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Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and Mn/Pave Pavement Design

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16. Abstract (Limit: 200 words)

The primary objective of this study was to quantify stiffness (resilient modulus) of aggregate base containing recycled asphalt and concrete pavements. After a survey of other state's specifications and implementation guidelines, Minnesota recycling projects were selected based on the availability of laboratory resilient modulus (M_R) tests and field measurements from FWD. The projects were County State Aid Highway 3, Trunk Highway 23 and Trunk Highway 200. Based on the results of a parametric study, it was found that traditional peak-based analysis of FWD data can lead to significant errors in elastostatic backcalculation. A procedure for extracting the static response of the pavement was formulated and implemented in a software package called *GopherCalc*. Laboratory resilient modulus measurements were compared with moduli backcalculated from the FWD data. The FWD data was analyzed using conventional (peak-based) and modified (FRF-based) elastostatic backcalculation (*Evercalc*) as well as a simplified mechanistic empirical model called *Yonapave*. Laboratory values from sequences in the M_R protocol that produced a similar state-of-stress were used. Additionally, a seasonal analysis of FWD test data revealed a significant increase in stiffness when the pavement is in the frozen state.

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Resilient Modulus Development of Aggregate Base and Subbase Containing Recycled Bituminous and Concrete for 2002 Design Guide and Mn/Pave Pavement Design

Final Report

Prepared by

Thomas M. Westover, Joseph F. Labuz, & Bojan B. Guzina,
Department of Civil Engineering
University of Minnesota

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Prepared for

Minnesota Department of Transportation
Office of Materials and Road Research
1400 Gervais Avenue
Maplewood, MN 55109

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EXECUTIVE SUMMARY

The primary objective of this study was to quantify stiffness (resilient modulus) of aggregate base containing recycled asphalt and concrete pavements. This was accomplished by (1) reviewing other states' specifications related to implementation of the recycled materials in pavement design and (2) using the statewide (cities, counties and Mn/DOT) testing data, such as falling weight deflectometer (FWD), to develop resilient modulus values that can be used as input for Mn/PAVE and the Design Guide. A brief survey of neighboring states, as well as states that frequently use recycled materials, revealed that the use of resilient modulus in design is limited, though considerable research is being conducted. Thus, only rehabilitation projects in the state of Minnesota were selected for study. The projects were County State Aid Highway 3, Trunk Highway 23, and Trunk Highway 200. These projects were selected based on the availability of laboratory results of resilient modulus and field measurements from FWD. Information regarding pavement thickness and actual design was also collected. Based on the results of a parametric study, it was found that traditional peak-based analysis of FWD data can lead to significant errors in elastostatic backcalculation due to dynamic effects. A procedure for extracting the static response from the dynamic test data by using the frequency-response-functions (FRFs) of the pavement was formulated. The analysis was simplified by the development of a software package called *GopherCalc*.

Field measurements in the form of FWD testing on rehabilitated pavements were analyzed and compared with resilient modulus values measured in the laboratory. By using conventional (peak-based) and modified (FRF-based) elastostatic backcalculation with *Evercalc*, as well as a simplified mechanistic-empirical model called *Yonapave*, representative values of base layer moduli were determined. These values were then compared with laboratory resilient modulus values obtained from the NCHRP 1-28A protocol. The laboratory values selected were from sequences in the protocol that produced a state-of-stress similar to that imparted by FWD loading. In addition, FWD data from the MN/Road facility was analyzed to determine the seasonal behavior of base material. Three sections (Low-volume Section 31, Mainline Sections 2 & 21) were examined for the year 1999. It was found that the base material exhibited a considerable increase in stiffness from the thawed months to frozen months, with modulus values changing from approximately 120 MPa to 760 MPa (17,500 psi to 110,500psi). Surface deflections in the frozen state were so small as to prevent accurate elastostatic recovery of the base moduli. For Cells 2 and 21, *Evercalc* analysis recovered a modulus of 120 MPa (17,500psi) for both sections, while *Yonapave* returned values of 100 MPa and 130 MPa (14,500 psi and 19,000 psi), respectively. Cell 31, analyzed with *Yonapave*, exhibited a base modulus of 110 MPa (16,000 psi).

Chapter 1
Introduction

Owing to the increasing scarcity of economical virgin aggregate supplies and increasing fuel costs, attention is now being focused on the use of recycled concrete pavements, reclaimed bituminous pavements, and other poured concrete as replacement materials in unbound pavement base applications. The practice of using recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP) in unbound base has been in place for some time. Research on the mechanical and chemical properties of these recycled materials following their field removal and processing has been extensively conducted for use as aggregate in bound applications. In unbound applications, recycled materials have been shown to perform in a similar manner to virgin aggregates in a number of laboratory comparison studies [1].

Although the pavement behavior is strongly influenced by the base and subgrade material characteristics, sufficient sampling and laboratory testing of the base materials is problematic due to the spatial variability of the materials and large number of tests that would be required over a typical reclamation project. It is therefore advantageous to determine an appropriate measure of base layer stiffness, such as resilient modulus, from a simple, non-destructive field pavement test. One such testing device that is commonly used in pavement evaluation is the Falling-Weight Deflectometer (FWD). In an FWD test, a load is applied to a pavement by dropping a weight from a specified height onto a buffered loading plate directly in contact with the pavement surface. Using an array of sensors, the pavement response near the load can be extracted and used to infer stiffness properties of the pavement layers. In this study, the stiffness of unbound aggregate bases containing recycled materials will be examined using FWD field test data and laboratory resilient modulus tests.

1.1 Background

In the area of pavement recycling, full-depth reclamation is a technique in which the existing pavement surface course along with a portion of the aggregate base are uniformly blended and compacted as a rehabilitated base course. Full-depth reclamation provides an economical alterative to total reconstruction, owing to the conservation of existing aggregate resources along with reduced material hauling and waste disposal costs. Due to the substantial contribution of the base layer to overall pavement quality and longevity, accurate determination of the material properties of this blended material is central to proper pavement design.

1.1.1 Recycled Concrete Aggregate (RCA)

The specifications regarding the use of recycled materials vary widely from state to state. In the Federal Highway Administration's State of Practice National Review from September 2004, a survey was conducted to determine the amount and type of recycled material application. The five states with the greatest amount of recycled material experience were further surveyed in the FHWA report: Texas, Virginia, Michigan, Minnesota and California. Of these states, all strongly encourage the use of RCA in unbound pavement base courses. It is generally acknowledged that the large amount of fines present in RCA can lead to workability and dust-control issues in the field, so it is commonly recommended that the material be placed and compacted at or near the saturation point to ensure the proper dispersion of fines and a reduction in dust. Minnesota and Michigan expressed considerable concern over the excess fines in RCA clogging drains. With regard to the field compaction of this material, it is also recommended that steel-drum rollers should be used, as small amounts of metal scrap can be problematic for rubber-tire type rollers.

1.1.2 Reclaimed Asphalt Pavement (RAP)

The use of RAP in both bound and unbound applications is also quite common.   Several of the states reviewed place a limitation on the percentage of RAP, ranging anywhere from 0.5 to 25% by weight. This is also accomplished by limiting the amount of asphalt binder in the mix to below 3.0% by weight. As noted in [1] and [2], unbound aggregate bases may have a greater potential for significant permanent deformation. A study by Molenaar [3] stated the most important factor controlling the stiffness and strength properties in unbound recycled materials is the degree of compaction. From a field study performed by Garg [4] some difficulty was experienced with field compaction of the material using both vibratory drum and sheep-foot rollers.

