling weight (standard, high, very high); the user needs to select the deflections corresponding to a certain level of load.
3. Back-Calculate: selected FWD deflection data are used to back-calculate the layer moduli. First it is done under a high precision convergence (low error tolerance) to seek the best match with the measured FWD deflections. Then a second back-calculation may be needed for those, if any, back-calculated moduli that are not within acceptable ranges, this time under a lower precision convergence (higher error tolerance). Subsequently, the user examines the match with the measured FWD deflections and determines whether to keep these back-calculated moduli. This is an interactive process and potentially the most time-consuming step of the entire design.
4. Adjust Temperature Effects: this feature is provided to take into account the effects of the temperature at FWD testing on the AC layer moduli, but the user does have the flexibility of skipping this step when deemed appropriate. The AC moduli are adjusted to those at a standard temperature (68°F).
5. Calculate Overlay: in this final step the layer moduli are converted to the effective moduli and the effective thickness of composite pavement is determined and overlay thickness is calculated.

CHAPTER 6

Summary, Conclusions, and Recommendations

6.1 Summary

The overlay thickness design procedure currently employed by ODOT works well for both flexible and rigid pavements, but it tends to produce very conservative design for composite pavements. For composite pavements with relatively thick existing asphalt overlays, the existing design procedure consistently recommends very high overlay thickness that is often deemed structurally unnecessary. In this research study, overlay design with the existing overlay design procedure for composite pavements is evaluated using the actual field FWD data.

A revised composite pavement overlay design procedure is developed based on a layered elastic back-calculation process. A three-layer back calculation model is used to calculate the modulus of AC, PCC and subgrade. Precision relaxation and moduli constraints are applied to ensure that the back-calculated values of moduli are realistic. The comparison between the existing procedure and the revised procedure shows that the revised procedure produces design thicknesses that are much more in line with engineering judgement.

The revised overlay composite design procedure is validated using both pre- and post-construction FWD data. In addition, the research team conducted field coring to verify the layer thickness of composite pavements in select stations on several county routes and the relevant results are analyzed. Temperature effects on AC moduli are also considered and addressed through an investigation of two correction approaches. Finally, the revised overlay design procedure is implemented into a design software program.

6.2 Conclusions

The primary cause for the overly conservative design of the existing design is mainly due to the simplistic treatment of the AC and PCC layers as a combined layer in the two-layer back-calculation model. As a result, this back-calculated modulus of the existing pavement is considerably underestimated.

Overall the revised overlay design procedure for composite pavements is consistent and produces much more efficient overlay thickness design. A comparison of the revised procedure and the existing procedure shows that the three-layer model produces higher effective thickness than the two-layer model for the same pavement structure. Therefore, the required overlay thickness is reduced.

The main challenge for further improving the overlay design procedure is the large variations in back-calculated moduli as a result of questionable FWD data. Two strategies are introduced in the revised procedure: (1) relaxation of precision (error tolerance), if a precise matching with the measured deflections yields unrealistic layer moduli; this allows one to obtain realistic layer moduli while maintaining reasonable matching with the measured deflections; (2) moduli constraints imposed, if the back-calculation under a low precision still produces moduli outside the commonly acceptable ranges. In the software implemented, the user can examine the back-calculated results and compare with the measured deflections before rendering a decision on whether to use or discard the back-calculation results associated with questionable FWD deflection data.

The moduli of the AC layer depend on the temperature and the pavement deflections are often measured under a wide range of temperature at different construction sections. Hence it is necessary to correct to the back-calculated AC layer moduli to a standard reference temperature. Two different approaches for temperature correction on AC layer moduli are explored in the present study: deflection correction and moduli correction. Overall moduli correction approach is more consistent; in particular, Chen's method can be recommended as a simple and straightforward means for moduli corrections for the composite pavements.

Results of field coring reveal that there is significant variation in layer thickness at some locations. However, calculations show that the influence of the layer thickness variation as observed is quite modest, and such thickness variation cannot solely explain the large variation in the FWD deflections or back-calculated moduli. It should be noted that the problem of large variations in back-calculated moduli is not necessarily tied to the three-layer back-calculation model adopted in the revised design procedure; it remains as a major challenge for any deflection based design method. The cause of the large variations in the deflection data is a subject worth further studying.

6.3 Recommendations

The following recommendations regarding the development of an improved overlay design for composite pavements have already been implemented in the revised design procedure and software:

- A three-layer back-calculation model should be adopted into the deflection based overlay design procedure and be implemented in the design software.
- In the design software, the user should be provided an option to examine and compare deflection matching and determine whether to keep or discard the questionable deflection data.
- Temperature based correction on layer moduli should be offered as an optional feature in the design software.

Based on the results of this research study, some suggestions for future investigations can be made:

- Records about pavement maintenance regarding milling, overlay or replacements should be constantly updated and made available to design engineers who may need accurate layer thicknesses in the overlay design.

- Large variations in the measured FWD deflection data remain a major source for potential errors or inaccuracies. These very large deflections may result in unreasonably small moduli and effective thickness of existing pavement, thus requiring very large overlay thickness. The research team recommends that this problem be further investigated so that the design overlay thickness is not distorted by the inclusion or exclusion of these very large deflections. It is suggested that future investigation may potentially include additional FWD deflection tests to verify the original large deflection measurements and identify their sources or causes.

Appendix-A

Existing Design Procedure for Composite Pavements

Existing Design Procedure for Composite Pavements

Back Calculation

a) Find the road deflection data at:

0 inch = $D(1) = W_1$
12 inch = $D(2) = W_2$
24 inch = $D(3) = W_3$
36 inch = $D(4) = W_4$

b) Compute the area of the deflection basin in inches as follows: -

$$\boldsymbol{Area = \frac{1}{D(1)}[\,6D(1) + 12D(2) + 12D(3) + 6D(4)]} \tag{A1}$$

Determine the radius of relative stiffness, *l*, from the area- *l* relationship graph.

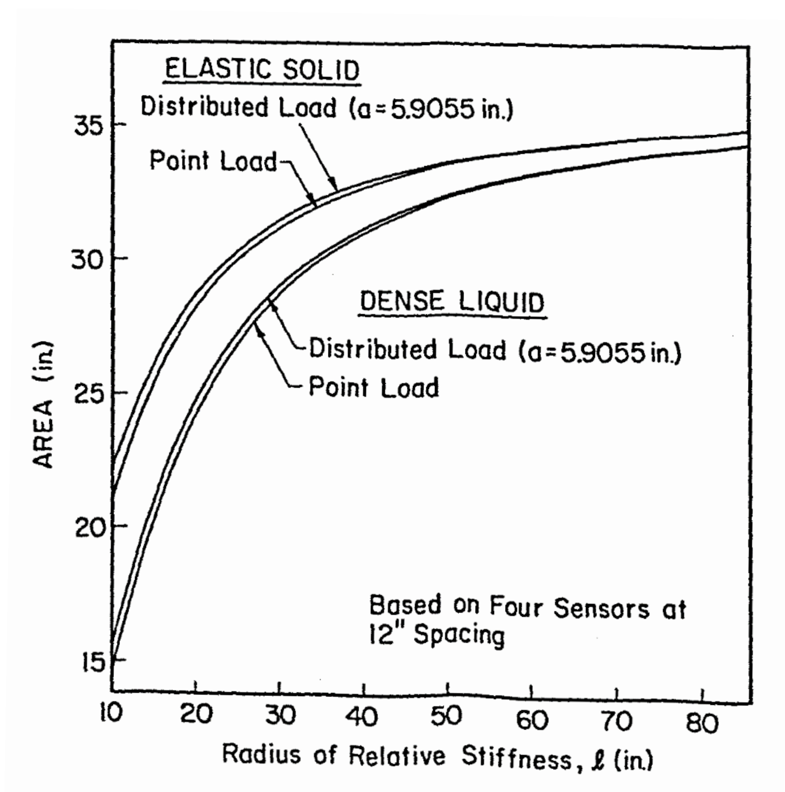


Figure A1. Variation of Area with *l* [After Ioannides (1990)]

c) Determine the non-dimensional deflection at first sensor (d_0), using the following graphs (Figure A2 or A3)

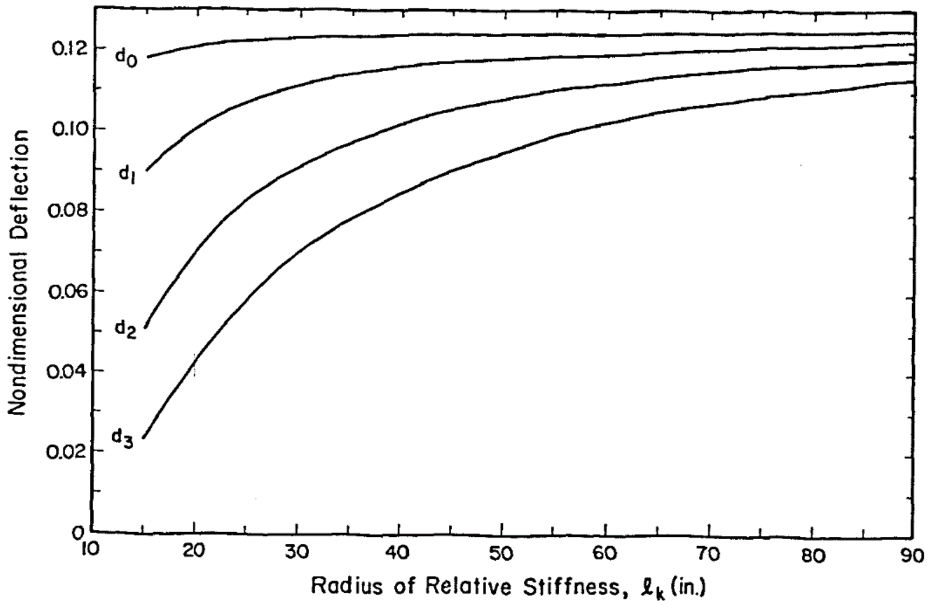


Figure A2. Variation of Dimensionless Deflections with l [After Ioannides (1990)], for Dense Liquid Foundation

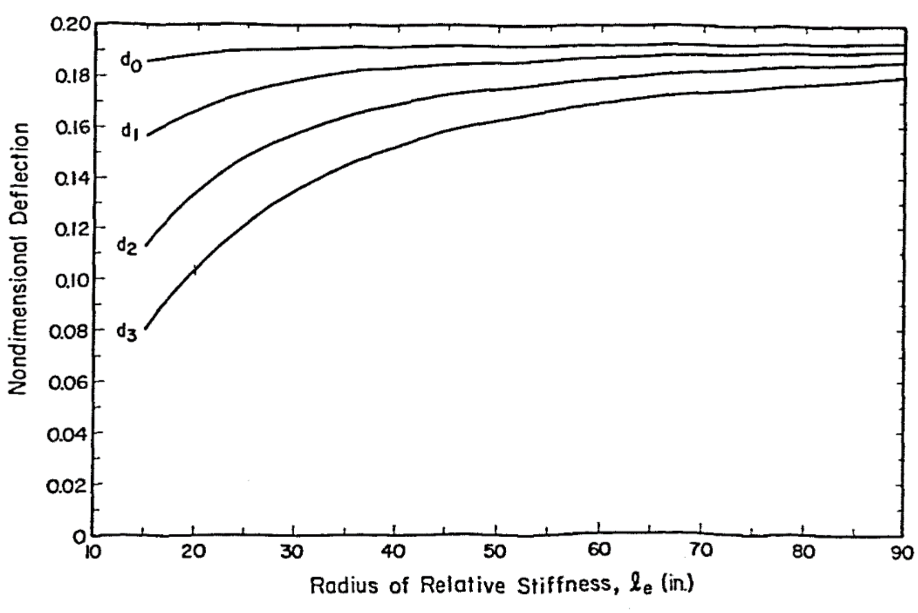


Figure A3. Variation of Dimensionless Deflections with l [After Ioannides (1990)], for Elastic Solid Foundation

d) Back-calculate the effective modulus, (E_p)

$$E_p = \frac{12 * P * l^2 * (1-\mu^2) * d_0}{h^3 * W_1} \tag{A2}$$

e) The subgrade reaction (k) is calculated via the following relationship,

$$k = \frac{d_0 * P}{W_1 * l^2} \tag{A3}$$

Effective thickness of existing pavement

f) Calculate the rigidity of AC layer (R_1) and PCC layer (R_2) with following relationship,

$$R_1 = \frac{E_{ac}[\frac{h_{ac}^3}{12} + h_{ac}(0.5 * h_{ac} + h_{pcc} - b)^2]}{1 - v_{ac}^2} \tag{A4}$$

$$R_2 = \frac{E_{pcc}[\frac{h_{pcc}^3}{12} + h_{pcc}(b - 0.5 * h_{pcc})^2]}{1 - v_{pcc}^2} \tag{A5}$$

where b can be computed with following relationship,

$$b = \frac{\left(\frac{E_{ac}}{E_{pcc}}\right) * h_{ac} * (0.5 * h_{ac} + h_{pcc}) + 0.5 * h_{pcc}^2}{\left(\frac{E_{ac}}{E_{pcc}}\right) * h_{ac} + h_{pcc}} \tag{A6}$$

Calculate E_{eff}, the equivalent elastic modulus of new combined pavement layer with the relationship,

$$E_{eff} = \frac{12 * (1 - v^2)(R_1 + R_2)}{h^3} \tag{A7}$$

g) Calculate D_{new} with the following relationship,

$$D_{new} = \frac{h_{ac}}{2} + h_{pcc} \tag{A8}$$

h) From E_p (Step d), D_{new} and E_{eff}, calculate the effective thickness of existing pavement with the relationship,

$$D_{eff} = \frac{D_{new}}{[E_{eff} / E_p]^{0.333}} \tag{A7}$$

Required Pavement Thickness, (Dreq)

i) The required pavement thickness ($D=D_{req}$) is determined using 1993 AASHTO Guide's rigid pavement design equation as follows,

$$\boldsymbol{log_{10}W_{18} = Z_R S_0 + 7.35\,log_{10}(D+1) - 0.06 + \frac{log_{10}[\Delta PSI/(4.5-1.5)]}{1+[(1.624\times 10^7)/(D+1)^{8.46}]} + (4.22 - 0.32P_t)\,log_{10}\left\{\frac{S_c' C_d}{215.63J}\left(\frac{D^{.75}-1.132}{D^{.75}-[18.42/(E_c/k)^{.25}]}\right)\right\}} \qquad \text{(A8)}$$

Calculation of AC overlay Thickness

j) Required overlay thickness can be calculated by,

$$\boldsymbol{H_{over} = A(D_{req} - D_{eff})} \qquad \text{(A9)}$$

Where, AC to PCC factor, A is determined as,

$$\boldsymbol{A = 2.2233 + 0.0099\,(D_{req} - D_{eff})^2 - 0.1534(D_{req} - D_{eff})} \qquad \text{(A10)}$$

Statistical Calculation

The final design overlay thickness is computed as,

$$\boldsymbol{Design\ H_{over} = \bar{H}_{over} + Z_R S_{over}} \qquad \text{(A11)}$$

where $\mathrm{\bar{H}_{over}}$ = mean value of $\mathrm{H_{over}}$

$\mathrm{S_{over}}$ = Standard deviation of $\mathrm{H_{over}}$

$\mathrm{Z_R}$ = Reliability term, determined based on reliability level R.