1.2 Objectives

The motivation of this study is to improve the quality of pavement design by examining the relationship between laboratory measurements made on the base materials and field measurements conducted on the in-place pavement sections. In this context, laboratory testing was carried out on base course aggregates containing recycled materials in a concurrent project entitled *Resilient Modulus and Strength of Base Course with Recycled Bituminous Material*, following the National Cooperative Highway Research Program (NCHRP) 1-28A test protocol to obtain a value of resilient modulus. Resilient modulus (M_R) is similar to a secant Young's modulus based on recoverable axial strain, $\Delta\varepsilon_a^r$, from an induced cyclic axial stress, $\Delta\sigma_a$:

$$M_R = \frac{\Delta\sigma_a}{\Delta\varepsilon_a^r} \tag{1.1}$$

The cyclic axial loading applied to a cylindrical specimen within a conventional triaxial cell is designed to simulate traffic loading. The protocol specifies that the specimen should be tested at several different levels of axial (deviator) stress and confining pressures. The samples were a collection of in-place blended material from reclamation projects within the state of Minnesota.

Field data, in the form of falling-weight deflectometer (FWD) measurements, were performed on these sections. The FWD data was interpreted in the framework of elastostatic back-analysis, which produces elastic moduli for each layer of the pavement system. Comparison of the laboratory and field values was accomplished by selecting sequences from the 1-28A test protocol for which the confining and deviator stresses were similar to those imparted by FWD loading.

1.3 Organization

Chapter 2 discusses the project selection procedure and identification of recycling projects suitable for this investigation within the State of Minnesota. Chapter 3 presents the data collection procedure and describes the information available from each of the selected projects. Chapter 4 covers the analysis for the field data. Chapter 5 describes the results, including a comparison with the laboratory findings. Chapter 6 summarizes and concludes the findings of the research.

Chapter 2
Project Information

Based on information obtained by a survey conducted in conjunction with the LRRB 808 study, 15 projects were selected from a total of 117 for further review based on the amount of information that was returned by the survey participants. This group was further narrowed based on the quality and type of information submitted. Special consideration was given to projects for which FWD data were available. This was done in order to relate the projects to those that have the laboratory determination of M_r and shear strength namely, Wright CSAH 3, TH23, and TH200. Table 2.1 displays the list of projects, including those selected for further review.

Table 2.1 Project selection criteria.

Project #	Project Information		Original Design		
	City/County/State	Hwy	Year of Const	AASHTO Class Soil Type	R-Value
6928-22	Duluth, MN	TH 73	1977	Silt Loam	29
3107-27	TH6 to Effie	TH1	1955	clay/silty clay	10
5804-51	Pine County	TH 48		loamy fine sand	na
0110-29	0.1 mi S of CSAH 2 to 0.1 mi N of CSAH 4	TH 65	1939	loamy sand and gravel	20

Project #	Pre-Rehab Analysis				Rehab Information				
	Date	PSR (Ride)	SR	PQI	Year of Rehab	CIR/ FDR/ M&O/	Depth of Mill/ Reclai	Emulsion %	Oil Type
6928-22	1993	2.3	2.6	2.4	1995	CIR	4		N/A
3107-27	1995	1.9	1.5	1.7	1997	FDR	6.5		58-28
5804-51	1998	2.1	3	2.5	1999	FDR	12		
0110-29	2003	2.2	2	2.1	2005	FDR	14		

Chapter 3
Data Collection

To determine a proper correlation between laboratory and field values of resilient modulus suitable for this climate, projects within Minnesota (and neighboring states) were selected that could provide data for analysis. Data were collected on three projects that were recently reconstructed using recycled materials in Minnesota: County State Aid Highway (CSAH) 3 in Wright County, Trunk Highway (TH) 23 in District 1, and TH 200 in District 4.

3.1 Minnesota Reclaiming Projects

Table 3.1 outlines the data collected on the projects listed above.

Table 3.1 Data collected from recycling projects in Minnesota.

Project	Data Type	Description	Date
CSAH-3	Resilient Modulus	Values of M_r were obtained from a previous project for the in-situ blend, and the following blends of RAP/Virgin Aggregate: 0/100, 25/75, 50/50, and 75/25.	January, 2007
	FWD Data	FWD peak values prior to rehabilitation.	May 10, 2004
	FWD Data	FWD peak values after rehabilitation	June 10, 2005
	FWD Data	FWD truncated time-histories after rehabilitation.	June 10, 2005
	GPR Data	Layer thickness information from Ground Penetrating Radar prior to rehabilitation	May 15, 2004
	Original Construction Data	Layer thicknesses and material types from GPR report	May 15, 2004
TH-23	Resilient Modulus	Values of M_r for the in-situ blend of recycled material from a previous project.	January, 2007
	Design Recommendations	Reclaim depths by station, traffic forecast, existing pavement, soils and R-value	April 30, 2002
	Typical Section	Obtained via fax from the district materials engineer (Rod Garver)	February 22, 2007
	FWD Data	FWD peak values prior to rehabilitation	October 19, 2000
	FWD Data	FWD peak values after rehabilitation.	July 2, 2002
	808 Database	SR Data (2 years)	2002, 2004
TH-200	Resilient Modulus	Values of M_r for the in-situ blend of recycled material from a previous project.	January, 2007
	Pavement Thickness	Obtained via email from the district materials engineer (Perry Collins)	February 26, 2007
	FWD Data	FWD peak values after rehabilitation. (2 sets)	September 1, 2004 July 28, 2005
	808 Database	SR Data (10 years)	1989-2004

3.2 Recycled Materials Survey

To determine the proper implementation of resilient modulus for recycled materials used in pavement design for Minnesota, a short survey was submitted to the DOT's of neighboring states (North Dakota, South Dakota, Iowa, Wisconsin, and Michigan) to determine the state-of-practice for this climate region. In addition, California and Virginia were contacted due to their widespread use of recycled materials, as outlined in the FHWA State-of-Practice Review, September 2004.

The survey requested the following information:

1. Resilient moduli and shear strength values used in design for virgin aggregate bases, with seasonal adjustments;
2. Resilient moduli and shear strength values used in design for aggregate bases containing recycled materials, with seasonal adjustments;
3. Recycled material implementation guidelines and any additional information regarding successful/unsuccessful projects using recycled materials.

The responses will be summarized by state. The detailed communications can be found in Appendix A.

Michigan

Aggregate bases containing recycled materials are treated the same as virgin aggregates. For dense-graded bases, a resilient modulus of 200 MPa (30,000 psi) is used and assumed to be seasonally adjusted. Recycled materials are not allowed in open-graded bases, or where geotextiles or unfiltered underdrains are used. Michigan does not use resilient modulus for open-graded virgin bases.

Michigan does not have any implementation guidelines. Experience suggests that most successful recycling projects from the late 1980's and early 1990's were recycled concrete with asphalt stabilization. These pavements outperformed the unbound (virgin) aggregate projects from the same area.

South Dakota

Virgin aggregates are assigned a resilient modulus value of 145 MPa (21,000 psi). Alternatively, a Structural Number (SN) is defined for this material as 0.1 per inch of material. Aggregate bases containing recycled materials have a resilient modulus of 200 MPa (30,000 psi) or an SN of 0.14 per inch of material.

South Dakota has been using recycled materials in aggregate bases for over 20 years. Reconstruction of any existing pavement involves salvaging all of the in-place asphalt and granular base for reuse. The target blend is 50% granular/50% recycled asphalt material, but in the field, a blend of 40% granular/60% recycled asphalt is allowed. They do not allow Portland Cement Concrete (PCC) pavement as salvaged base below asphalt pavements. Recycled PCC can be used below concrete pavements, provided it meets the criteria for "Gravel Cushion".

California

The California design method is currently an empirical method similar to the 1993 AASHTO method using a gravel factor characteristic of the strength of the material. California is currently developing a mechanistic-empirical method that will utilize resilient modulus and shear strength.

The California DOT (Caltrans) allows up to 100% substitution of recycled or reclaimed materials. They are currently developing specifications for cold foam in-place recycling and pulverization. In general, the target mixture is 30% base material/70% recycled asphalt for cold-foamed projects.

Wisconsin

Resilient modulus values are not used in pavement design, although research is in progress.

North Dakota

Resilient modulus values are not used in pavement design.

Iowa

Iowa DOT did not respond to the survey.

Virginia

Virginia DOT did not respond to the survey.

Chapter 4
Data Analysis

4.1 FWD Data Analysis

In the area of nondestructive pavement testing, the FWD test has become a standard way of characterizing subsurface properties. Interpretation of these results to obtain the properties of the pavement, base, and subgrade is the focus of considerable research in areas such as dynamic and static layered elastic and visco-elastic modeling, finite element analysis, neural networks, experimental or empirical correlations, and laboratory testing. In this study, the data obtained from the FWD test will be interpreted using an elastostatic back-calculation method (*Evercalc*), as well as a simplified mechanistic-empirical model (*Yonapave*).

Due in large part to its simplicity, elastostatic back-calculation remains the norm in estimating the mechanical properties of the pavement layers. Using information on layer thicknesses, assumed or calculated Poisson's ratios, and initial or seed moduli values, the backcalculation procedure mimics the deflection basin obtained from the test by varying the input to an elastostatic forward model until a proper fit of surface deflection profiles is achieved.

To improve the accuracy and reliability of FWD data interpretation, a modification of the existing back-calculation procedure should be executed to remedy a fundamental inconsistency in the back-calculation input. Traditionally, the peak values of deflection together with the corresponding peak value of force are used to describe the deflection basin. These peak values are obtained by dropping a weight from a specified height onto the buffered loading plate of the FWD. These events, and the peak values that are generated, are dynamic in nature. The problem arises of performing a *dynamic* test and using its *dynamic* peak values as an input to elasto*static* back-calculation. This issue is especially significant in the case of shallow stiff layer, wherein the contribution of dynamic effects to surface displacement can be significant. As in Figure 4-1, this phenomenon can cause substantial errors in recovery of layer moduli through backcalculation if not properly treated. One such treatment involves using frequency response functions to extract the static response of the pavement from the dynamic test data. Shown in Figure 4-2, using the static pavement response greatly reduces the potential for serious error in backcalculation. A parametric study investigating the effect of layer thickness, base moduli, and stiff layers on the dynamic (peak) and static (FRF) backcalculation procedures is discussed in Appendix D**.**

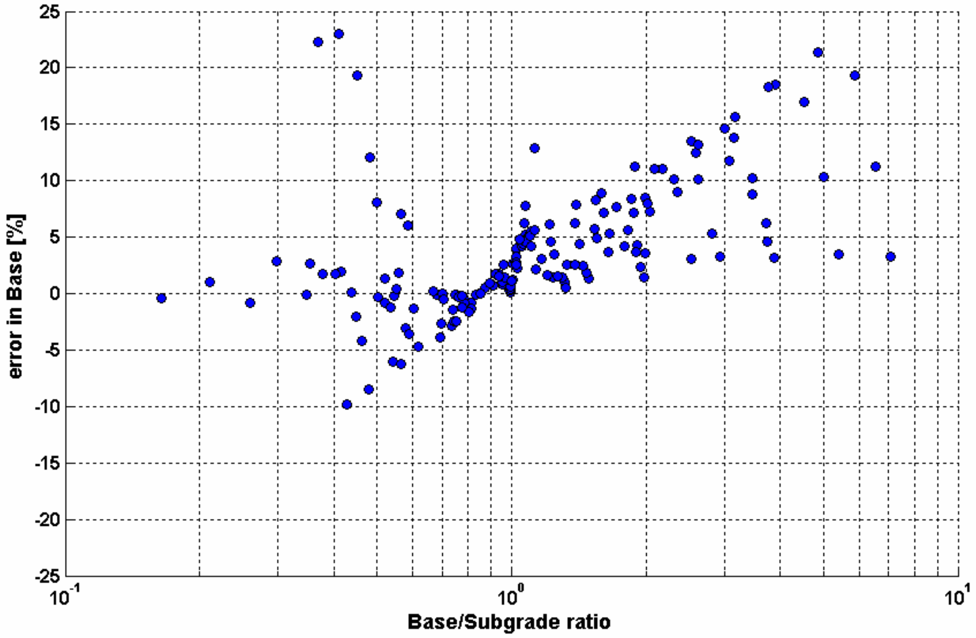

Figure 4-1 Error in base modulus using peak-based elastostatic backcalculation (175 test cases).

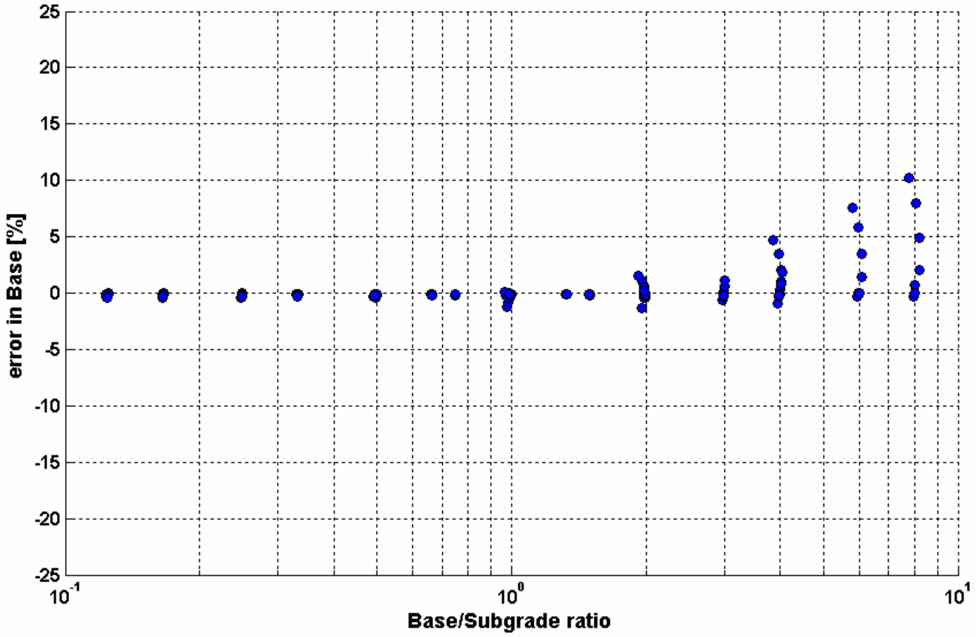

Figure 4-2 Error in base modulus using FRF-based backcalculation (175 test cases).

In what follows, a procedure to extract the static response of the pavement from the dynamic FWD test data using the concept of a frequency-response-function (FRF) will be presented and discussed as a way to elevate traditional elastostatic backcalculation procedures. Due to the large amount of data generated by the FWD test, a graphical user interface, *GopherCalc*, was developed to expedite the data analysis procedure.

4.1.1 GopherCalc

GopherCalc is a graphical user interface developed using MATLAB. The purpose of the program is to facilitate both traditional and modified elastostatic back-analysis of pavement properties and provide a convenient tool to visualize the time- and frequency-domain signatures of the FWD test. It allows a user to: 1) perform automated averaging of device-stored data records, 2) apply and visualize a proper baseline correction, 3) compute and extrapolate frequency-domain response, 4) compare peak-based and extrapolated-static deflection basins and, 5) export deflection basin data into a form that is compatible with external elastostatic back-calculation programs.

Using *GopherCalc* to extract the static basin involves three major steps: 1) baseline correction, 2) calculation of a frequency-response-function (FRF) and, 3) low-frequency extrapolation. To perform this analysis, the full time history of the test is required. The time-history should contain the initial pulse from the loading as well as the free-vibrations that follow. Performing this procedure using these longer records is essential to avoid potentially serious errors associated with signal truncation.

Baseline Correction

In an FWD test, geophones record the pavement surface velocity over the duration of the test. These velocity records are then integrated to obtain the displacements at each geophone location. Random noise inherent to the transducers and data collection system is accumulated during this integration resulting in a non-zero displacement at the end of the record known as baseline offset. While this noise is typically not significant in terms of peak-based methods, it can lead to significant errors in the frequency-based interpretation. It is therefore necessary to account for this non-zero displacement with a proper baseline correction. The effect of baseline correction can be seen in Figure 4-3. Note the non-zero drift known as baseline offset, Figure 4-3a, and significant reduction in FRF noise seen in Figure 4-3d.