A Design Example Using the Existing Method

An example (TUS-250) is demonstrated here with the following design parameters:

PROJECT: 045603
DISTRICT: 11
COUNTY: TUS
ROUTE TYPE: Interstate
ROUTE NUMBER: 250
PAVEMENT TYPE: Composite
NUMBER OF LANES: 4
LANE TESTED: 1
TEST DATE: 04/18/11
EXISTING PAVEMENT TYPE: Composite
OVERLAY PAVEMENT TYPE: AC Overlay

GEOMETRY OF EXISTING PAVEMENT:
THICKNESS OF AC LAYER = 4.50
POISSON RATIO OF AC = 0.35
ELAS. MODULUS OF NEW AC = 450,000
THICKNESS OF PCC SLAB = 9.00
POISSON RATIO OF PCC = 0.15
ELAS. MODULUS OF NEW PCC = 5,000,000

TOTAL DEPTH OF PAVEMENT = 13.50
EQUIVALENT POISSON RATIO = 0.22
EQUIVALENT ELAS. MODULUS = 1,928,175

OVERLAY DESIGN:
DESIGN TRAFFIC E18 = 29,150,000
RELIABILITY R = 90%
ZR = -1.28
TRAFFIC STANDARD DEVIATION S0 = 0.10
INITIAL PSI Pi = 4.50
TERMINAL PSI Pt = 2.50
ELASTIC MODULUS OF NEW PCC Ec = 5,000,000
NEW PCC MODULUS OF RUPTURE Sc = 700.00
LOAD TRANSFER COEFFICIENT J = 3.20
DRAINAGE FACTOR Cd = 1.00

(1) The following results were obtained through ODOT's design software

Station	Lane	Load (lbf)	W(0)	W(12)	W(24) (mils)	W(36)	Lk (in.)	Ep (ksi)	k (pci)	Deff (PCC)	Dreq (PCC) (in.)	Hover (AC)
12.775	Right	10,155	3.98	3.14	2.62	2.05	22.91	757.17	295.0	8.24	9.93	3.36

(2) A manual calculation confirms the software design results; in what follows all the calculation steps are presented

a) Deflection data at,
D (1) = w1= 0.00398
D (2) = w2 =0.00314
D (3) = w3=0.00262
D (4) = w4=0.00205

b) Area of the deflection basin in inches as follows:
Area = $\frac{1}{D(1)}[\,6D(1) + 12D(2) + 12D(3) + 6D(4)]$

=26.4573 in.
The radius of relative stiffness:
l = 22.9146 in.

c) Non-dimensional deflection at first sensor (d_0) = 0.1216

d) Back Calculation of Effective modulus,(E_p) and (k),
From P = 10155 lb.; μ = 0.21667; h= 13.5; w1 = 0.00398
Calculation yields: E_p = 757.17 ksi

e) Back Calculation of the subgrade reaction (k)
k= 295.40 pci

f) b= 4.79
R_1 = 100177952.08
R_2 = 314631205.57
E_{eff} = 1928175.20 psi

g) D_{new} = 11.25 in.

h) D_{eff} = 8.241 in.

i) D_{req} = 9.927 in.

j) $A = 2.2233+0.0099(D_{req} - D_{eff})^2 - 0.1534(D_{req} - D_{eff}) = 1.993$ in.
$H_{over} = A\,(D_{req} - D_{eff}) = 3.36$ in.

Appendix- B
Revised Design Procedure and Examples

Revised Design Procedure and Examples

A design has been done based on the revised design procedure for Ashland (ASD 42) county and presented in this appendix. For convenience, a step by step procedure has been summarized here before an example is presented.

a) E_1, E_2 and E_3 of three different layers (Asphalt, PCC and subgrade) are obtained.

(Note: Back-calculated results can be obtained from a file named "ReCalculateFWD" inside a temporary folder named "BAKTemp" in C:\ drive)

b) E_p is calculated based on the rigidity concept using E_1 and E_2.

$$\mathbf{E_p} = \frac{\mathbf{12*(1-v^2)(R_1+R_2)}}{\mathbf{h^3}} \tag{B1}$$

where

$$\boldsymbol{v} = \frac{\boldsymbol{v_{ac}h_{ac}+v_{pcc}h_{pcc}}}{\boldsymbol{h_{ac}+h_{pcc}}} \tag{B2}$$

$$\boldsymbol{h} = \boldsymbol{h_{ac}} + \boldsymbol{h_{pcc}} \tag{B3}$$

And,
h_{ac} = thickness of AC layer
h_{pcc} = thickness of PCC layer
E_{ac} = elastic modulus of AC layer calculated from back-calculation
E_{pcc} = elastic modulus of AC layer calculated from back-calculation
v_{ac} = Poisson's ratio of AC material
v_{pcc} = Poisson's ratio of PCC material
R_1 = Rigidity of the AC layer
R_2 = Rigidity of the PCC layer

R_1 and R_2 can be calculated as,

$$\boldsymbol{R_1} = \frac{\boldsymbol{E_{ac}[\frac{h_{ac}^3}{12}+h_{ac}(\,0.5*h_{ac}+h_{pcc}-b)^2]}}{\boldsymbol{1-v_{ac}^2}} \tag{B4}$$

$$\boldsymbol{R_2} = \frac{\boldsymbol{E_{pcc}[\frac{h_{pcc}^3}{12}+h_{pcc}(\,b-0.5*h_{pcc})^2]}}{\boldsymbol{1-v_{pcc}^2}} \tag{B5}$$

and *b* can be computed with following relationship,

$$\boldsymbol{b} = \frac{\boldsymbol{\left(\frac{E_{ac}}{E_{pcc}}\right)*h_{ac}*(0.5*h_{ac}+h_{pcc})+0.5*h_{pcc}^2}}{\boldsymbol{\left(\frac{E_{ac}}{E_{pcc}}\right)*h_{ac}+h_{pcc}}} \tag{B6}$$

c) k is calculated using the relationship,

$$\boldsymbol{k} = \left(\frac{\boldsymbol{E_f}}{\boldsymbol{E_{eff}}}\right)^{\frac{1}{3}} \times \left(\frac{\boldsymbol{E_f}}{\boldsymbol{1-v_f^2}}\right) \times \frac{\boldsymbol{1}}{\boldsymbol{h}} \quad \text{(B7)}$$

where $E_f = E_3$ = elasticity of subgrade; ν_f= Poisson's ratio of subgrade.
k is the dynamic subgrade reaction and is multiplied by 0.42 to yield the static value.

d) Assuming E_{ac} =450,000 and E_{pcc} = 5,000,000 for new pavement, E_{eff} is calculated using Eq. (A8)
e) D_{new} is calculated using Eq. (A7)
f) D_{eff} is calculated using Eq. (A9)
g) D_{req} is calculated using Eq. (A10)
h) Finally, the overlay calculations are done using Eqs. (A11) ~ (A13).

<u>Example of Calculation:</u>

To illustrate the application of the revised design method as described the calculation has been performed for the pre-construction FWD data of the first station from ASD-42. (Ashland County).

a) From the back-calculation results, we have

E_{ac} = 295023 psi
E_{pcc} = 5000000 psi
E_{sub} = 34316 psi

b) For Ashland County we have,

h_{ac} = 6 in.
h_{pcc} = 9 in.
v_{ac} = 0.35
v_{pcc} = 0.15

Eqs. (B7), (B5) and (B6) yield

b = 4.78 in.
R_1 = 111095512.16 psi
R_2 = 314451015.84 psi

Eqs. (B2) and (B3) yield

v = 0.23
h = 15 in.

Based on Eq. (B1), the effect modulus can be obtained

E_p = 1433.01 ksi

c) Eq (B.7) yields

k_{dyn}= 826.84 ksi

Thus, by multiplying k_{dyn} with 0.42 we obtain,

k_s = 347.27 ksi

d) To calculate E_{eff}, we need to have the parameters of a newly constructed composite layers, which are as follows,

E_{ac} = 450,000 psi;
E_{pcc} = 5,000,000 psi

Eqs. (B7), (B5) and (B6) yield,
$b = 4.92$ in.
R_1 = 163268614.62
R_2 = 319038457.86
Also, note that $D_{new} = \frac{h_{ac}}{2} + h_{pcc}$ = 12.00 inches
Eq (A8) produces
E_{eff} = 1624152.99 psi

e) $D_{new} = \frac{h_{ac}}{2} + h_{pcc}$ = 12.00 in.

f) Eq (A.9) yields
D_{eff} = 11.51 in.

g) The required depth of rigid pavement for current traffic (ESAL = 3.39 millions), based on Eq. (A10), is
D_{req} = 6.70 in.

h) Eqs. (A11) and (A12) yield
A = 3.19
H_{over} = - 15.33 inches

Repeating the above calculation for all stations, the design thickness at each station can be readily obtained. The statistical parameters are then calculated:

$\overline{H}_{over}$ = -10.65 in.
S_{over} = 4.75 in.
Z_R =1.282

Therefore, the final design thickness is

H_{over} = -4.56 inches

In the similar way, all the calculations can be done for other stations of the county and the results are presented in Table B1.

Table B1. ASD 42: design results with the revised design procedure

Station	Load (lbf)	Modulus (psi)			k (pci)	E (ksi)	Dreq (PCC) (in.)	Deff (PCC) (in.)	A	Hover (AC) (in.)
		E1	E2	E3						
9.26	10681	295,023	5,000,000	34,316	347.27	1433.01	6.70	11.51	3.19	-15.33
9.183	10538	291,899	5,000,000	23,540	210.29	1429.08	7.04	11.50	3.10	-13.85
9.093	10155	406,089	4,971,859	28,062	257.89	1564.74	6.92	11.85	3.22	-15.91
9.045	10133	928,851	1,878,406	27,345	262.42	1339.10	6.90	11.25	3.08	-13.39
8.983	10188	523,028	4,006,975	26,619	244.16	1492.80	6.95	11.67	3.17	-14.95
8.889	9979	236,402	4,689,240	44,309	505.31	1292.95	6.36	11.12	3.18	-15.12
8.772	10089	344,367	3,262,475	33,147	359.93	1120.46	6.67	10.60	2.98	-11.71
8.656	10220	334,091	4,023,353	29,905	300.71	1272.90	6.81	11.06	3.06	-13.00
8.549	10155	328,582	3,988,612	28,443	282.33	1258.71	6.85	11.02	3.04	-12.66
8.485	10275	626,026	4,897,569	34,140	319.11	1809.36	6.77	12.00	3.30	-17.25
8.407	10199	378,886	4,268,488	27,699	264.28	1380.15	6.90	11.37	3.11	-13.88
8.318	10199	439,991	5,000,000	35,852	353.99	1612.04	6.69	11.97	3.31	-17.48
8.232	10133	749,157	5,000,000	32,534	290.78	1972.14	6.83	12.00	3.28	-16.95
8.166	10242	847,623	3,787,123	35,506	337.22	1793.72	6.73	12.00	3.31	-17.45
8.096	10231	950,503	2,755,336	41,041	422.85	1624.04	6.54	12.00	3.36	-18.33
7.857	10067	422,405	4,973,343	31,801	303.40	1584.95	6.80	11.90	3.26	-16.64
7.802	10133	389,730	4,448,771	28,565	271.98	1432.20	6.88	11.51	3.15	-14.56
7.723	10067	367,630	4,609,153	25,890	238.14	1439.78	6.96	11.53	3.13	-14.28
7.651	10155	946,011	4,767,693	33,618	295.96	2132.32	6.82	12.00	3.28	-17.00
7.589	10034	379,726	4,283,498	27,805	265.36	1384.41	6.89	11.38	3.11	-13.94
7.506	9990	233,946	1,917,729	30,231	373.18	695.56	6.65	9.05	2.65	-6.36
7.425	10045	345,765	2,940,690	31,633	345.42	1051.51	6.71	10.38	2.92	-10.74
7.335	10100	443,323	4,223,245	18,847	155.67	1447.51	7.20	11.55	3.08	-13.38
7.257	9859	254,828	4,214,395	26,835	264.30	1215.60	6.90	10.90	2.99	-11.97
7.189	9760	456,502	4,077,556	38,269	401.78	1431.17	6.58	11.51	3.22	-15.84
7.055	9640	243,425	4,382,352	26,594	259.64	1236.87	6.91	10.96	3.01	-12.18
6.975	9706	258,283	3,678,495	25,846	259.45	1105.79	6.91	10.56	2.91	-10.63
6.897	9881	347,178	3,682,607	25,364	245.19	1215.20	6.95	10.90	2.98	-11.78
6.821	9914	161,732	1,098,371	35,859	550.03	430.04	6.27	7.71	2.46	-3.54
6.749	9979	296,732	5,000,000	25,816	237.49	1435.16	6.97	11.52	3.13	-14.22
6.666	10012	461,473	5,000,000	29,402	270.29	1638.00	6.88	12.00	3.27	-16.71
6.587	9903	323,562	2,642,279	29,525	324.81	959.78	6.75	10.07	2.84	-9.43

Station	Load (lbf)	Modulus (psi)			k (pci)	E (ksi)	Dreq (PCC) (in.)	Deff (PCC) (in.)	A	Hover (AC) (in.)
		E1	E2	E3						
6.446	10297	1,000,000	1,000,000	34,511	391.43	1023.67	6.61	10.29	2.92	-10.77
6.321	10188	423,556	4,984,474	31,892	304.31	1588.74	6.80	11.91	3.27	-16.70
6.23	9969	285,949	2,000,179	23,980	264.49	773.47	6.90	9.37	2.66	-6.60
6.152	9914	206,965	4,785,256	36,314	389.31	1275.56	6.61	11.07	3.11	-13.86
6.079	9804	307,928	1,000,000	16,901	185.23	555.68	7.11	8.40	2.44	-3.13
6.005	10012	256,659	2,354,359	14,899	137.62	818.20	7.26	9.55	2.63	-6.02
5.937	10264	341,405	3,686,044	24,027	228.50	1208.99	6.99	10.88	2.97	-11.53
5.861	9947	345,661	1,000,000	24,281	294.32	590.04	6.83	8.57	2.52	-4.38
5.781	9804	259,971	1,000,000	23,433	294.70	509.88	6.83	8.16	2.45	-3.26
5.712	9837	360,107	1,464,319	21,987	240.59	726.27	6.96	9.18	2.61	-5.80
5.643	9914	381,438	1,000,000	25,184	303.73	621.33	6.80	8.71	2.55	-4.88
5.564	9771	179,270	2,084,928	21,701	243.22	667.10	6.95	8.92	2.56	-5.06
5.472	9925	306,211	1,999,775	17,975	178.37	796.12	7.13	9.46	2.64	-6.15
5.4	9936	272,640	2,737,721	21,157	211.17	920.81	7.04	9.93	2.75	-7.96
5.323	9870	255,074	2,879,176	24,369	254.10	930.34	6.92	9.97	2.78	-8.46
5.24	9914	272,539	3,600,159	26,409	266.95	1106.65	6.89	10.56	2.92	-10.71
5.153	9892	361,521	1,041,440	31,464	409.91	615.86	6.57	8.69	2.59	-5.51
5.083	9990	225,159	4,285,116	23,381	221.32	1193.13	7.01	10.83	2.95	-11.28
5.013	9914	406,964	2,182,054	21,568	214.55	948.28	7.03	10.03	2.77	-8.33
4.935	9432	118,123	1,000,000	10,000	106.51	358.20	7.37	7.25	2.21	0.26
4.84	9837	463,733	1,146,339	28,523	339.09	734.71	6.72	9.21	2.67	-6.65
4.754	9793	160,835	2,545,613	19,671	205.85	742.93	7.05	9.25	2.61	-5.73
4.663	9881	150,914	4,285,852	33,247	363.84	1097.91	6.67	10.53	2.96	-11.46
4.463	10056	424,213	4,996,405	31,952	304.86	1592.11	6.80	11.92	3.27	-16.74
4.384	9958	339,005	2,011,843	33,991	410.52	835.11	6.56	9.62	2.78	-8.50
4.307	10001	431,920	1,000,000	28,413	349.00	663.53	6.70	8.91	2.61	-5.77
4.236	9793	188,554	1,869,569	20,463	229.03	631.64	6.99	8.76	2.53	-4.48
4.167	9782	450,833	1,754,383	24,808	264.15	889.35	6.90	9.82	2.76	-8.05
4.098	9804	231,602	2,576,877	19,442	194.79	836.67	7.08	9.62	2.68	-6.80
4.022	9596	223,978	1,000,000	16,930	195.78	473.80	7.08	7.96	2.37	-2.08
3.944	9596	358,551	1,082,485	20,294	227.35	624.66	6.99	8.73	2.52	-4.37

STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS =	63.00
AVG A(Dreq - Deff) =	-10.65
STD A(Dreq - Deff) =	4.75
DESIGN AC OVERLAY THICKNESS	
AT 90% RELIABILITY LEVEL =	-4.56

Appendix- C

A Study on Temperature Correction of Back-calculated AC Layer in Overlay Design

A Study on Temperature Correction of Back-calculated AC Layer in Overlay Design

INTRODUCTION

Pavement surface deflections such as those measured by the falling weight deflectometer (FWD) have been widely used to back-calculate pavement layer moduli to evaluate the structural capacity of the existing pavement and for structural overlay design. The moduli of the asphalt concrete (AC) layer depend on the temperature and the pavement deflections are often measured under a wide range of temperature at different construction sections. Therefore, it is necessary to correct to the back-calculated AC layer moduli to a standard reference temperature.

In general, there are two approaches for temperature correction on asphalt layer moduli. Moduli of asphalt concrete at different temperatures can be converted to moduli at a reference temperature by applying temperature correction factors. The other approach is to modify deflections to those at a reference temperature; the corrected deflections are then used for back-calculation of asphalt concrete moduli. There have been a variety of methods developed in the literature. A review of a number of these methods can be found in Akbarzadeh et al. (2012). The current study explores a few such methods and this appendix presents a case study of temperature correction of asphalt concrete layer moduli on five select construction sections of composite pavements in Ohio, comparing the two approaches: deflection correction and moduli correction.

The main objective of this study is to assess the important characteristics of moduli modification in different methods and identify suitable methods for temperature correction for pavement design in the state of Ohio. The combination of an asphalt concrete (AC) layer and a Portland cement concrete (PCC) layer in composite pavements renders an additional intricacy. Deflections may also vary significantly across different stations even within the same pavement section; the consistency of temperature correction needs to be better assessed. Therefore, evaluation of such consequences of temperature correction in composite pavements is also part of the research objectives.