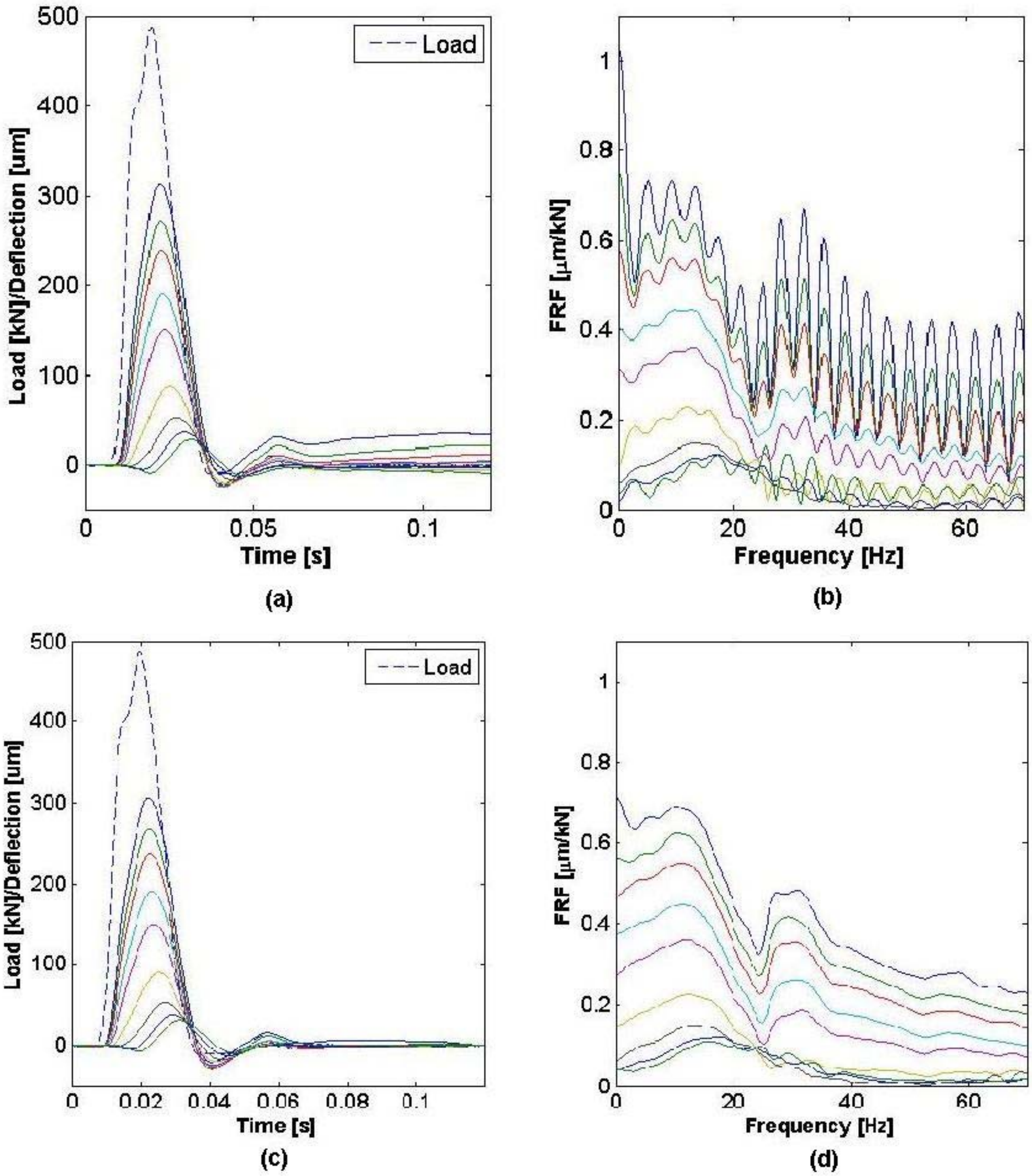

Figure 4-3(a-d) Effect of baseline correction on frequency response functions, a) Original time-history b) original FRF c) baseline-corrected time-history d) baseline corrected FRF.

For a given geophone displacement record *w(t)* and corresponding time-history *t,* the general form for the baseline correction at time t_i is:

$$w_{bc}(t_i) = w\left(t_i\right) - \frac{\left(w\left(t_f\right) - w\left(t_0\right)\right)}{\left(t_f - t_0\right)^n}\left(t_i\right)^n \tag{4.1}$$

where *n* is the power of the baseline correction. In most cases, a linear baseline correction (*n*=1) is a proper choice and results in a ”rotation” of the record to achieve the desired zero-offset. The power of the baseline correction is dependent upon the amount of noise present in the record. Application of the baseline correction is implemented automatically in the program.

Frequency Response Function

Once the record has been treated with a proper baseline correction, the next step in extracting the static response is to perform a frequency domain analysis by using a Fourier transform. Since the signal from an FWD device is of finite duration and digitized, a discrete Fourier transform

$$\left[G\left(f_m\right)\right] = \Delta t \sum_{j=0}^{M} g\left(t_j\right) e^{-i\left(2\pi f_m\right)t_j}, \qquad m = 0,1,2,...,M \tag{4.2}$$

is applied to the time-domain record, $g(t_j)$, to find its frequency-domain counterpart, $G(f_m)$. This procedure is commonly and efficiently implemented by means of a Fast Fourier Transform (FFT) in many computer applications. In the context of FWD test analysis, this FFT procedure is applied to the falling-weight force, $q(t)$, and the deflection record for each of the N geophones, $w_k(t)$ (k=1,2,…,N) to obtain the frequency-domain representations $Q(f)$ and $W_k(f)$ respectively. Once these records have been transformed, it is possible to compute the frequency response function (FRF) for the k^{th} geophone as

$$FRF_k(f_m) = \frac{W_k(f_m)}{Q(f_m)}. \tag{4.3}$$

This resulting function represents *deflection per unit force at each frequency of excitation*, which is essential to extracting the static response.

When multiple drops are available at a particular test point, the records should be combined by using the cross-spectral, S_{qk} and auto-spectral S_{qq} density functions:

$$S_{qk}\left(f_m\right) = \frac{1}{T}\sum_{i=1}^{T}\left[Q^*\left(f_m\right)\right]_i\left[W_k\left(f_m\right)\right]_i, \qquad m = 0,1,2,...,M \tag{4.4}$$

$$S_{qq}\left(f_m\right) = \frac{1}{T}\sum_{i=1}^{T}\left[Q^*\left(f_m\right)\right]_i\left[Q\left(f_m\right)\right]_i, \qquad m = 0,1,2,...,M \tag{4.5}$$

where ‘*’ denotes the complex conjugate. The FRF is then defined as

$$FRF_k(f_m) = \frac{S_{qk}(f_m)}{S_{qq}(f_m)}, \qquad k = 1,2,...,N. \tag{4.6}$$

It is useful to note that the FRF is defined at each frequency m in the record. The static response of the system is then given, by definition, as the value of the FRF at a frequency of zero.

Low-Frequency Extrapolation

Due to the physical construction of a geophone, the data in the lowest frequency range (<10Hz) is inherently characterized by a poor signal-to-noise ratio and is thus deemed unreliable for the extraction of the zero-frequency (static) response of the system. It is therefore necessary to develop an extraction scheme anchored in a frequency range with better signal-to-noise ratios and extrapolate through the noise polluted region. For FWD applications, a single-degree-of-freedom (SDOF) model provides a stable, consistent means for dealing with this low frequency noise. Additionally, the SDOF model provides a proper analog to the physical behavior of the pavements in the low frequency ranges, manifest in its ability to capture resonant peaks within the fit range and remain stable when extrapolated towards zero.

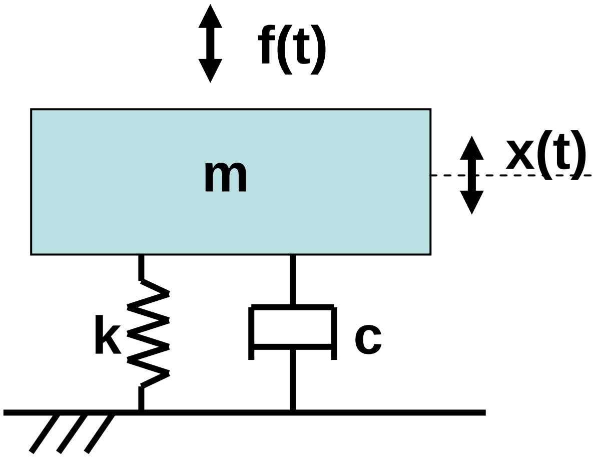

Figure 4-4 Schematic of a single-degree-of-freedom (SDOF) system.

The governing equation for the motion of a SDOF model consisting of a mass *m*, a spring with spring constant *k,* and a dashpot with damping constant *c,* can be formulated as

$$FRF_{SDOF}(f_m) = \frac{1/k}{\sqrt{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(2\xi\frac{\omega}{\omega_0}\right)}}, \qquad \omega_0 = \sqrt{\frac{k}{m}},\ \xi = \frac{c}{2\sqrt{km}} \qquad (4.7)$$

Using this representation, along with a proper choice of initial values based on the characteristics of the geophone record being fit, the zero-frequency values can be recovered despite the limitations imposed by the geophone.

4.1.2 Yonapave

As is often the case in pavement evaluation, accurate layer thicknesses are not always available. This can have a significant effect on the layer moduli determined from a multi-layer back-calculation, particularly when the peak values of force and deflection are used. A way to circumvent this lack of reliable data is to use a methodology that generates an *equivalent* subgrade modulus that encompasses both the aggregate base and in-place subgrade material. One such method, *Yonapave* [5] is based on the Hogg model of a thin slab resting on an elastic foundation. By using this representation of the pavement structure and determining the properties of the elastic layer based on the deflections obtained, a suitable equivalent modulus can be recovered.

The *Yonapave* method uses the basic relationships of the Hogg model together with the MODULUS program to generate curves from which modulus values can be inferred based on the characteristics of an individual deflection basin. The "area" of a deflection basin can be determined by using the deflections at 0, 30, 60, and 90 cm from the load plate by

$$Area = 6\left(1 + 2\frac{D_{30}}{D_0} + 2\frac{D_{60}}{D_0} + \frac{D_{90}}{D_0}\right) \quad [inches] \tag{4.1}$$

Yonapave suggests that the ratio of the actual depth to the bedrock or stiff layer, *h*, and the characteristic length is related to this deflection basin area. The relationship between the characteristic length, l_0, and the area can then be defined as

$$l_0 = A \times e^{B \times Area} \tag{4.2}$$

where the values of A and B are determined from curve fitting and are found in Table 4.1 *Yonapave coefficients* for determining characteristic length, l0.

Table 4.1 *Yonapave* coefficients for determining characteristic length, l_0.

Range of Area Values, inch	**h/l₀**	**A**	**B**
Area ≥ 23.0	5	3.275	0.1039
21.0 ≤ Area < 23.0	10	3.691	0.0948
19.0 ≤ Area < 21.0	20	2.800	0.1044
Area < 19.0	40	2.371	0.1096

Based on this characteristic length, the equivalent subgrade modulus E_{sg} in units of MPa can be determined as a function of the load plate pressure *p* in units of kPa, center deflection D_0 and an additional set of curve fitting coefficients found in Table 4.2 *Yonapave* curve fitting constants for determining equivalent subgrade modulus, *Esg.* as

$$E_{sg} = m \times \frac{p}{D_0} \times l_0^n \tag{4.3}$$

Table 4.2 *Yonapave* curve fitting constants for determining equivalent subgrade modulus, E_{sg}.

h/l₀	**m**	**n**
5	926.9	-0.8595
10	1152.1	-0.8782
20	1277.6	-0.8867
40	1344.2	-0.8945

The *Yonapave* algorithm presents further procedure for determining the AASHTO Structural Number (SN), but for the purpose of comparison with other methods in this report, those methods have been omitted.

Chapter 5
Results and Discussion

The FWD data analyzed following the methodology previously presented will be discussed in detail and compared with laboratory resilient modulus values.

5.1 Wright County State Aid Highway 3

FWD and Ground-Penetrating-Radar (GPR) testing was performed on the roadway prior to its reconstruction. During reconstruction, field sampling of the virgin aggregate, reclaimed asphalt, and in-situ blend created from the recycling process was conducted. Using these materials, laboratory resilient modulus tests were conducted following NCHRP protocol 1-28A. Once the rehabilitation was completed, FWD testing was again performed on the completed roadway. Truncated (60 ms) time-histories were acquired during this testing procedure. Although full length (120 ms) time-histories are preferable, a brief investigation from Mn/ROAD data suggests that the value of the error in the fit range to be less than 5%. While this error is fairly low, its effect on the extrapolation procedure and subsequent elastostatic backcalculation can not be reliably determined.

Using the methods described in the previous section, the results from data obtained from CR-3 are presented in Table 5.1. As a basis for comparison, the data obtained from the field will be compared with similar cycles in the resilient modulus test protocol.

Table 5.1 CR-3 modulus comparison.

CR-3 Material	Before Reconstruction (Virgin Aggregate) MPa (psi)	After Reconstruction (Unbound RAP) MPa (psi)
FWD (Peak)	70 (10,000)	192 (28,000)
FWD (FRF)	n/a	177 (25,500)
YONAPAVE	89 (13,000)	152 (22,000)
M_r (σ_3 = 21 kPa)	124 (18,000)	154 (22,000)
M_r (σ_3 = 41 kPa)	181 (26,500)	230 (33,500)

In the FWD data taken prior to reconstruction, there is no record of the exact station or mile-post of the test. As a result, the spatial relationship of the data can not be directly determined. The base moduli generated from *Evercalc* are presented in Figure 5-1 and Figure 5-2. The equivalent subgrade modulus calculated using *Yonapave* is presented in Figure 5-3 and Figure 5-4.

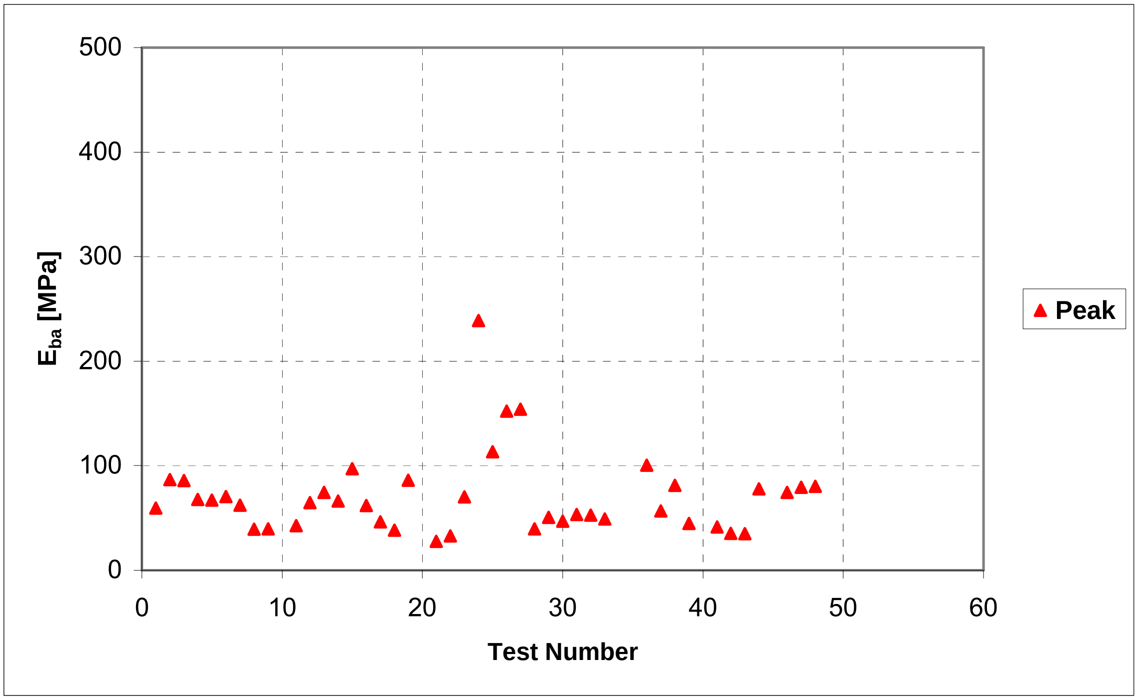

Figure 5-1 CR-3 base modulus prior to reconstruction.