BACKGROUND OF THE CASE STUDY

Five pavement sections from five different locations in Ohio: Cuyahoga, Huron, Guernsey, Miami and Washington Counties, were selected for this case study. FWD data were obtained from each section of composite pavements. Information about the layer thicknesses and temperature is summarized in Table C1. Each section is denoted by the abbreviation of the county followed by the route number (with beginning and ending station numbers given in the parentheses). CUY-422 and HUR-20 are two sections where FWD deflections were measured under relatively low temperatures, MIA-75 and WAS-50 were two sections with relatively high FWD testing temperature; GUE-70 was selected because its FWD deflections were measured under moderate temperature, near the reference temperature of 68°F (20°C).

Table C1. Summary of temperature at the time of FWD test

County	Thickness (in.)		Number of Stations	AC Surface Temp (°F)	Air Temp (°F)	Mid-depth Temp (°F)
	AC	PCC				
CUY 422 (14.058 - 18.507)	4.00	9.00	52	39.9 ~ 51.6	32.2 ~ 39.6	48.6 ~ 63.8
GUE 70 (23.308 - 28.438)	7.00	9.00	63	63.0 ~ 79.0	59.0 ~ 65.0	60.8 ~ 79.8
HUR 20 (6.834 - 8.555)	5.75	9.00	33	55.5 ~ 58.0	51.9 ~ 53.9	59.2 ~ 62.4
MIA 75 (10.983 -14.112)	8.25	9.00	37	82.9 ~ 96.2	78.5 ~ 85.0	84.8 ~ 99.5
WAS 50 (0.012 - 3.353)	4.25	9.00	34	89.7 ~ 100.5	80.9 ~ 86.7	91.0 ~ 105.2

TEMPERATURE CORRECTIONS METHODS USED IN THE CASE STUDY

The present case study explores two approaches: moduli correction and deflection correction. Two widely used methods for each approach are employed in the investigation. In this section some essential features about the methods used are briefly discussed.

Reference Temperature and Mid-depth Temperature in the Field

The reference temperature used in this study is 68°F (20°C), since in AASHTO pavement design, the structural number is computed at a standard temperature of 68°F. Most of the research studies (Johnson and Baus, 1992; Baltzer and Jansen, 1994; Chen et al., 2000; Park et al., 2002) have chosen a reference temperature in the range of 68~77°F (20~25°C).

One important temperature needed for correction is the average temperature at the mid-depth of AC layer; it is usually selected as the representative value for the effective temperature of the AC layer where temperature typically varies through its depth. There have been a number of studies devoted to the prediction of the average asphalt layer temperature (e.g., Barker et al., 1977; Ullidtz 1987; Asphalt Institute, 1992; Stubstad et al., 1998; Park et al., 2002). In the present study, the BELLS2 equation (Stubstad et al., 1998) is employed for predicting the mid-depth temperature,

$$T_d = \beta_0 + \beta_1 \, IR + [log_{10}(d) - 1.25][\beta_2 \, IR + \beta_3 \, T_{(1-day)} + \beta_4 \sin(hr_{18} - 15.5)] + \beta_5 \, IR \sin(hr_{18} - 13.5) \quad \text{(C1)}$$

where T_d is the pavement temperature (°C) at depth *d* within the asphalt layer; IR is the surface temperature (°C) measured with infrared gauge; *d* is the depth (mm) at which the temperature is to be predicted; $T_{(1-day)}$ is the average of the previous day's high and low air temperatures (°C); hr_{18} is the time of day in a 24-hour system and calculated using an 18-hour asphalt temperature rise and fall function (Stubstad et al., 1998). The coefficients used in Eq. (C1) can be found in Stubstad et al. (1998): β_0 = 2.780; β_1 = 0.912; β_2 = –0.428; β_3 = 0.553; β_4 = 2.630; β_5 = 0.027.

Moduli Correction Approach

Two representative methods from this approach are explored, a method developed by Chen et al. (2000), hereafter referred to as Chen's method, and a recommendation from Asphalt Institute (1982), hereafter referred to as AI's method.

Chen et al. (2000) developed a correction equation based on the FWD data from several projects in Texas and the results of back-calculation program MODULUS. The following equation is used in the present study,

$$E_{Tr} = E_T \left(\frac{1.8\,T+32}{1.8\,T_r+32}\right)^{2.4462} \tag{C2}$$

where E_{Tr} is the modulus corrected to the reference temperature of T_r (20°C) and E_T is the modulus determined at temperature of T (°C).

Asphalt Institute (1982) developed a correction equation, considering the aggregate properties and loading frequency:

$$log_{10}|E^*| = 5.553833 + 0.028829\,(p_{200})f^{-0.17033} - 0.03476V_a + 0.070377\eta_{70} + 0.000005\left[t_p{}^{(1.3+0.49825log_{10}f)}\,p_{ac}^{0.5}\right] - 0.00189\left[t_p{}^{(1.3+0.49825log_{10}f)}\,p_{ac}^{0.5} * f^{-1.1}\right] + 0.931757f^{-0.02774} \tag{C3}$$

$|E^*|$ is the absolute value of complex modulus (psi); p_{200} is percent passing No. 200 sieve by total aggregate weight; f is loading frequency (Hz); V_a is percent air voids by volume; η_{70} is bitumen viscosity at 70°F measured in 10^6 poises; p_{ac} is the percent asphalt content by weight of mix; t_p is the temperature measured (°F).

To simplify the temperature correction analysis, Strategic Highway Research Program National Research Council (1993) recommended the properties of asphalt concrete as 5.0% for p_{200}, 20 Hz loading frequency, 4% air voids, 1.5 × 10^6 poises bitumen viscosity, and 5.0% asphalt content. Substituting these values into Eq. (C3) yields,

$$E_{tr} = E_t \times 10^{0.000145\left(t_p{}^{1.94824} - t_{pr}{}^{1.94824}\right)} \tag{C4}$$

E_{tr} is the modulus corrected to the reference temperature of t_{pr} (68°F), and E_t is the modulus determined from testing at temperature of t_p (°F).

Deflection Correction Approach

Two methods from the deflection correction approach are used in this study. The first correction method examined was proposed by Park et al. (2002) based on temperature correction procedure developed by Kim et al. (1995) This method (hereafter referred to as Park's method) proposes the temperature correction be applied to only deflections within an effective radial distance, D_{eff} (mm), which is related to the AC thickness (mm), H_{ac},

$$D_{eff} = 4.75H_{ac} - 413 \tag{C5}$$

For FWD deflection sensors within the effective radial distance, the correction factor, $\lambda_w = w_{T_0}/w_T$, should be applied. This correction factor is defined as the ratio of the corrected deflection, w_{T_0}, at the reference temperature (T_0), to the measured deflection, w_T, at the field temperature T. It is computed as,

$$\lambda_w = 10^{-C(H_{ac})(T-T_0)} \tag{C6}$$

C is the regression constant and H_{ac} is AC thickness (mm). C at a given offset distance is determined via,

$$C = -Ar + C_0 \tag{C7}$$

where r is the radial distance from the center of the load plate to the sensor. Typical values of C_0 and A value were recommended in Park et al. (2002); in the present study they are tentatively taken as 4.65×10^{-5} and -5.47×10^{-8}, respectively. Once the temperature correction is applied to deflections, the corrected deflections are subsequently used to back-calculate the layer moduli.

SHRP also developed a correction method for FWD deflection. SHRP's long term pavement performance (LTPP) program had been using the FWDCHECK computer program (Rada et al. 1992) to check the reasonableness of deflection data for use in structural capacity computation in the AASHTO design procedure. Later a temperature correction procedure was developed by SHRP (1993) and implemented into the computer program. This correction method is used in the present case study and hereafter referred to as SHRP's method.

SHRP's method uses Asphalt Institute's modulus predictive equation (Eq. C3) while introducing some simplifying assumptions. The moduli of subgrade are computed using the deflection from farthest (i.e. 60 inches away) sensor of FWD, and subsequently deflection data from other sensors are used to compute moduli for layers above the subgrade. Using equal stiffness concept for each layer, thickness and moduli are converted to single layer and Boussinesq equation is applied to calculate the deflection. The calculated and field measured deflection data are used to calculate temperature correction factor, D_r. A generalized equation is offered,

$$D_r = \frac{\delta o_s}{\delta o_f} = \frac{\frac{1}{E_{1s}}(1-F_{b1B})+\sum_{i=2}^{n-1}\frac{1}{E_i}(F_{biT}-F_{biB})+\frac{1}{E_n}F_{bnT}}{\frac{1}{E_{1f}}(1-F_{b1B})+\sum_{i=2}^{n-1}\frac{1}{E_i}(F_{biT}-F_{biB})+\frac{1}{E_n}F_{bnT}} \tag{C8}$$

δo_s is the maximum deflection at the standard (reference) temperature and δo_f is the maximum deflection at the field temperature. E and F_b represent the moduli and Boussinesq one-layer deflection factor, respectively. The subscript "s" indicates a variable at the standard (reference) temperature and "f" indicates a variable at the field temperature. The subscript "B" represents the bottom layer and "T" represents the top layer. n is the total number of layers. The first, second and third term in the numerator or denominator represent the contribution associated with AC layer, intermediate layers and subgrade, respectively. It is evident that only AC layer moduli modification can result from this equation.

For convenience in practical use, two charts were developed by SHRP (1993), one for composite pavement with weak subgrade support (subgrade with moduli of 10 ksi or less) and the other for strong subgrade support (subgrade with moduli of 20 ksi or higher). For subgrades of intermediate strength, moduli of pavement layers need to be either calculated from lab samples or approximated from engineering judgement. Table C2 presents the correction factors extracted from the relevant chart and used in the present study where all subgrade supports are found to be strong according to this recommendation.

Table C2. Temperature Correction Factors based on SHRP correction method

	AC Thickness (in.)					
Temperature (°F)	**2**	**4**	**6**	**8**	**10**	**12**
0	1.05	1.12	1.21	1.29	1.35	1.4
20	1.05	1.11	1.18	1.25	1.32	1.36
40	1.04	1.1	1.15	1.18	1.22	1.27
60	1.02	1.04	1.05	1.07	1.09	1.1
80	0.98	0.95	0.93	0.9	0.88	0.85
100	0.9	0.8	0.72	0.62	0.6	0.55
120	0.72	0.56	0.42	0.35	0.31	0.3

Since SHRP suggested correcting the maximum deflection only, there is a possibility that in some cases the corrected deflection immediately below the load may become smaller than the deflections at other locations; as a consequence, such an unreasonable deflection distribution may lead to questionable back-calculated moduli. Fernando et al. (2001) recommended distributing the temperature correction factor on four deflection sensors based on the thickness of pavement. This idea is used in the present study and can be expressed in the following formulation:

$$\frac{\Delta w_i}{w_{i0}} = \frac{w_i - w_{i0}}{w_{i0}} = (D_r - 1)\alpha \tag{C9}$$

The correction factor, D_r is calculated from Eq. (C8). w_i is the corrected deflection of sensor *i* at the reference temperature (T_r); w_{i0} is the measured deflection of sensor *i* at the field temperature *T*. It is evident from Eq. (C9) that a coefficient, α, is introduced to offset the modification at deflections away from the falling weight. Fernando et al. (2001) suggested $\alpha = 1, 0.62, 0.34, 0.1$ for the four deflections: at 0, 12, 24 and 36 inches away from the load, respectively, if the AC layer thickness is greater than 125 mm. Similarly, for AC layers between 75 and 125 mm, $\alpha = 1, 0.45, 0.12, 0.05$ is suggested for these four deflections. For AC layer thinner than 75 mm, no correction is needed (i.e., $\alpha = 0$) for any deflection.

RESULTS AND DISCUSSION

The results of corrected moduli are presented in Figures C1~C3. For each correction, a ratio of the corrected modulus to the uncorrected modulus is referred to as correction factor for presentation and discussion of results in this section. Figure 1 shows the correction of the moduli from Park's deflection correction method, plotted with the results from Chen's method and AI's method. It is noted that in the moduli correction approach, Chen's method directly uses Eq. C2 and AI's method uses Eq. C4 for moduli correction, hence, all data points, if marked, essentially lie on the two functions (Eqs. C2 and C4). Therefore, we chose to present the moduli correction functions only without including the data markers for Chen's and AI's methods. Hollow markers are used for pavement sections in cold temperatures and solid markers for warm temperatures throughout the figures in this section.

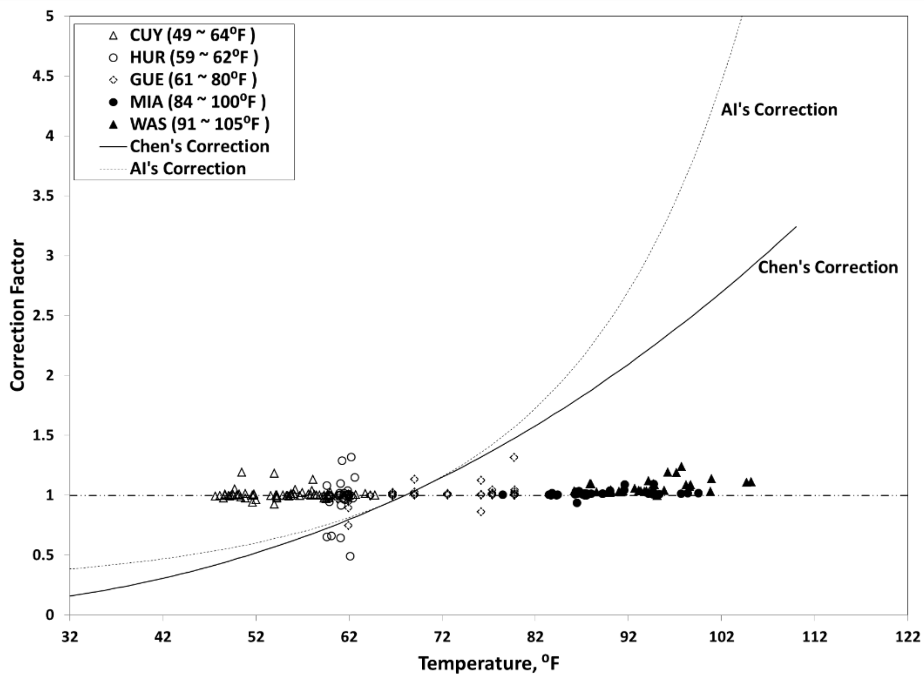


Figure C1. Moduli correction from Park's deflection correction method, with the originally reported coefficients

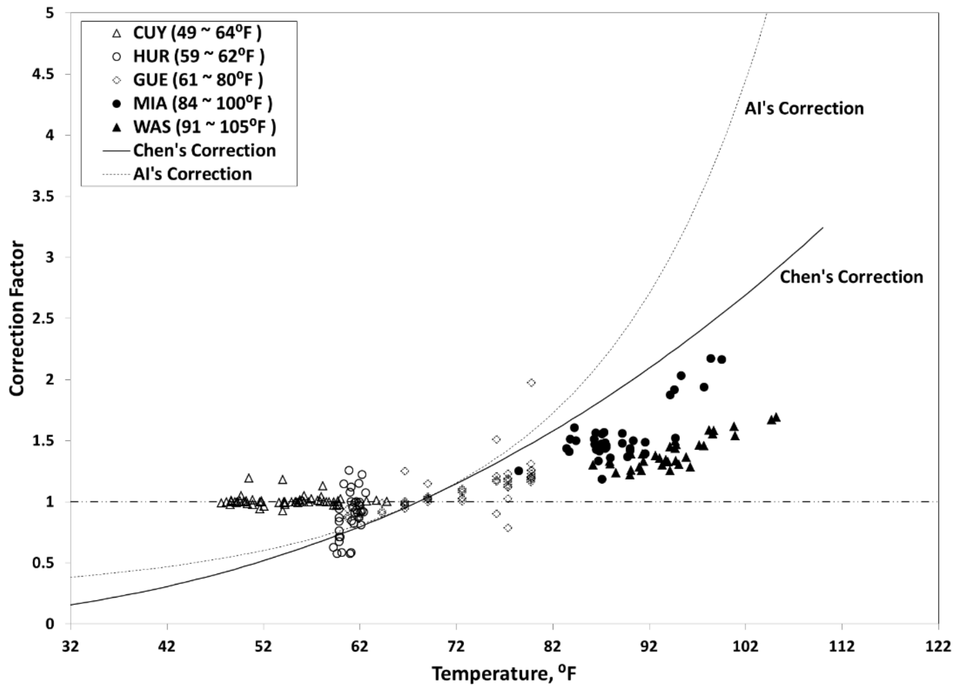


Figure C2. Moduli correction from Park's deflection correction method, with the coefficients varied, C_0=3.80× 10^{-4} and A=-5.47× 10^{-8}

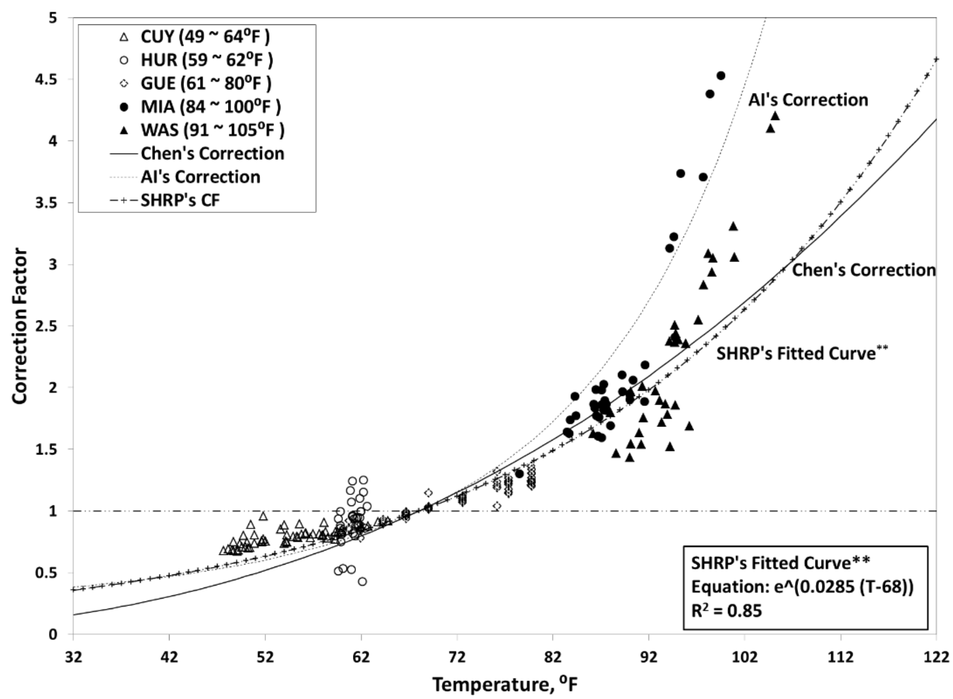


Figure C3. Moduli correction from SHRP's deflection correction method

Figure C1 shows that Park's method yields very little modification on the moduli. It should be noted that the coefficients used in Eq. (C7) adopted the original values reported in Park et al. (2002), C_0=4.65×10^{-5} and A=-5.47×10^{-8}. By varying the first coefficient, C_0=3.80×10^{-4} to better match the SHRP's deflection correction, the correction becomes more significant, as shown in Figure C2. This suggests that it may be important to calibrate the coefficients for Park's method according to the location and climatic conditions before applying it in specific projects.

Figure C3 shows that the moduli correction from SHRP deflection correction method. Of course, the data points are scatted as a result of back-calculation using the corrected deflections, but reside reasonably around the correction curve from Chen's method. It may be of some interest to introduce the fitting curve based on these moduli correction results, $CF = e^{0.0285(T-68)}$, *CF* is the correction factor for temperature, T (°F). This fitting curve has a reasonable regression R^2=0.85, and may be useful for a quick estimation for moduli correction for similar projects to those in this case study.

Details of the temperature correction are shown in Figure C4 and C5, for two specific sections, HUR-20 (under cold testing temperatures) and WAS-50 (under warm testing temperatures), respectively. X-axis of all subfigures shows the distribution of stations where the FWD deflections were measured. It is worth noting that FWD testing was carried out in the morning at these two sections and temperature generally rose from the beginning to the end of the sections. Overall Figure C4 shows originally overestimated AC layer moduli, which are modified by different methods to produce corrected AC layer moduli; similarly, Figure C5 presents a case of originally underestimated AC layer moduli.

It is of interest to examine individual moduli corrections and compare the results from different correction methods. Figure C6 compares the results of the two moduli correction methods. It shows a very reasonable agreement between AI's method and Chen's method, especially for cold conditions (hollow markers). At some stations under very low temperatures, Chen's method seems to produce larger corrections (reductions), but overall the results of these two methods correlate very well. For warm conditions (solid markers), Chen's methods seem to be more conservative with smaller corrections (increases) in AC moduli. Of course, the theoretical correction functions for these two methods are already presented in Figure C1.

Since the correction from Park method is sensitive to the adopted coefficients, we will focus on the SHRP's method in a comparison with moduli correction approach. Comparison of SHRP's deflection correction method with AI's moduli correction method, and Chen's moduli correction methods are presented in Figure C7 and Figure C8, respectively. It is evident that the SHRP correction are conservative for both cold (less reduction and thus higher moduli) and warm (less increase and thus lower moduli) climatic condition, compared with AI's method. But in comparison with Chen's method as shown in Figure C8, this effect is significant only for cold temperatures.

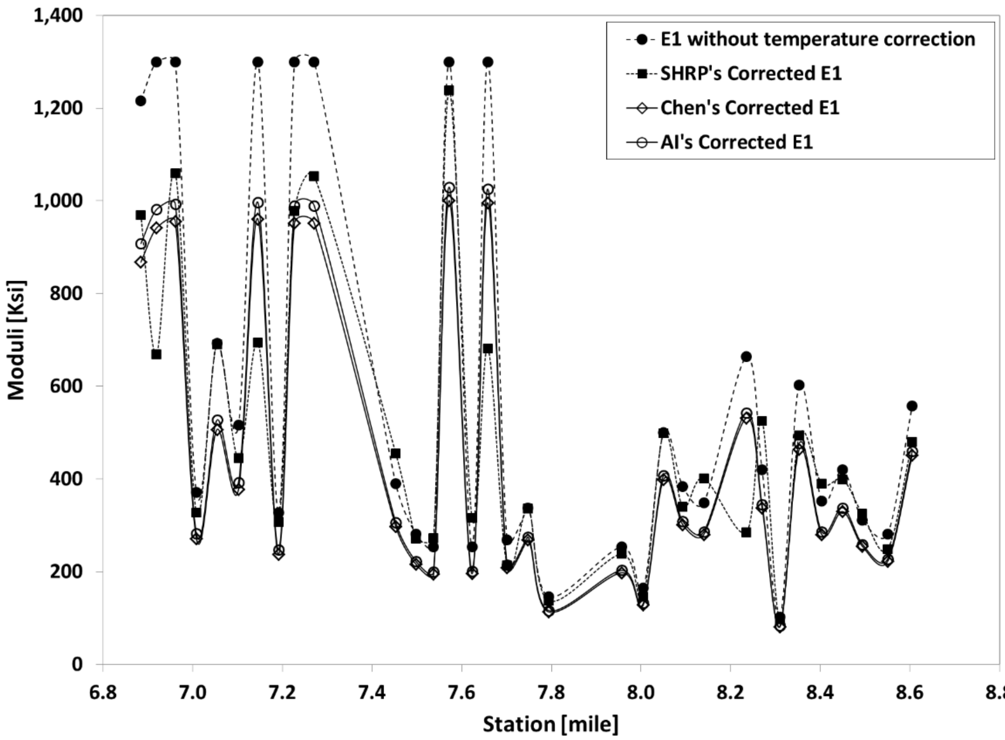


Figure C4. Deailed results of AC layer moduli correction for HUR-20 (AC Mid-depth temp: 59~62°F)

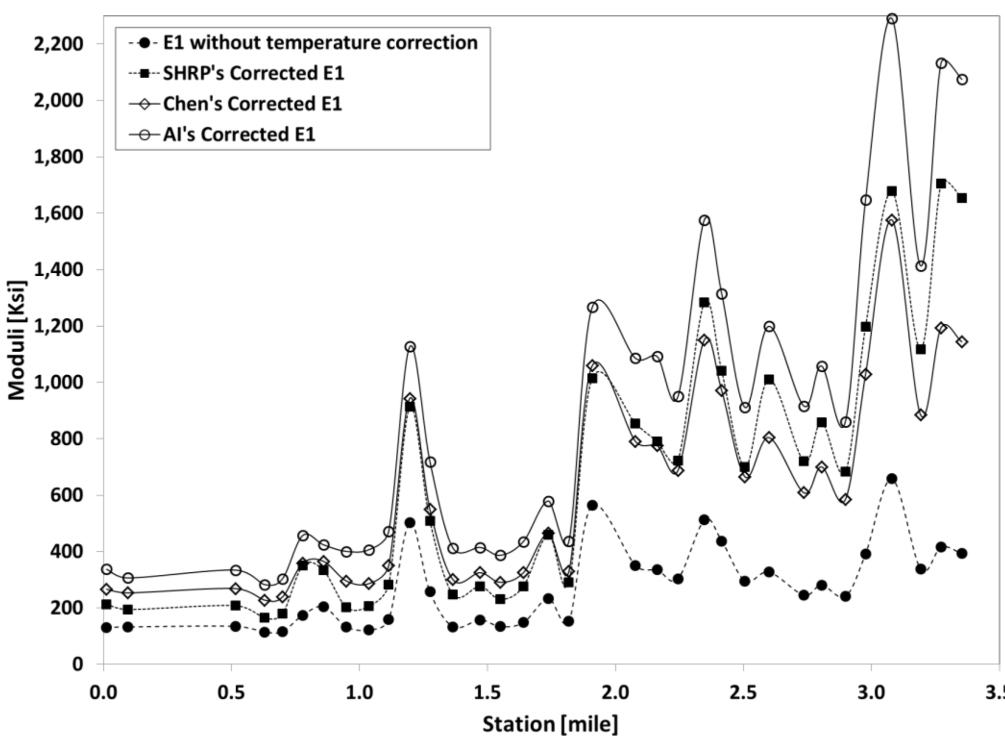


Figure C5. Deailed results of AC layer moduli correction for WAS-50 (AC Mid-depth temp: 91~105°F)

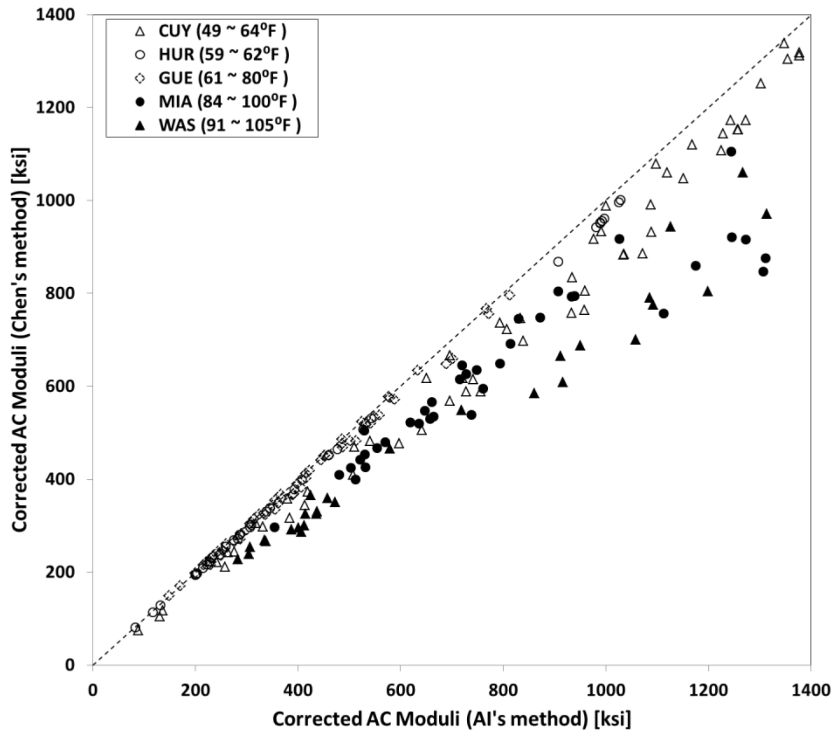


Figure C6. Comparison of corrected AC layer moduli from Chen's moduli correction method and AI moduli correction method

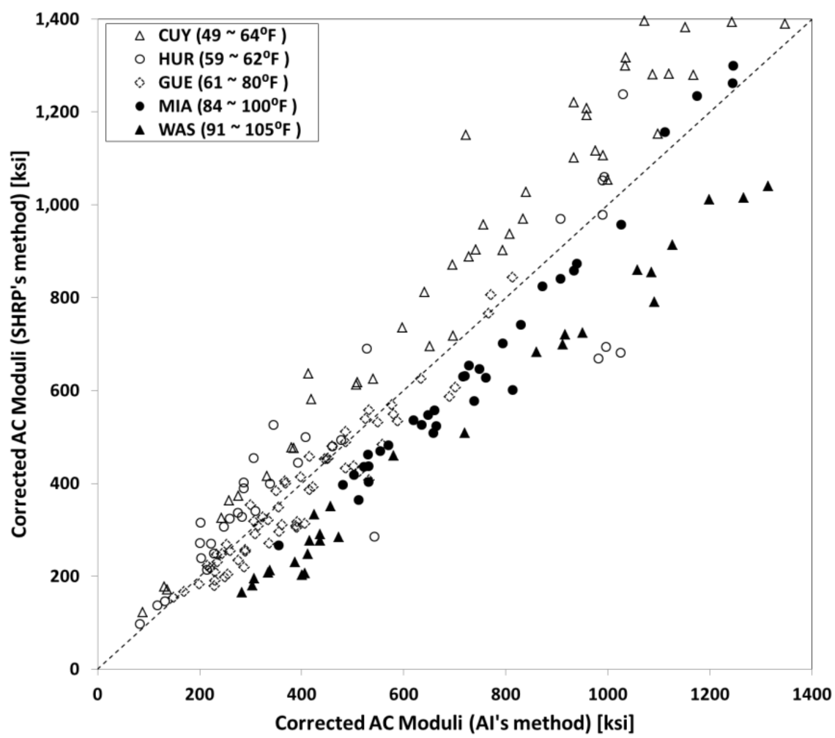


Figure C7. Comparison of corrected AC layer moduli from SHRP deflection correction method and AI moduli correction method

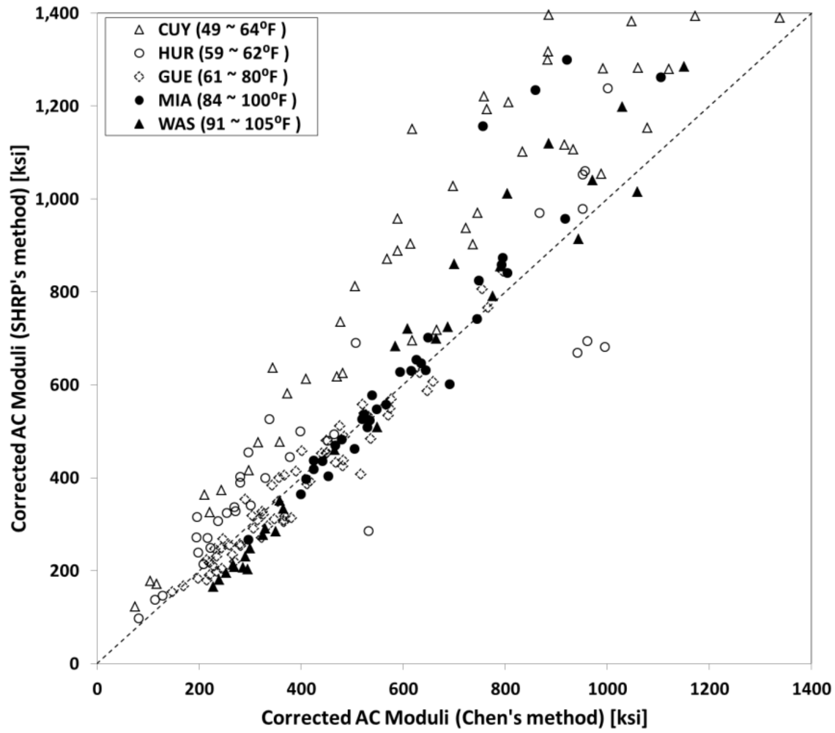


Figure C8. Comparison of corrected AC layer moduli from SHRP deflection correction method and AI moduli correction method

CONCLUSION

This case study explores two different approaches for temperature correction on AC layer moduli: deflection correction and moduli correction. It examines five composite pavement sections containing totally over 200 stations. Two correction methods for each approach are used.

Moduli correction methods directly modify the back-calculated AC layer moduli. Therefore, they generally maintain the same or similar patterns of moduli distribution, even though the temperature at FWD testing may vary slightly across the section. Overall AI's method and Chen's method produce reasonably matched results. For warm temperatures, Chen's method tends to be more conservative.

Deflection correction methods modify the FWD deflections which are then used for back-calculation. Hence, their performance is generally sensitive to the back-calculation processes and the overall quality of the FWD data. The results from deflection correction method seems scattered although overall a match in pattern can be observed. The deflection basin represents the property of all the layers present in the pavement and changes in the deflection data can alter the back-calculated moduli for all the layers. However, effect of temperature change shall be considered only for AC layer. A coefficient in the Park's original formulation had to be varied to better fit with the studied cases and yielded reasonable match with SHRP method but slightly smaller modifications. Overall moduli correction approach is more consistent compared to deflection correction approach, in particular, Chen's method can be recommended as a simple and straightforward means for moduli corrections for the composite pavement projects studied in this work.