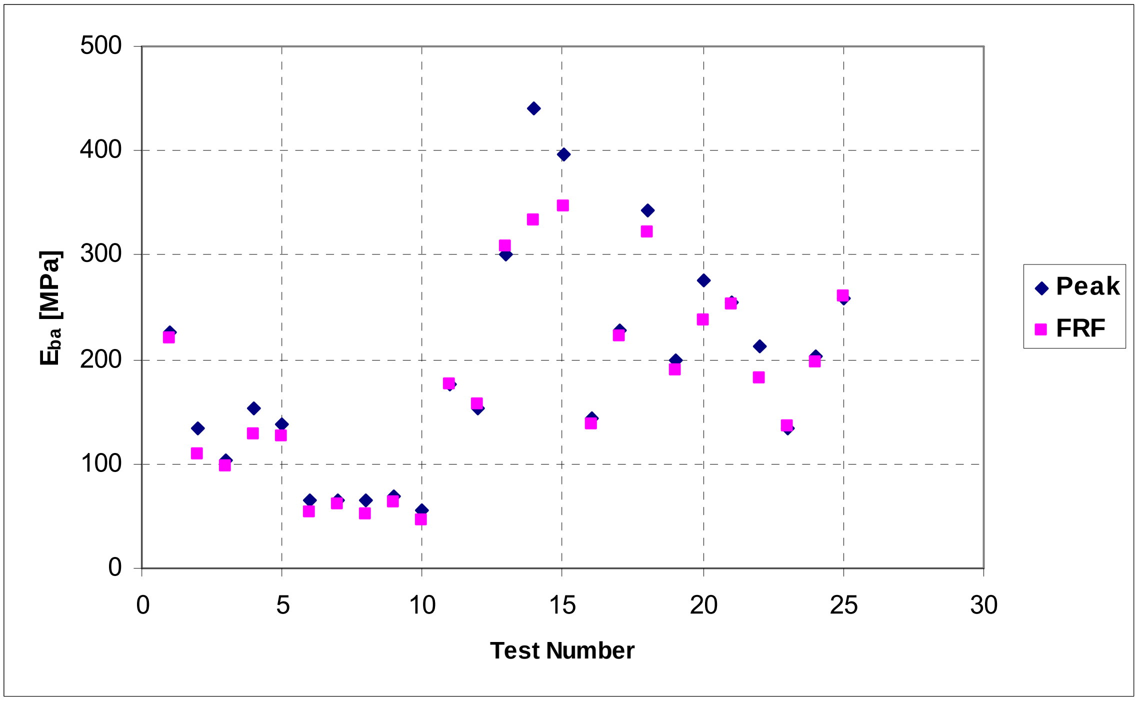

Figure 5-2 CR-3 base modulus after reconstruction.

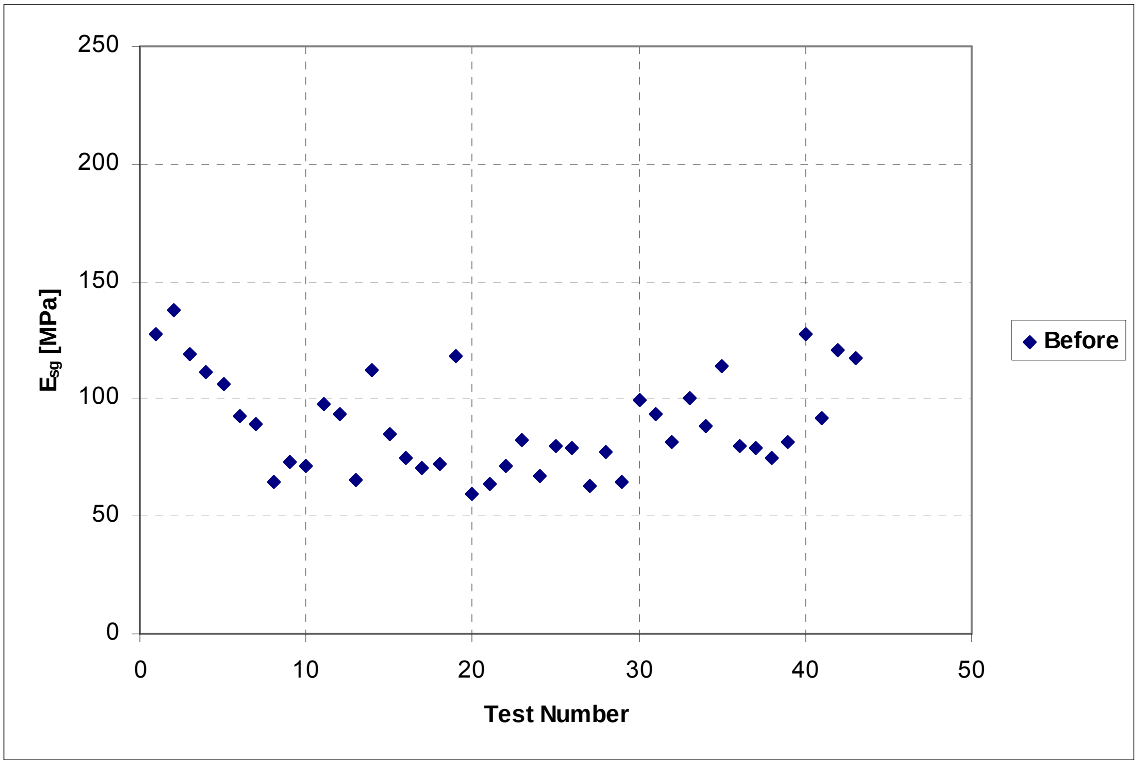

Figure 5-3 CR-3 equivalent subgrade modulus before reconstruction.

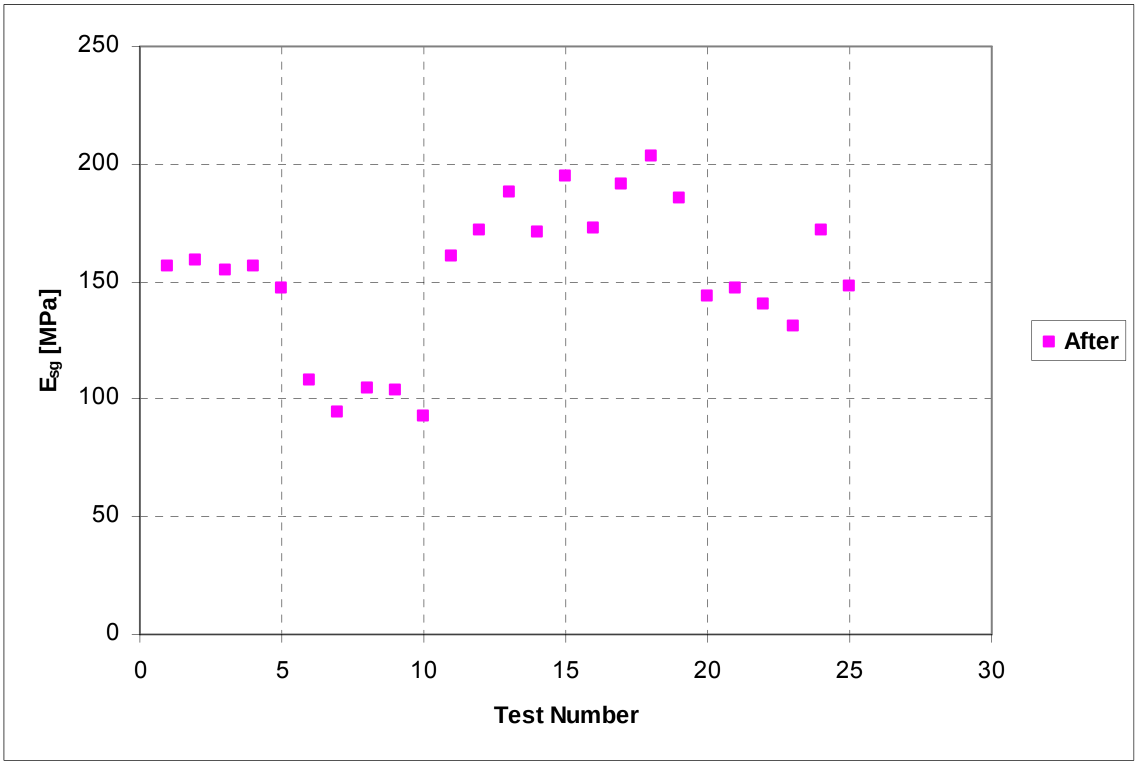

Figure 5-4 CR-3 equivalent subgrade modulus after reconstruction.