Appendix- D

Field Coring Results and Analysis

Field Coring Results and Analysis

Field coring was conducted to verify the thickness of AC and PCC layer at select stations in four construction projects based on a careful examination of FWD data. At each route, several station locations with FWD data that resulted in questionable back-calculated layer moduli were identified. Field coring on these locations was carried out and the results are analyzed in this section.

Coring was done in four different county routes, ASH-42 (Ashland), CYU-422 (Cuyahoga), HUR-20 (Huron) and UNI-33 (Union). It has been found that at some locations there are considerable variations in the thickness of the AC and/or PCC layers. For example, at several locations only flexible pavement was observed in place of supposed composite pavement.

Using the corrected layer thicknesses, back-calculations are performed to evaluate the sensitivity of back-calculated moduli as affected by layer thicknesses. Relevant analysis is also included along with the coring results for each route.

ASD 42 (Ashland County)

Pavement type: Composite
Pavement Thickness Provided: AC- 7.50 in / PCC- 9.00 in.
Test Date (Coring): Wednesday, April 29th, 2015.

After the inspection of thickness in Route 42 of Ashland County, the back-calculation was done for the data in twelve locations. The table below (Table 4.1) shows the details coring and subsequent calculation results. The originally provided thicknesses for the overlay design are: 7.5 inches of AC layer and 9 inches of PCC layer, these two thicknesses were used to back-calculate the layer moduli presented in the first row for each station; the second row shows the back-calculated moduli based on measured, corrected layer thicknesses.

The key observations can be made regarding the coring and the subsequent back-calculation with corrected thicknesses:

- On 5 out of 12 stations the pavements are significantly different, as shown in Table 4.1. At these stations, there is no PCC layer. Three of these five identified stations are associated with very high deflections, which can be explained by the absence of PCC layer as previously unknown.
- Correction of layer thicknesses clearly improves the back-calculation at the stations without PCC layer. Previously AC moduli are very high and even higher than PCC moduli, now back-calculation offers reasonable results.
- For the rest of stations with certain PC layer, the back-calculation is improved at two stations (Station 8.894 and 8.801) with the corrected thicknesses, while originally PCC moduli reach the upper bound.

Table D1. Deflections, thicknesses and back-calculation results for ASD 42

Station	Load	W(0)	W(12)	W(24)	W(36)	Thickness measured (inches)		Backcalculation Results (From design thickness on top row and actual thickness on bottom row)		
	(lbf)	(mils)				AC	PCC	E1	E2	E3
8.894	10,034	3.41	2.15	1.78	1.54			434,576	5,000,000	46,545
						9	**9**	483,654	3,745,823	45,771
8.801	10,012	3.58	2.58	2.3	1.98			580,857	5,000,000	34,391
						8.5	**9**	621,642	4,012,337	33,897
8.664	9,925	3.37	2.92	2.56	2.18			726,358	5,000,000	29,109
						7.5	**9**	726,358	5,000,000	29,109
6.613	9,706	4.69	3.74	2.97	2.28			363,284	4,001,081	26,601
						12	**-**	1,000,000	-	34,875
6.534	9,771	5.68	4.61	3.53	2.6			2,305,233	33,413	32,419
						12.75	**-**	802,246	-	29,771
6.442	9,782	3.67	3.18	2.64	2.1			419,730	4,929,600	31,546
						12.75	**-**	1,000,000	-	43,932
5.559	9,673	4.63	3.36	2.89	2.44			501,923	1,602,769	29,330
						8.5	**9**	550,656	1,118,332	28,962
5.515	9,563	12.18	9.54	6.22	3.68			771,960	6,257	29,505
						8.625	**9**	771,960	6,257	29,505
5.404	9,728	4.83	3.39	3	2.65			415,341	1,853,576	29,477
						8.5	**9**	452,919	1,352,922	29,029
4.672	9,618	11.15	7.57	4.9	3.26			448,832	28,222	24,657
						14.25	**-**	190,292	-	21,472
4.572	9,530	14.34	10.12	6.55	4.33			427,735	15,134	19,304
						14.25	**-**	150,447	-	15,881
4.465	9,738	4.72	3.42	2.85	2.35			540,947	987,866	31,315
						8.125	**9.25**	330,735	2,893,117	28,914

Deflection very high

Data that were removed in overlay design

CUY 422 (Cuyahoga County)

Pavement type: Composite
Pavement Thickness Provided: AC- 5.25 in / PCC- 9.00 in.
Test Date (Coring): Thursday, May 14th, 2015.

Table 4.2 shows the details about the coring and subsequent calculation results, while the originally provided thicknesses for the overlay design are: 5.25 inches of AC layer and 9 inches of PCC layer.

Table D2. Deflections, thicknesses and back-calculation results for CUY 422

Station	Load	W(0)	W(12)	W(24)	W(36)	Thickness measured (inches)		Backcalculation Results (From design thickness on top row and actual thickness on bottom row)		
	(lbf)	(mils)				AC	PCC	E1	E2	E3
14.553	10,242	3.36	3.04	2.67	2.3			1,000,000	5,000,000	31,387
						5	**8**	1,000,000	5,000,000	34,337
14.605	10,188	5.41	4.06	2.89	2.26			1,000,000	1,000,000	30,237
						6	**8.5**	326,991	1,162,151	34,953
14.663	10,199	3.29	2.83	2.3	1.83			522,153	5,000,000	40,490
						6	**8.5**	725,395	5,000,000	38,158
15.781	9,958	3.27	2.98	2.61	2.25			1,000,000	5,000,000	30,496
						4.75	**8.5**	1,000,000	5,000,000	32,690
15.846	9,969	3.25	2.79	2.38	2			836,309	5,000,000	35,237
						5.25	**8**	1,000,000	5,000,000	36,764
15.909	9,969	4.26	3.97	3.26	2.53			383,035	4,333,608	28,147
						11.5	**-**	1,000,000	-	36,224
17.424	9,903	3.59	2.96	2.42	1.98			981,952	1,395,012	38,412
						5.25	**9.5**	981,952	1,395,012	38,412
17.516	9,837	4.36	3.51	2.83	2.28			396,081	4,539,745	29,047
						5.5	**9**	366,551	2,777,305	32,032
17.608	9,837	2.87	2.63	2.28	1.95			1,000,000	5,000,000	36,286
						5.25	**9**	1,000,000	5,000,000	36,286
18.206	9,804	2.78	2.63	2.23	1.95			1,000,000	5,000,000	36,661
						6	**8.25**	1,000,000	5,000,000	37,935
18.384	9,717	3.5	2.98	2.55	2.13			636,851	5,000,000	31,929
						4	**9.5**	590,093	5,000,000	32,315
18.475	9,684	4.03	3.59	3.11	2.61			380,574	4,297,356	27,917
						4.75	**8.75**	391,176	4,476,686	28,745

Deflection very high

The following observations can be made regarding the coring and the subsequent back-calculation with corrected thicknesses:

- Out of 12 stations one station appears to be of no PCC. Its deflections are normal.
- Station 14.605 has very high deflection and both AC and PCC moduli reach the bounds, correction of layer thickness improves the back-calculation.
- Correction of thicknesses improves Station 14.605, but do not have a significant effect on Stations 14.553, 14.663, 15.781, 15.846, 18.206, and 18.384, at which the original certain back calculated moduli reach the bound.

HUR 20 (Huron County)
Pavement type: Composite
Pavement Thickness Provided: AC- 5.75 in / PCC- 9.00 in.
Test Date (Coring): Wednesday, June 10th, 2015.

Table 4.3 shows the detailed coring results. The originally provided thicknesses for the overlay design are: 5.75 inches of AC layer and 9 inches of PCC layer.

Table D3. Deflections, thicknesses and back-calculation results for HUR 20

Station	Load	W(0)	W(12)	W(24)	W(36)	Thickness measured (inches)		Backcalculation Results (From design thickness on top row and actual thickness on bottom row)		
	(lbf)	(mils)				AC	PCC	E1	E2	E3
6.869	10,779	8.42	6.31	4.7	3.7			174,911	2,602,306	19,348
						6.5	**9.5**	270,993	2,623,684	17,101
6.911	10,724	10.6	8.23	5.8	4.3			1,850,774	33,016	20,687
						7.25	**8.75**	238,189	2,072,594	12,778
6.958	10,768	3.15	2.82	2.54	2.28			1,000,000	5,000,000	33,758
						7.5	**9.5**	1,000,000	5,000,000	30,322
7.357	10,538	4.32	3.91	3.54	3.2			1,000,000	5,000,000	21,144
						5.25	**9.25**	1,000,000	5,000,000	21,233
7.426	10,461	7.41	5.81	4.44	3.4			1,082,677	221,933	24,481
						5	**7.25**	280,406	1,672,300	24,828
7.448	10,461	4.46	4	3.3	2.28			397,430	4,559,548	29,278
						4.75	**9**	401,050	4,633,106	29,682
7.907	10,330	2.3	2.05	1.81	1.65			1,000,000	5,000,000	48,817
						5.25	**7.5**	690,107	9,301,529	58,013
7.955	10,264	9.15	6.71	4.42	3.22			955,407	80,853	25,231
						18	**-**	233,820		22,179
8.002	10,308	3.57	3.25	2.9	2.53			421,465	4,963,204	31,734
						6.75	**9.75**	1,000,000	5,000,000	24,784
8.353	10,210	3.69	3.32	2.87	2.41			422,396	4,967,331	31,779
						4	**9.5**	418,955	4,910,022	31,368
8.4	10,210	2.6	2.28	1.87	1.5			838,174	5,000,000	49,580
						3.5	**9.25**	670,175	5,000,000	53,930
8.441	10,122	5.91	5.03	3.93	3			7,234,786	10,285	36,234
						11	**6**	337,685	3,450,463	21,944

Deflection very low
Deflection very high
Data that were removed in overlay design

The key observations can be made regarding the coring and the subsequent back-calculation with corrected thicknesses:

- Out of 12 stations, one station appears to contain no PCC layer. This station (Station 7.955) has very high deflections, which may be explained by the absence of PCC layer. Correction of layer thicknesses improves the back-calculation.
- Three Stations (Stations 6.869, 6.911 and 7.426) also have very high deflection. Two of them were originally discarded from design. Now all have been improved with the corrected thicknesses and remain in the design. One station (Station 7.907) has very low deflection. Coring indicates slightly different thicknesses, which do not change much about the back-calculated moduli.
- Correction of layer thicknesses does improve the back-calculation at four stations (Stations 6.958, 7.357, 8.002 and 8.4).

UNI 33 (Union County)
Pavement type: Composite
Pavement Thickness Provided: AC- 6.00 in / PCC- 9.00 in.
Test Date (Coring): Tuesday, June 30th, 2015.

Table 4.4 shows the details of the coring results. The originally provided thicknesses for the overlay design are: 6.0 inches of AC layer and 9 inches of PCC layer.

The key observations can be made regarding the coring and the subsequent back-calculation with corrected thicknesses:

- Thicknesses of all stations are close to provided ones.
- There are two stations (Stations 9.594 and 10.352) with very large deflections. Correction improves significantly on Station 10.352, which originally had to be removed due to very high AC modulus. There is not much change on Station 9.594.
- Correction also improves Stations 8.936 and 9.512, but without much significant effect on other stations.

Table D4. Deflections, thicknesses and back-calculation results for UNI 33

Station	Load	W(0)	W(12)	W(24)	W(36)	Thickness measured (inches)		Backcalculation Results (From design thickness on top row and actual thickness on bottom row)		
	(lbf)	(mils)				AC	PCC	E1	E2	E3
8.936	9,881	4.3	3.54	3.1	2.62			562,258	5,000,000	24,752
						5.25	**9**	382,368	4,330,350	28,090
9.005	9,892	4.98	4.06	3.49	2.96			753,449	1,575,931	24,236
						6.75	**9**	391,384	4,352,645	22,317
9.099	10,034	5.11	4.24	3.76	3.31			649,392	3,377,146	20,413
						4.75	**9**	501,763	5,000,000	20,550
9.512	9,914	5.88	4.74	4.05	3.41			728,854	1,000,000	21,230
						5	**8.5**	549,478	2,063,191	21,656
9.594	9,903	6.58	5.21	4.38	3.57			394,222	1,126,013	21,026
						5	**9**	394,222	1,126,013	21,026
9.672	9,925	5.41	4.54	3.89	3.25			1,000,000	1,000,000	21,768
						5.25	**9**	383,113	3,750,665	20,997
10.273	9,881	4.02	3.19	2.66	2.16			416,872	4,893,843	31,278
						7	**9**	409,826	4,798,384	30,728
10.352	9,826	6.36	5.81	3.61	2.81			3,076,082	42,641	29,263
						3.25	**9**	170,316	1,950,605	24,891
10.405	9,870	3.54	2.94	2.61	2.24			786,639	5,000,000	30,153
						6.5	**9**	1,000,000	2,923,119	30,908
11.983	9,793	4.7	3.62	3.05	2.53			584,125	1,647,458	28,938
						6.25	**8**	387,123	4,358,384	28,387
12.017	9,760	3.76	3.12	2.73	2.34			1,000,000	2,454,907	29,555
						6.75	**8**	783,553	5,000,000	28,575
12.099	9,738	4.95	4.03	3.41	2.88			340,949	3,673,095	23,934
						6	**9**	340,949	3,673,095	23,934

Deflection very high

Data that were removed in overlay design

Appendix- E

Software Installation Instruction and User Manual

Software Installation Instruction and User Manual

Software Installation

The software should be in a folder named “wholeoverlaydesign”. The user is suggested to place this folder in drive C. This folder has one Excel Add-Ins named “NewOverlay” and another visual basic project folder named “bakfaa--new version”. The Add-In must be loaded in the Excel for the first run which can be done with the following steps:

1. Open a new blank excel workbook.
2. Select “Options” under “File” menu, which opens a window as shown in Figure E1.

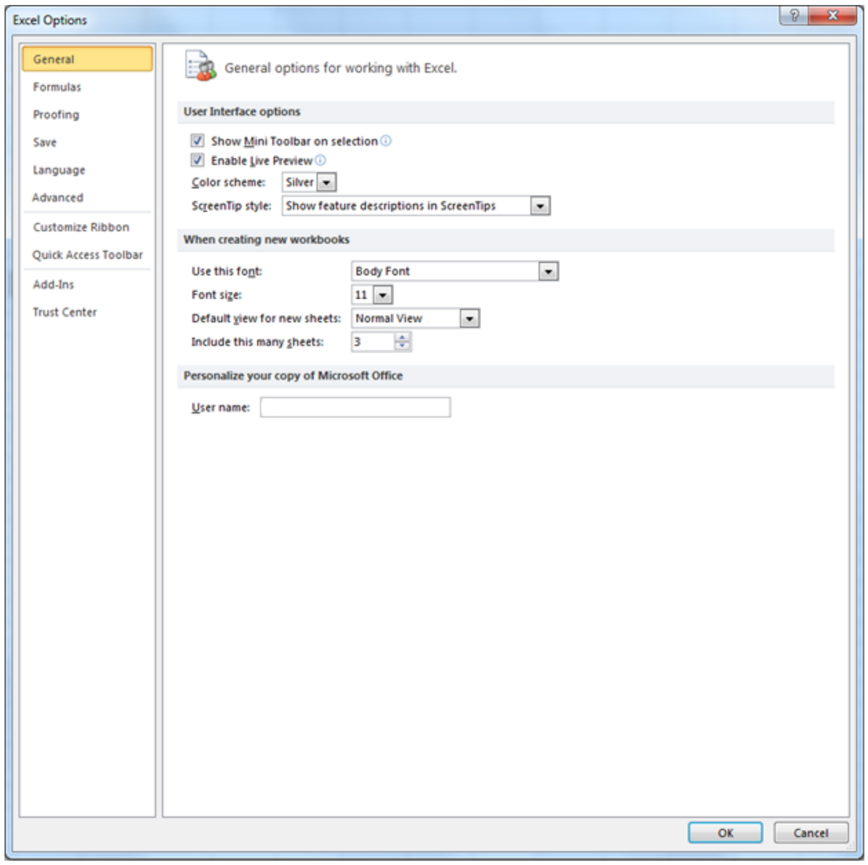


Figure E1. Excel options tab.

3. Click on Add-Ins tab and ensure that Excel Add-Ins is selected in the drop down menu in the manage section at the bottom of Excel option tab (Figure E2). Click on Go located next to the drop down menu.

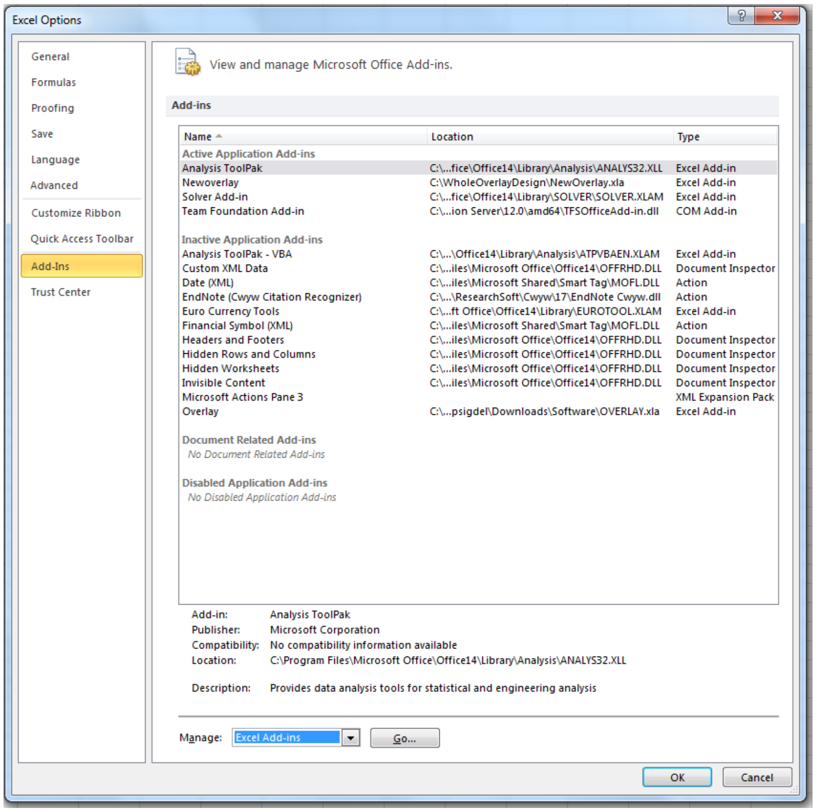


Figure E2. Excel options tab with Add-Ins option selected.

4. After Add-Ins tab is opened, browse to locate the Excel Add-Ins named "NewOverlay" as shown in Figure E3. Then select it and click OK. (Note: it is already in the folder "wholeoverlaydesign" in the C: / drive)

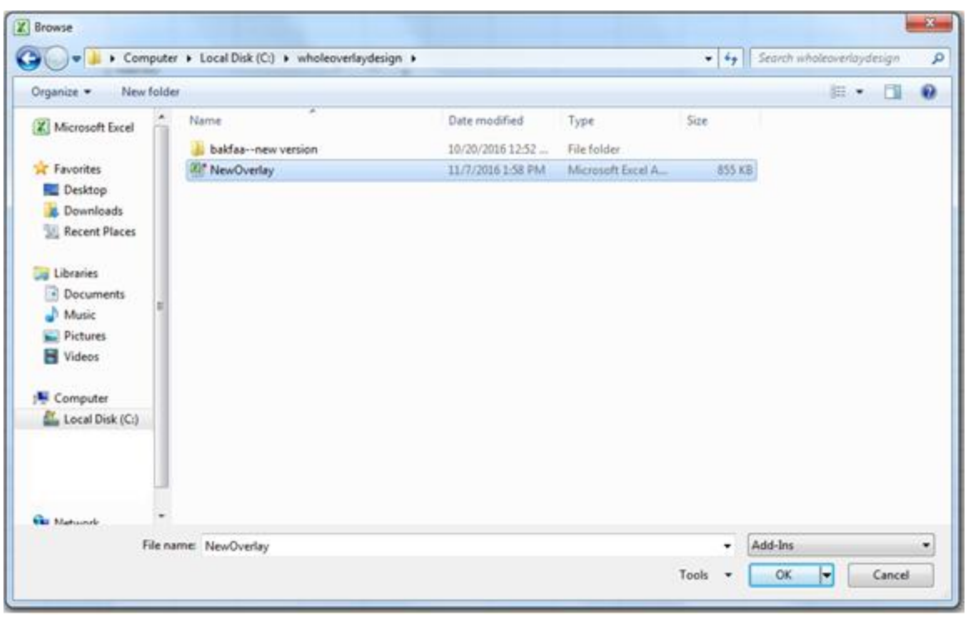


Figure E3. Browse tab for browsing excel Add-Ins file.

5. Click OK to close Add-Ins tab.

The Add-Ins is now loaded in the Excel and the program can be run in Excel, this is only required for the first time run. To open the program, the user can click on the Add-Ins menu at top and click on Revised_Overlay.

Software Use Instructions

Before using the software, Excel Ad-Ins must be activated in Excel for one time in the beginning, as descried above. The user can then open the design software by clicking the Revised_Overlay under the "ADD-INS" menu of the excel sheet. A window will appear indicating that the Overlay Design Procedure is ready to start (Figure E4), clicking the "Start" Button would initiate the design process.

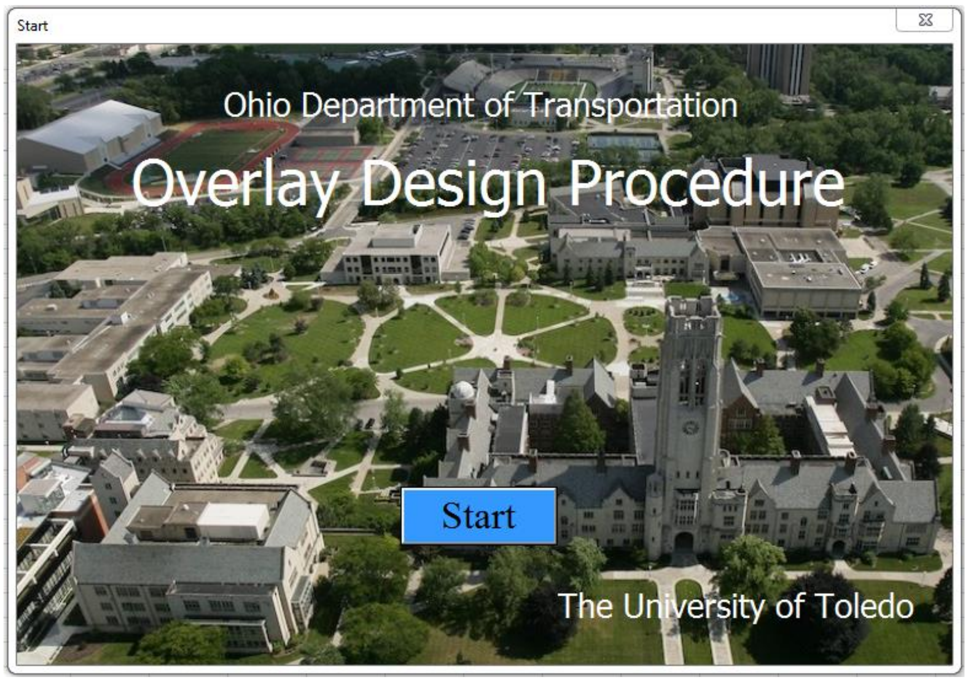


Figure E4. Start-up window for the overlay design procedure

In what follows the five major steps are addressed with details of a typical overlay design.

Step 1: Read FWD data file

After the design is started, a readfile window appears as shown in Figure E5. Select the "Composite" as the pavement, provide an analysis title and output file name, and locate the FWD file to be used for the overlay design. Then click "Next".

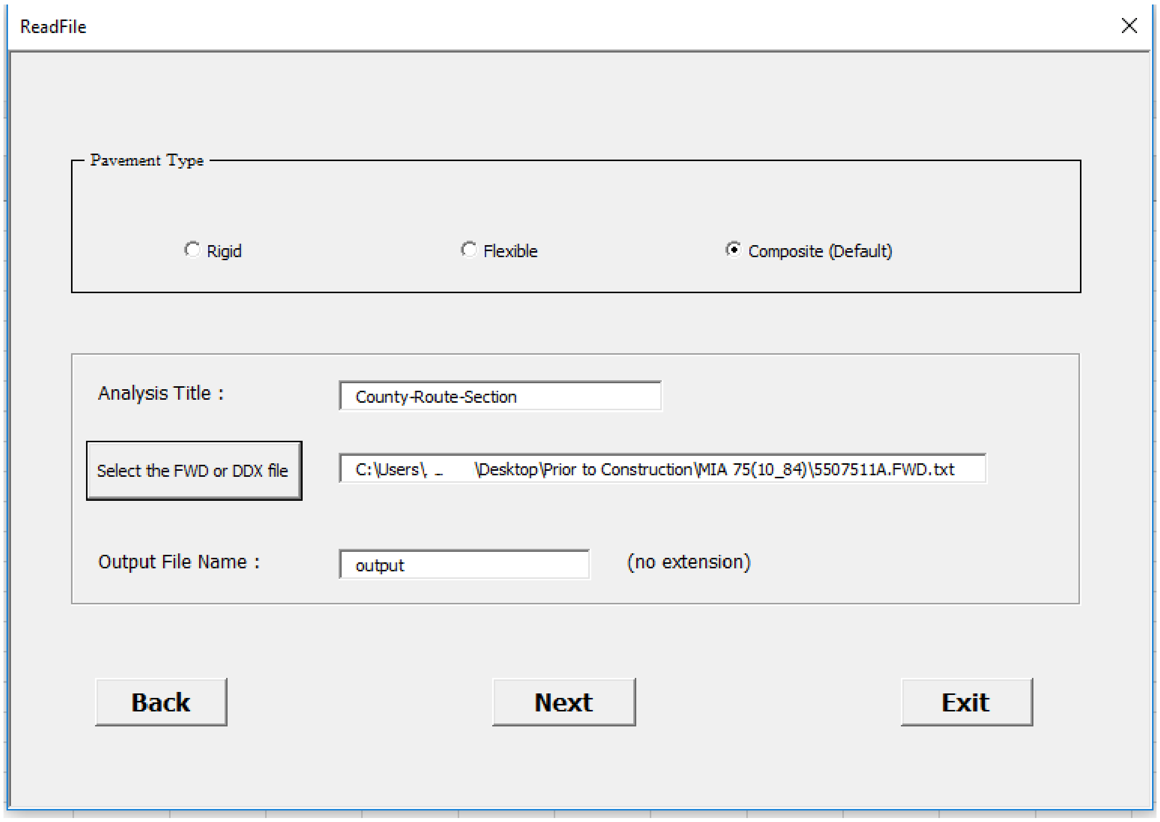


Figure E5. Step 1: read FWD data file

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Step 2: select FWD data under a specific level of load

A datafilter window appears as shown in Figure E7. Select the FWD deflection data under a desired load level (Level 1 (standard) or Level 2 or Level 3) for back-calculation and overlay design. A small box below “Filter information” shows the outcome of the selection: how many stations are selected. Click on “Done” to move to the next step.

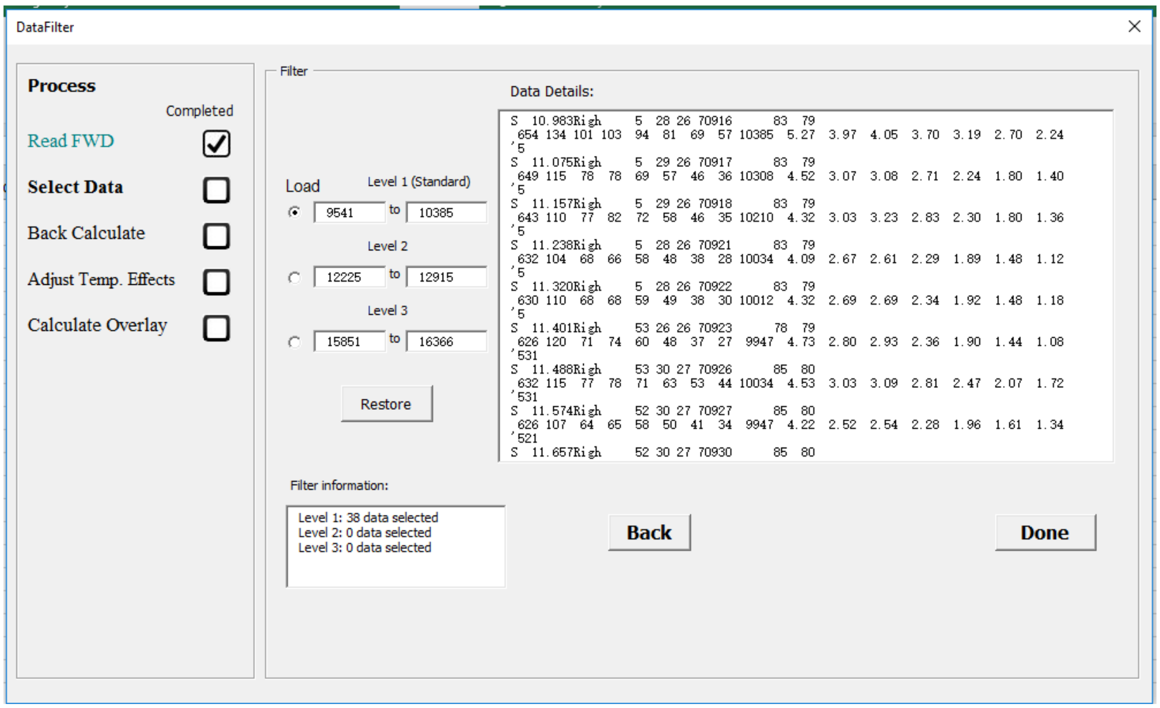

Figure E6. Step 2: select FWD data under a specific level of load

Step 3: back-calculate the layer moduli

- The screen now indicates that the first two steps have been completed (Figure E7). Clicking "Start-BackCalculation" initiates the backcalculation process.

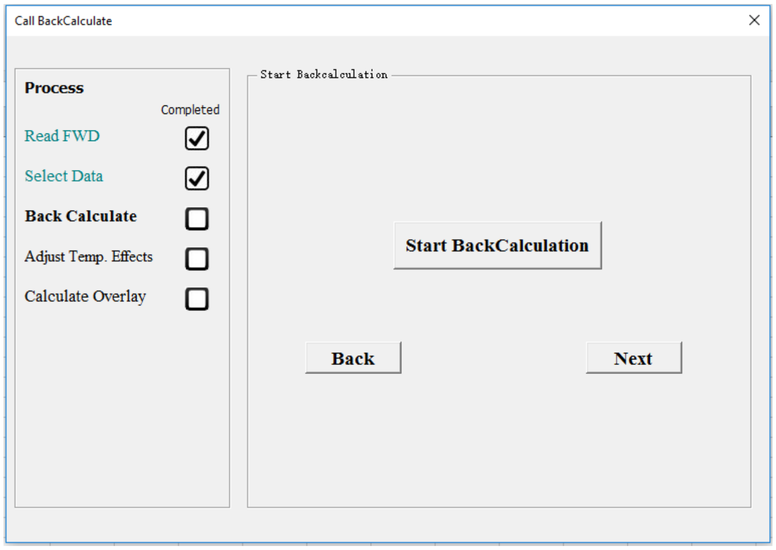

Figure E7. Step 3: back-calculate the layer moduli

- A back-calculation screen now appears as shown in Figure E8. Note that two input design parameters are needed: AC thickness and PCC thickness.

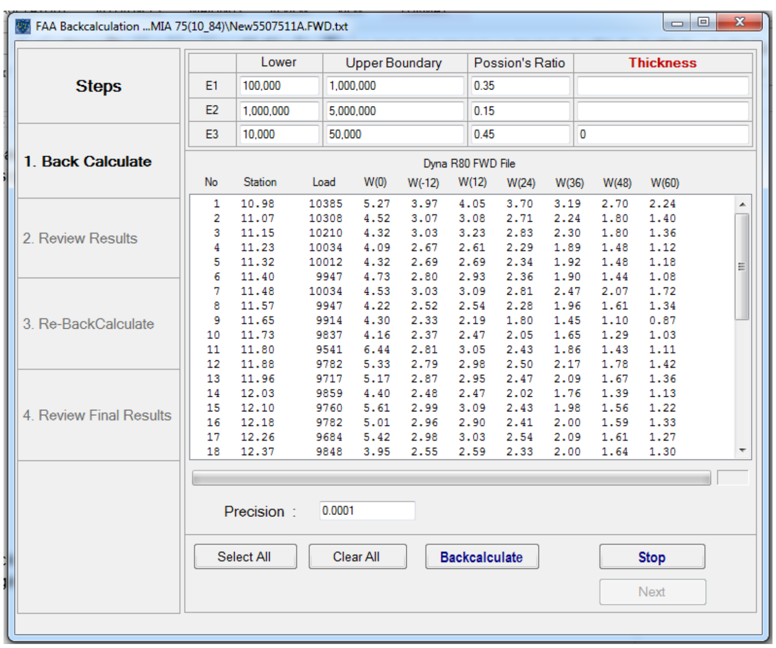

Figure E8. The back-calculation main screen

- Click the "Select All" button, which selects all the data; then click "Backcalulate" to begin the backcalculation for layer moduli (Figure E9). Note that this backcalculation is done under a very high precision (convergence): 0.0001 (default), to seek the best match with the measured deflections.