5.2 TH-23

FWD test data (peak values) were available from before and after the reconstruction. A portion of the in-situ blended material generated by full-depth reclamation was tested in the laboratory, following the 1-28A protocol. GPR data was unavailable for this project, and thus asphalt layer thickness could not be accurately determined. Since layer thickness plays a significant role in elastostatic backcalculation, some anomalous results were obtained. Based on backcalculation performed with design layer thicknesses, only stations with a base modulus of less than 500 MPa (72,500 psi) and an asphalt modulus of between 2-9 GPa (290-1300 ksi) were considered. These criteria were sufficient to prevent obviously erroneous results produced by backcalculation. For the purpose of comparison, the average value of base or equivalent modulus is compared with in Table 5.2 with resilient modulus values with a similar stress state to FWD loading. The spatial variation of the *Evercalc* and *Yonapave* analysis can be found in Figure 5-5 and Figure 5-6.

Table 5.2 TH-23 Modulus Comparison.

TH-23 Material	Before Reconstruction (Virgin Aggregate) MPa (psi)	After Reconstruction (Unbound RAP) MPa (psi)
FWD (Peak)	79 (11,500)	97 (14,000)
YONAPAVE	70 (10,000)	93 (13,500)
$M_r (\sigma_3 = 21$ kPa)	n/a	149 (21,500)
$M_r (\sigma_3 = 41$ kPa)	n/a	236 (34,000)

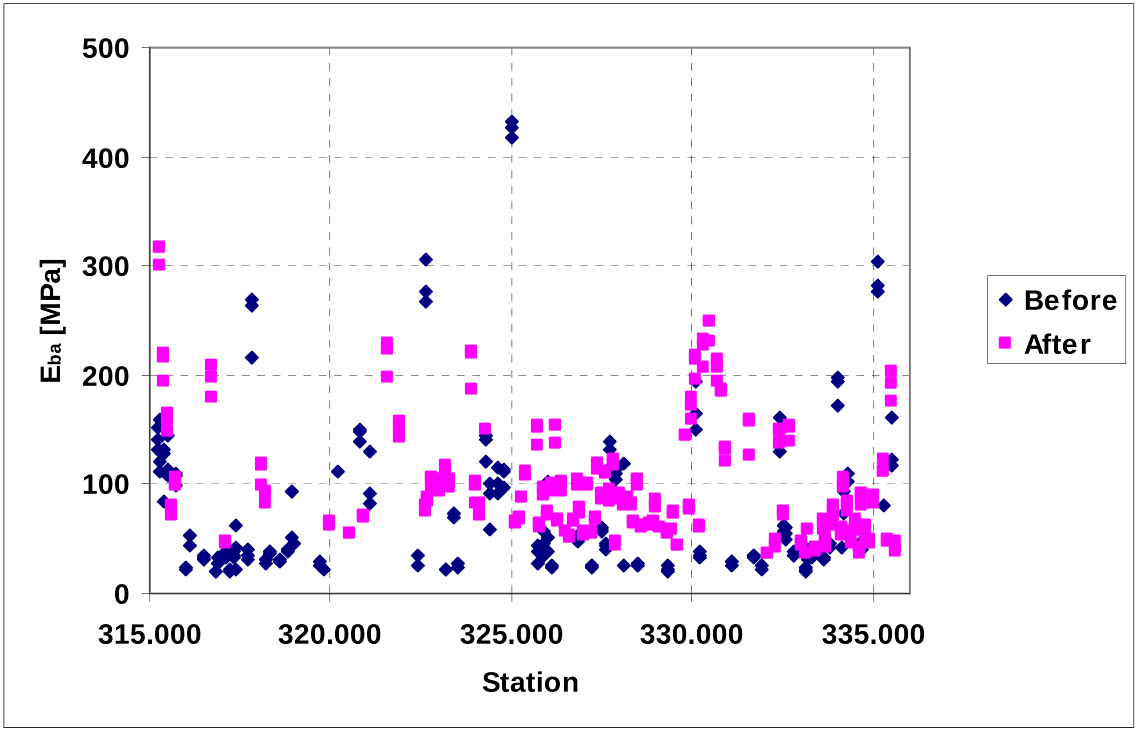

Figure 5-5 TH-23 base modulus.

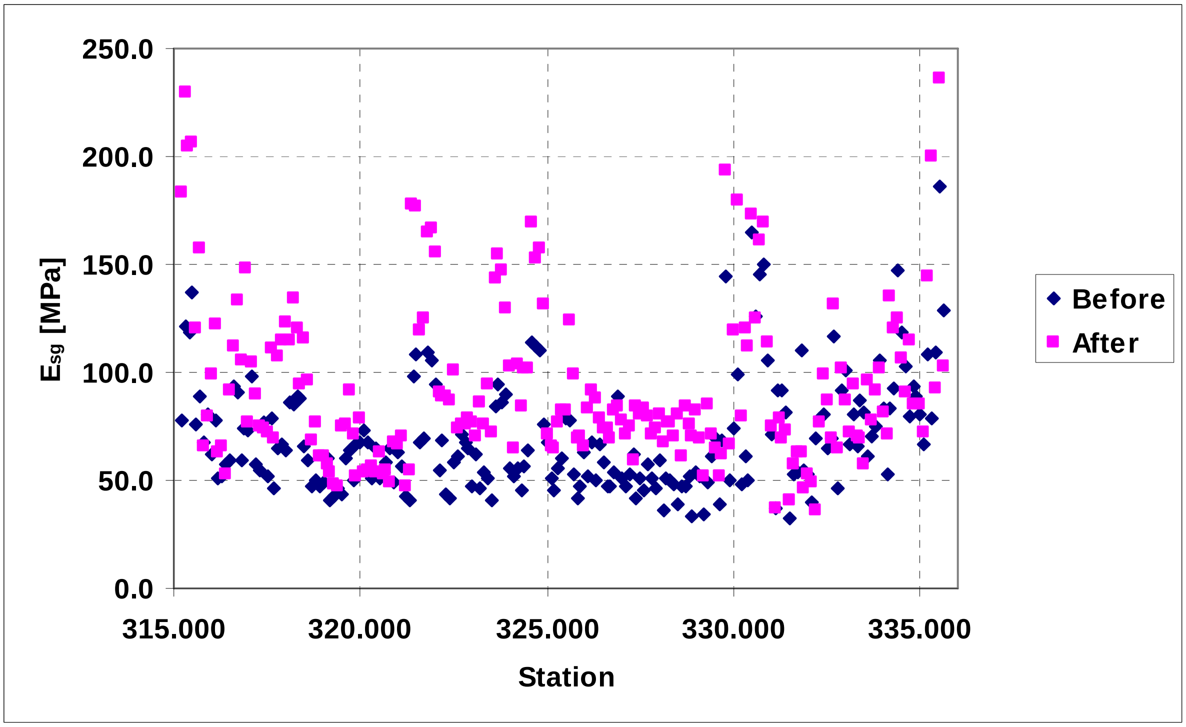

Figure 5-6 TH-23 equivalent subgrade modulus.