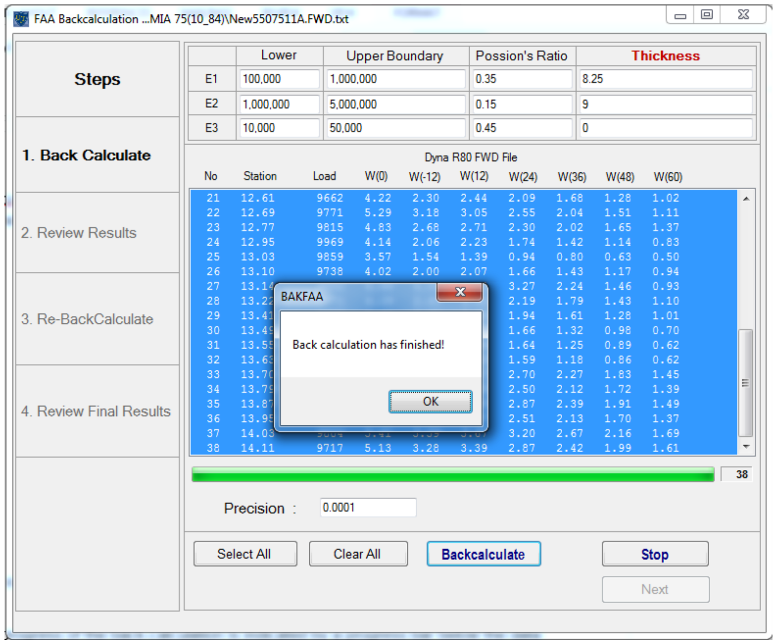

Figure E9. The first back-calculation under a high precision convergence

- The progress of the back-calculation is indicated by a progress bar below the data box, also on the right of the bar, it shows the number of stations for which the back-calculation is completed (Figure E9).
- When a message box appears after the completion of the back-calculation (Figure E9), click on the "OK" button to close the message box, and click "Next" on the bottom right corner. If all back-calculated moduli are in acceptable ranges (i.e., no questionable data), it leads to the next main step (adjusting for temperature effects); otherwise (in most of the cases there are likely some questionable data), it opens a "Backcalculation Results Review" window.

- Back Calculation Results Review window contains all the back-calculation results with some of the data highlighted (in yellow color) as shown in Figure E10. These highlighted data are those whose moduli value are not within acceptable moduli ranges. These data needs be re-backcalculated with a lower precision. Click “Re-BackCalculate” at the bottom right corner.

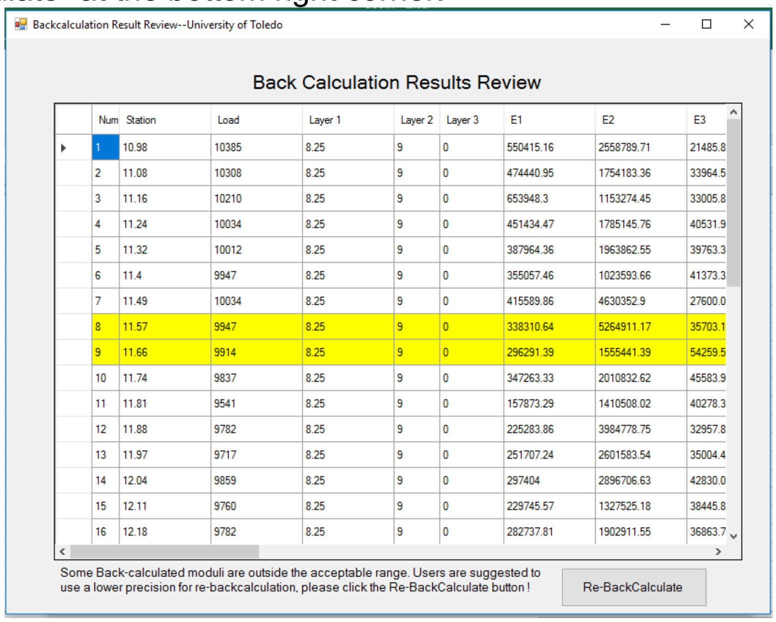

Figure E10. Backcalculation results review window

- Now the same back-calculation window returns, but contains only the questionable data that need to be re-backcalculated. Click “Backcalculate” button to start re-backcalculation, note that the precision is lowered to 0.01.

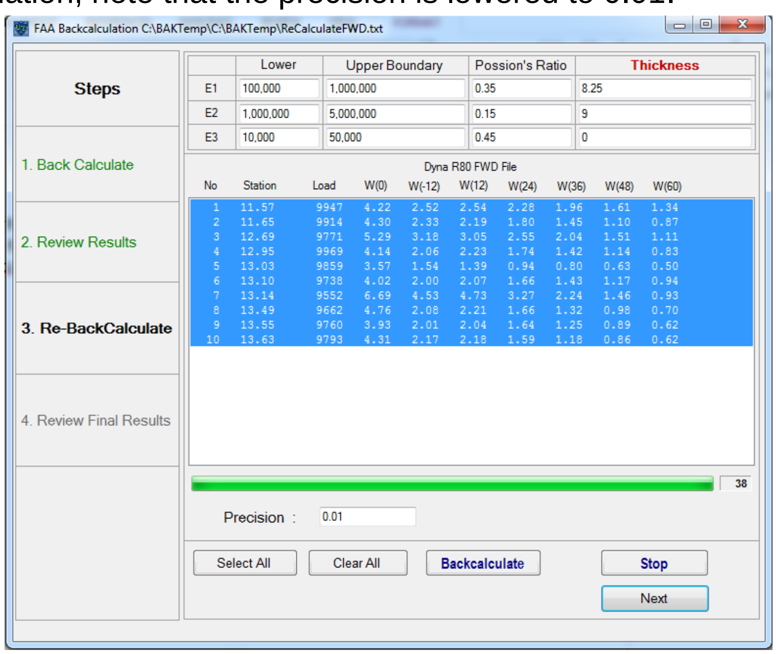

Figure E11. Re-backcalculation in progress

- Completion of re-backcalculation is indicated by a message box. Click “OK” to close the message box and click “Next” at the bottom right corner (Figure E11) to open Back Calculation Final Results Review (Figure E12). The highlighted data are the ones whose moduli were re-calculated; clicking on the highlighted data, details of the deflection matching appears the on the window, showing the measured deflection, calculated deflections from the (1^{st}) back-calculation (under the high precision) and the re-backcalculation (under the low precision).

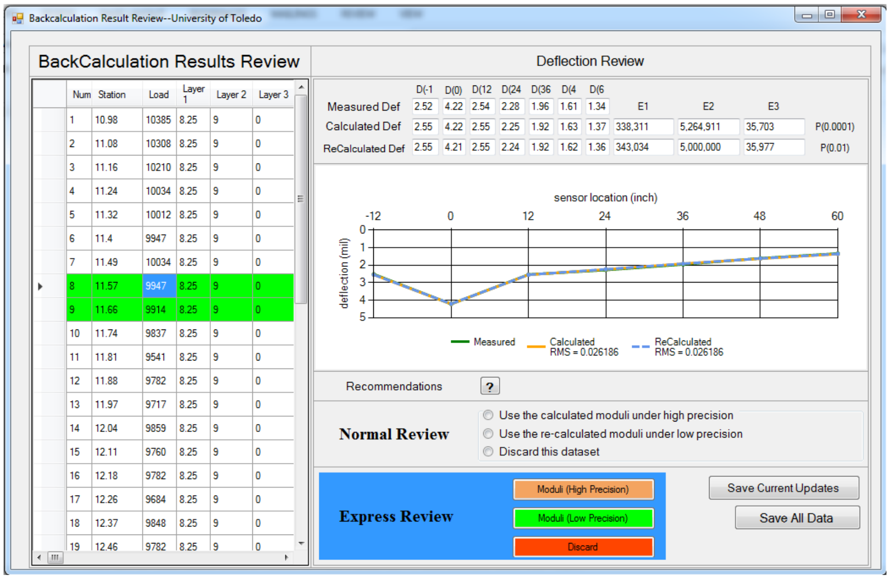

Figure E12. Reviewing final back-calculation results

- The user can choose how to proceed with reviewing and making decisions:
    - Normal Review Mode
    - Express Review Mode
- In the “Normal Review” Mode: the user reviews and makes a decision (when necessary) on each individual station:
    - The user has three options: (1) use the calculated moduli under high precision; (2) use the re-calculated moduli under low precision; or (3) discard this data set. After selecting the option, click “Save Current Updates”, a message will appear confirming that the choice has been saved (Figure E13).
    - Each highlighted data must be reviewed and a choice made. The color of the data line changes after the selection of the option for the convenience to the user.

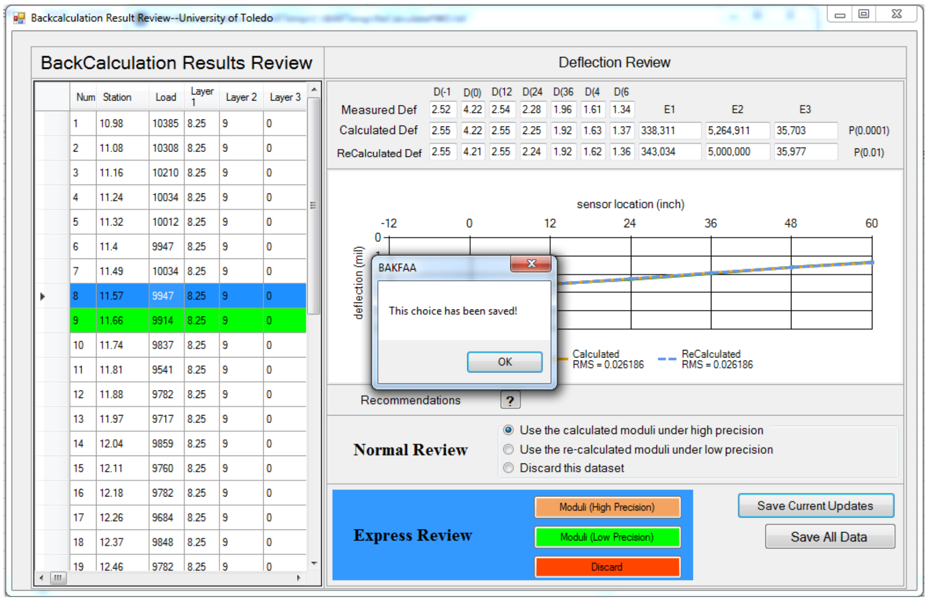

Figure E13. Selecting the option regarding back-calculation results

- In the "Express Review" Mode: the User can make the all the decision choices selection at once. The user needs to click on the Moduli (High), Moduli (Low Precision) and Discard buttons to select high precision, low precision and deleting the data, respectively, which will be applied to each suitable cases automatically while the user does not have to review the back-calculation results at each individual station.
- After all the choices have been made, click the button "Save All Data" on the bottom right corner (Figure E14). A green "Done" button now appears at the bottom right corner (Figure E14). Click it to proceed to the next main step.

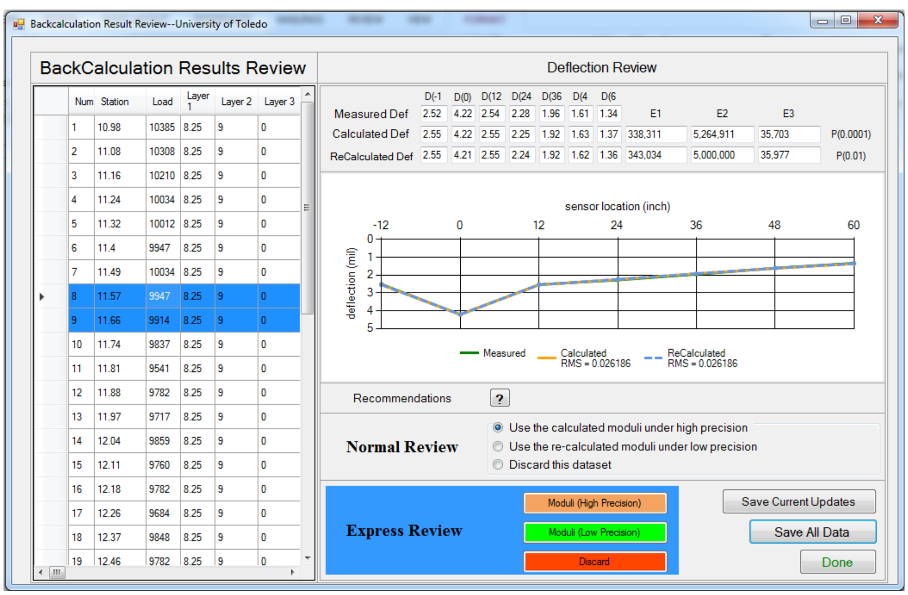

Figure E14. Completion of the back-calculation process

Step 4: Adjust for temperature effects (optional)

The temperature correction window is shown in Figure E15. Two input parameters are needed: the half of the thickness of AC layer and the mean temperature of the previous day of the FWD testing day (e.g., the average of maximum and minimum temperature of the day prior to FWD testing day can be used). Click on the "Temperature Calculation" button to start the moduli correction, a message will appear after it is completed. The user can also choose to skip this step by clicking the "Skip This Step" button. Click "Next" to proceed to the next step.

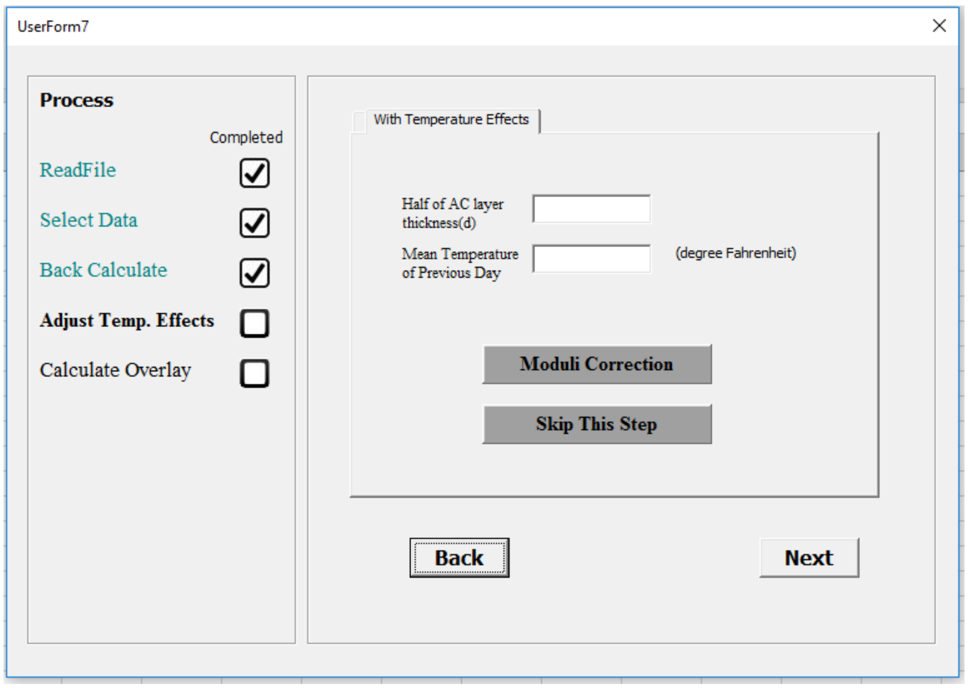

Figure E15. Step 4: Adjust for temperature effects

Step 5: Calculate overlay thickness

A design data input window now appears as shown in Figure E16. The user needs to provide the required input parameter (highlighted in red). Click the "Done" button at the bottom of the screen to stat the overlay thickness calculations. After the calculations are completed, the user can click "Open Output File and Folder" to open the overlay design file and the folder where it is located. This folder also contains an excel document named "FWD Data EXCEL" for the display of FWD data in an organized way.

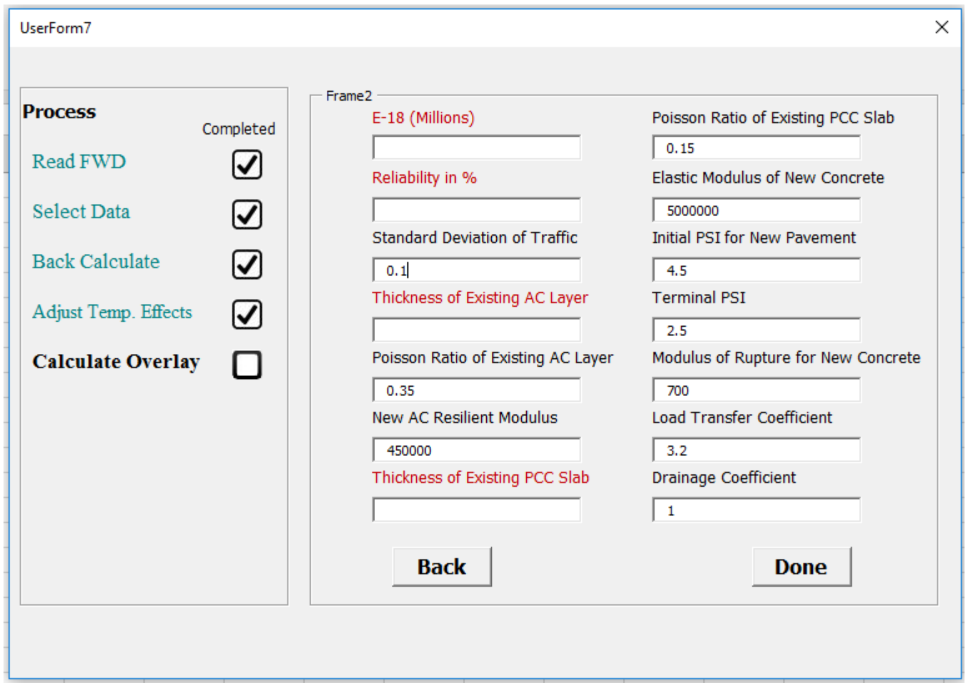

Figure E16. Step 5: Calculate overlay thickness

Appendix- F

Software Implementation: Examining Design Results from Software in Comparison with Manual Calculations

Software Implementation: Examining Design Results from Software in Comparison with Manual Calculations

INTRODUCTION

To verify that the results of the developed software match precisely with those from manual calculations and ensure that the software is implemented properly, an example (WAS-50) is presented in this appendix. We can compare both the relevant intermediate parameters (e.g., back-calculated moduli) and the design outcomes (overlay thicknesses).

Manual Calculations

Results of manual calculation are shown in Table F1. First six columns provide description from the FWD file about the station, load and deflection measurements. Columns 7-24 provide the back-calculation results and indications if they are within the boundary value of moduli. Flag “1” indicates not within the acceptable range. For the data whose moduli are not within the acceptable ranges, a 2nd back-calculation is done with a low precision. If still not within the acceptable ranges, finally a 3rd back-calculation is performed to produce the final back-calculated moduli by imposing boundary constraints. Columns 25-30 shows the values for k, E, D_{req}, D_{eff}, A, and overlay thickness. The average, standard deviation and final design of the overlay thickness are shown at the bottom of table using the provided reliability level (90%).

Software Computations

Table F2 presents the results from the developed software, and structured in a similar way to Table F1. It should be noted that in the software, for those data with questionable back-calculated moduli even after the 2nd back-calculation, boundary constraints are immediately imposed and the final moduli are directly obtained (e.g., the third step is merged with the second step). It is evident that the results from software match very precisely with manual calculations.

Table F1. Manual calculation results for WAS-50.

Station	Load, lbf	Measured Deflection W(0)	Measured Deflection W(12)	Measured Deflection W(24)	Measured Deflection W(36)	First Step Precision 0_0001 E1	E2	E3	Check E1	E2	E3	Second Step Precision 0_0001&0_01 E1	E2	E3	Check E1	E2	E3	Third Step E1	E2	E3	Check E1	E2	E3	k (pci)	E	Dreq (PCC) (in.)	Deff (PCC) (in.)	A	Hover (AC)
0.012	9585	5.89	3.44	2.96	2.42	130625	3545211	30835				130625	3545211	30835				130,625	3,545,211	30,835				359.35	1223.26	8.54	8.54	2.37	-2.18
0.094	9585	5.48	3.17	2.76	2.3	132870	4764355	31588				132870	4764355	31588				132,870	4,764,355	31,588				339.39	1599.20	8.57	8.57	2.52	-4.45
0.515	9530	5.36	3.04	2.64	2.18	134920	4248353	33965				134920	4248353	33965				134,920	4,248,353	33,965				386.87	1443.27	8.49	8.49	2.48	-3.71
0.629	9476	5.44	2.8	2.42	1.95	114729	4032449	38734				114729	4032449	38734				114,729	4,032,449	38,734				470.63	1355.92	8.35	8.35	2.46	-3.53
0.699	9487	5.79	3.13	2.71	2.21	116601	3722593	33904				116601	3722593	33904				116,601	3,722,593	33,904				403.50	1262.96	8.46	8.46	2.40	-2.63
0.778	9596	6.13	4.17	3.63	3.04	174391	3411563	23888				174391	3411563	23888				174,391	3,411,563	23,888				255.38	1227.58	8.74	8.74	2.34	-1.70
0.859	9497	5.54	3.9	3.44	2.9	204682	4089210	24323				204682	4089210	24323				204,682	4,089,210	24,323				246.52	1466.94	8.76	8.76	2.44	-3.13
0.948	9508	4.47	2.03	1.68	1.29	125016	3727964	60816			1	519350	6528143	41363		1		133,306	5,000,000	50,000				616.88	1671.84	8.13	8.13	2.64	-6.23
1.036	9607	5.06	2.71	2.26	1.75	383347	541215	51626		1	1	428830	5068955	32426		1		122,292	5,000,000	40,989				474.39	1660.22	8.34	8.34	2.59	-5.51
1.114	9640	4.96	2.74	2.24	1.71	159007	2257962	46718				159007	2257962	46718				159,007	2,257,962	46,718				704.11	856.89	8.01	8.01	2.28	-0.89
1.196	9552	3.9	2.96	2.53	2.07	503438	3009874	35793				503438	3009874	35793				503,438	3,009,874	35,793				416.81	1423.31	8.44	8.44	2.48	-3.73
1.275	9596	4.07	2.61	2.11	1.68	257370	2725215	46695				257370	2725215	46695				257,370	2,725,215	46,695				647.53	1099.54	8.09	8.09	2.39	-2.48
1.365	9421	5.63	3.24	2.67	2.16	133418	2931843	34862				133418	2931843	34862				133,418	2,931,843	34,862				447.07	1037.99	8.39	8.39	2.31	-1.30
1.471	9552	5.39	3.39	2.92	2.44	157637	4283758	29767				157637	4283758	29767				157,637	4,283,758	29,767				321.91	1477.88	8.60	8.60	2.47	-3.61
1.55	9519	5.45	3.12	2.56	2.09	134024	3268336	36586				134024	3268336	36586				134,024	3,268,336	36,586				461.87	1141.88	8.36	8.36	2.37	-2.07
1.64	9574	5.7	3.44	2.87	2.27	148127	2508047	34535				148127	2508047	34535				148,127	2,508,047	34,535				459.13	922.88	8.37	8.37	2.26	-0.54
1.738	9552	5.12	3.63	3.09	2.58	233691	3721725	27800				233691	3721725	27800				233,691	3,721,725	27,800				300.39	1383.62	8.65	8.65	2.42	-2.91
1.818	9497	5.53	3.38	2.97	2.49	153030	4061175	29063				153030	4061175	29063				153,030	4,061,175	29,063				317.11	1404.83	8.62	8.62	2.44	-3.12
1.909	9476	4.81	3.98	3.5	2.99	564278	3339222	23135				564278	3339222	23135				564,278	3,339,222	23,135				224.76	1584.35	8.81	8.81	2.47	-3.70
2.078	9508	4.97	3.88	3.21	2.63	350622	2621572	28020				350622	2621572	28020				350,622	2,621,572	28,020				322.17	1157.48	8.61	8.61	2.33	-1.57
2.163	9530	3.3	2.14	1.76	1.31	354248	2448676	60185			1	559558	7194474	45422		1		335,161	5,000,000	50,000				593.17	1880.36	8.16	8.16	2.72	-7.46
2.244	9530	6.44	4.46	4.33	3.71	154132	5914428	18135		1		303000	3030000	20200				303,000	3,030,000	20,200				203.58	1239.08	8.86	8.86	2.32	-1.48
2.347	9541	4.89	4.07	3.7	3.22	496378	5187630	20145		1		509321	5089737	20184		1		512,027	5,000,000	20,247				172.48	2056.47	8.94	8.94	2.61	-5.70
2.415	9574	4.89	3.87	3.41	2.89	437575	3369290	24674				437575	3369290	24674				437,575	3,369,290	24,674				250.81	1475.19	8.75	8.75	2.44	-3.20
2.506	9487	3.77	2.57	2.22	1.8	295753	4094122	41910				295753	4094122	41910				295,753	4,094,122	41,910				498.78	1561.22	8.30	8.30	2.56	-4.98
2.6	9508	4.18	3.07	2.72	2.3	327438	4860227	30974				327438	4860227	30974				327,438	4,860,227	30,974				316.12	1829.47	8.62	8.62	2.61	-5.72
2.736	9497	5.15	3.62	3.13	2.59	245313	3022363	28842				245313	3022363	28842				245,313	3,022,363	28,842				332.73	1179.60	8.59	8.59	2.34	-1.76
2.805	9607	4.83	3.51	3.06	2.54	281487	3714783	28762				281487	3714783	28762				281,487	3,714,783	28,762				310.91	1429.78	8.63	8.63	2.44	-3.25
2.898	9497	5.15	3.26	2.95	2.53	163000	6255528	26942		1		241103	2925231	31041				241,103	2,925,231	31,041				370.60	1145.36	8.52	8.52	2.34	-1.71
2.977	9487	5.24	3.99	3.36	2.76	391772	1912758	27380				391772	1912758	27380				391,772	1,912,758	27,380				331.40	969.56	8.59	8.59	2.25	-0.36
3.08	9618	4.39	3.69	3.34	2.89	658232	4706558	23352				658232	4706558	23352				658,232	4,706,558	23,352				207.00	2105.29	8.85	8.85	2.62	-5.97
3.192	9399	4.04	2.89	2.5	2.07	338043	3692075	35628				338043	3692075	35628				338,043	3,692,075	35,628				408.97	1479.12	8.45	8.45	2.50	-4.04
3.272	9421	3.7	2.7	2.27	1.87	415766	3172254	40400				415766	3172254	40400				415,766	3,172,254	40,400				493.41	1392.52	8.31	8.31	2.49	-3.87
3.353	9399	4.04	2.98	2.55	2.08	393490	2939871	36188				393490	2939871	36188				393,490	2,939,871	36,188				436.11	1298.30	8.40	8.40	2.43	-3.01

Revised Design Procedure

STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS =	34.00
AVG A(Dreq - Deff) =	-3.28
STD A(Dreq - Deff) =	1.71
DESIGN AC OVERLAY THICKNESS	
AT 85% RELIABILITY LEVEL =	-1.51

Table F2. Software design results for WAS-50

Station	Load, lbf	Measured Deflection W(0)	W(12)	W(24)	W(36)	First Step Precision 0_0001 E1	E2	E3	Check E1	E2	E3	Second Step Precision 0_0001&0_01 E1	E2	E3	Check E1	E2	E3	k (pci)	E	Dreq (PCC) (in.)	Deff (PCC) (in.)	Hover (AC)
0.012	9585	5.89	3.44	2.96	2.42	130624.88	3545211.27	30834.77				130624.88	3545211.27	30834.77				359.40	1223.26	8.54	9.45	-2.17
0.094	9585	5.48	3.17	2.76	2.3	132869.97	4764354.82	31588.15				132869.97	4764354.82	31588.15				339.40	1599.20	8.57	10.33	-4.45
0.515	9530	5.36	3.04	2.64	2.18	134920.38	4248352.80	33965.20				134920.38	4248352.80	33965.20				386.90	1443.27	8.49	9.99	-3.71
0.629	9476	5.44	2.8	2.42	1.95	114729.18	4032448.69	38733.64				114729.18	4032448.69	38733.64				470.60	1355.92	8.35	9.78	-3.53
0.699	9487	5.79	3.13	2.71	2.21	116600.93	3722592.71	33903.57				116600.93	3722592.71	33903.57				403.50	1262.96	8.46	9.55	-2.63
0.778	9596	6.13	4.17	3.63	3.04	174391.17	3411562.76	23887.66				174391.17	3411562.76	23887.66				255.40	1227.58	8.74	9.46	-1.69
0.859	9497	5.54	3.9	3.44	2.9	204682.30	4089209.68	24323.11				204682.30	4089209.68	24323.11				246.50	1466.94	8.76	10.04	-3.13
0.948	9508	4.47	2.03	1.68	1.29	125015.88	3727963.66	60816.09			1	133306.00	5000000.00	50000.00				616.90	1671.84	8.13	10.49	-6.23
1.036	9607	5.06	2.71	2.26	1.75	383347.33	541214.88	51625.54		1	1	122292.00	5000000.00	40989.00				474.40	1660.22	8.34	10.46	-5.50
1.114	9640	4.96	2.74	2.24	1.71	159007.46	2257962.32	46717.83				159007.46	2257962.32	46717.83				704.10	856.90	8.01	8.40	-0.89
1.196	9552	3.9	2.96	2.53	2.07	503437.73	3009874.02	35793.37				503437.73	3009874.02	35793.37				416.80	1423.31	8.44	9.94	-3.73
1.275	9596	4.07	2.61	2.11	1.68	257370.03	2725214.78	46695.44				257370.03	2725214.78	46695.44				647.50	1099.54	8.08	9.12	-2.48
1.365	9421	5.63	3.24	2.67	2.16	133417.65	2931842.77	34861.55				133417.65	2931842.77	34861.55				447.10	1037.99	8.39	8.95	-1.30
1.471	9552	5.39	3.39	2.92	2.44	157637.34	4283757.75	29766.85				157637.34	4283757.75	29766.85				321.90	1477.88	8.61	10.07	-3.60
1.55	9519	5.45	3.12	2.56	2.09	134023.50	3268336.29	36586.15				134023.50	3268336.29	36586.15				461.90	1141.88	8.36	9.24	-2.07
1.64	9574	5.7	3.44	2.87	2.27	148127.19	2508047.16	34534.79				148127.19	2508047.16	34534.79				459.10	922.88	8.37	8.61	-0.54
1.738	9552	5.12	3.63	3.09	2.58	233690.76	3721724.97	27800.18				233690.76	3721724.97	27800.18				300.40	1383.62	8.65	9.85	-2.91
1.818	9497	5.53	3.38	2.97	2.49	153030.03	4061175.45	29062.61				153030.03	4061175.45	29062.61				317.10	1404.83	8.62	9.90	-3.12
1.909	9476	4.81	3.98	3.5	2.99	564278.23	3339222.28	23134.71				564278.23	3339222.28	23134.71				224.80	1584.35	8.81	10.30	-3.70
2.078	9508	4.97	3.88	3.21	2.63	350622.10	2621572.12	28020.05				350622.10	2621572.12	28020.05				322.20	1157.48	8.60	9.28	-1.57
2.163	9530	3.3	2.14	1.76	1.31	354248.17	2448675.95	60185.30			1	335161.00	5000000.00	50000.00				593.20	1880.36	8.16	10.91	-7.47
2.244	9530	6.44	4.46	4.33	3.71	154131.91	5914427.94	18135.34		1		303000.00	3030000.00	20200.00				203.60	1239.08	8.86	9.49	-1.47
2.347	9541	4.89	4.07	3.7	3.22	496377.91	5187630.10	20145.36		1		512027.00	5000000.00	20247.00				172.50	2056.47	8.94	11.13	-5.70
2.415	9574	4.89	3.87	3.41	2.89	437575.48	3369290.27	24674.32				437575.48	3369290.27	24674.32				250.80	1475.19	8.75	10.06	-3.20
2.506	9487	3.77	2.57	2.22	1.8	295752.64	4094121.88	41910.20				295752.64	4094121.88	41910.20				498.80	1561.22	8.30	10.25	-4.99
2.6	9508	4.18	3.07	2.72	2.3	327437.77	4860226.97	30973.66				327437.77	4860226.97	30973.66				316.10	1829.47	8.62	10.81	-5.71
2.736	9497	5.15	3.62	3.13	2.59	245313.15	3022363.09	28842.18				245313.15	3022363.09	28842.18				332.70	1179.60	8.58	9.34	-1.77
2.805	9607	4.83	3.51	3.06	2.54	281487.46	3714782.72	28761.52				281487.46	3714782.72	28761.52				310.90	1429.78	8.63	9.96	-3.25
2.898	9497	5.15	3.26	2.95	2.53	162999.56	6255527.95	26941.64		1		241103.00	2925231.00	31041.00				370.60	1145.36	8.52	9.25	-1.71
2.977	9487	5.24	3.99	3.36	2.76	391771.65	1912758.15	27379.71				391771.65	1912758.15	27379.71				331.40	969.55	8.59	8.75	-0.36
3.08	9618	4.39	3.69	3.34	2.89	658232.32	4706558.05	23352.08				658232.32	4706558.05	23352.08				207.00	2105.29	8.85	11.13	-5.97
3.192	9399	4.04	2.89	2.5	2.07	338043.13	3692074.86	35628.32				338043.13	3692074.86	35628.32				409.00	1479.12	8.45	10.07	-4.05
3.272	9421	3.7	2.7	2.27	1.87	415766.43	3172254.20	40399.72				415766.43	3172254.20	40399.72				493.40	1392.52	8.31	9.87	-3.87
3.353	9399	4.04	2.98	2.55	2.08	393490.37	2939870.80	36188.13				393490.37	2939870.80	36188.13				436.10	1298.30	8.40	9.64	-3.00

Revised Design Procedure

STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS =	34.00
AVG A(Dreq - Deff) =	-3.28
STD A(Dreq - Deff) =	1.71
DESIGN AC OVERLAY THICKNESS	
AT 85% RELIABILITY LEVEL =	-1.51

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