5.3 TH-200

FWD test data (peak values) were available from two years after the reconstruction took place (2004, 2005). The in-situ blended material was tested in the laboratory. Backcalculation was performed with design layer thicknesses. Though moduli returned from *Evercalc* backcalculation (Figure 5-7) are higher than returned by *Yonapave* (Figure 5-8) or laboratory experiments (Table 5.3), the values are consistent from 2004-2005. Accurate layer thicknesses at the drop locations would most likely provide moduli values more similar to those found by other methods.

Table 5.3 TH-200 modulus comparison.

TH-200 Material	2004 Data (Unbound RAP) MPa (psi)	2005 Data (Unbound RAP) MPa (psi)
FWD (Peak)	325 (47,000)	392 (57,000)
YONAPAVE	106 (15,500)	110 (16,000)
M_r (σ_3 = 21 kPa)	n/a	109 (16,000)
M_r (σ_3 = 41 kPa)	n/a	210 (30,500)

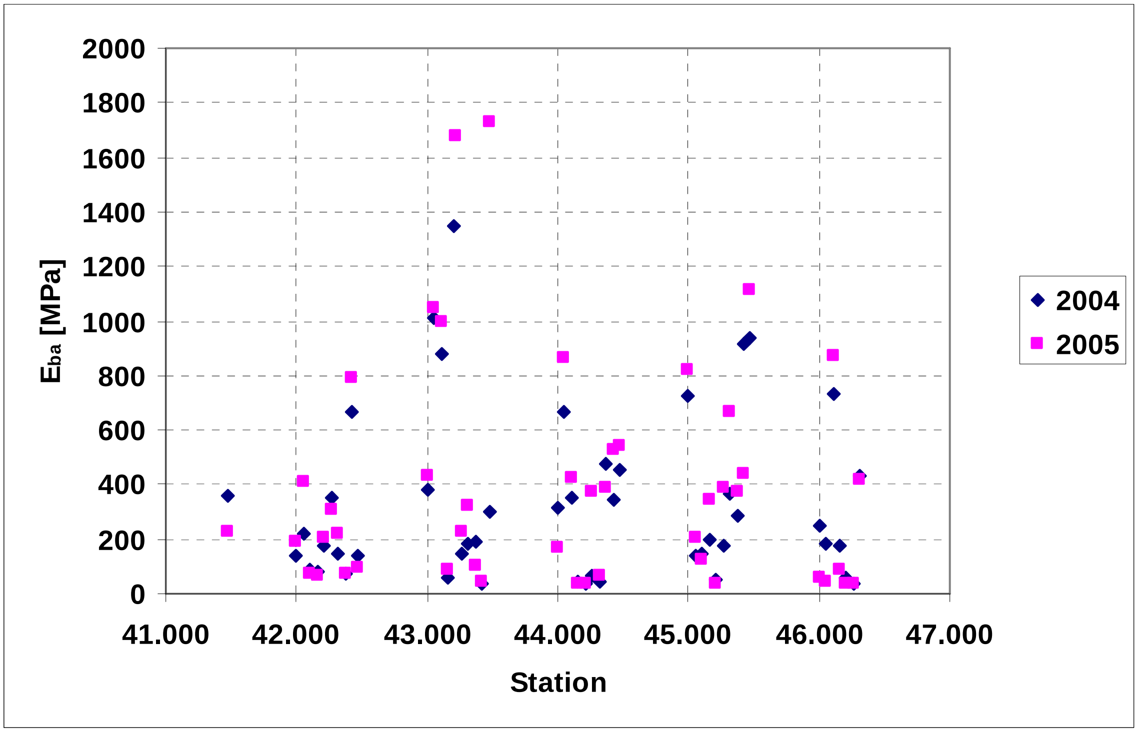

Figure 5-7 TH-200 base modulus.

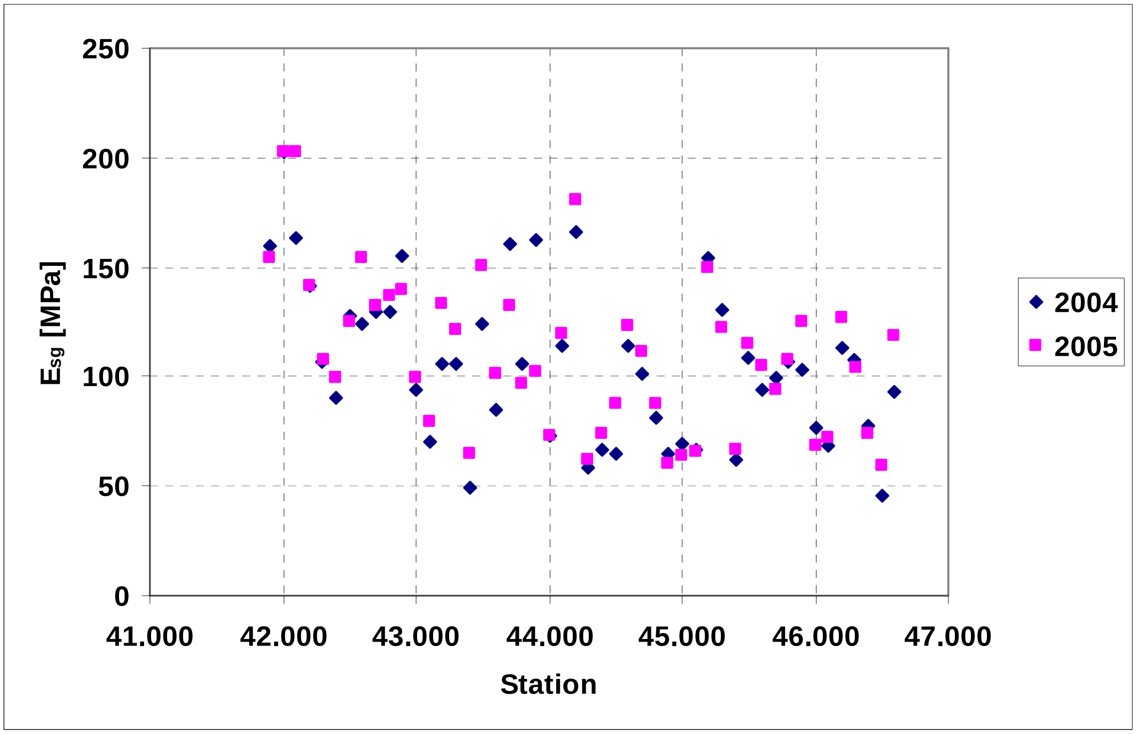

Figure 5-8 TH-200 Equivalent subgrade modulus.

5.4 Seasonal Effects

The influence of seasonal changes on FWD-backcalculated resilient moduli was investigated using data from the Mn/ROAD facility. Low-volume road Section 31, Mainline Section 2, and Mainline Section 21 were chosen based on the pavement profile and availability of sufficient FWD data. In this study, seasonal effects were studied for the year 1999. The FWD data from Sections 2 and 21 was evaluated using both *Evercalc* to obtain a base modulus and *Yonapave* to obtain an equivalent subgrade modulus. Section 31 was analyzed using *Yonapave* only. For each test section, the pavement is tested at 10 locations. At each location, there are two initial drops to seat the loading plate against the pavement. Following the seating drops, the pavement is subjected to three drops at each of three different drop heights. A time-history is saved from the last drop at each drop height, for each location. Variation over all locations in one section is small compared to the variation between different testing dates. For clarity, the average value of modulus over all locations is presented for each station in Figure 5-9 (*Evercalc*) and Figure 5-10 (*Yonapave*). It should be noted that in the *Evercalc* backcalculation (Figure 5-9), deflections for the beginning of the year (Days 26 & 53) were too small to produce reasonable backcalculation results and were thus omitted from the plot. These small deflections suggest a considerably stiffer behavior than the rest of the year, such as is evident in the *Yonapave* calculation (Figure 5-10). Plots of the moduli obtained for individual locations at each station are available in Appendix E.

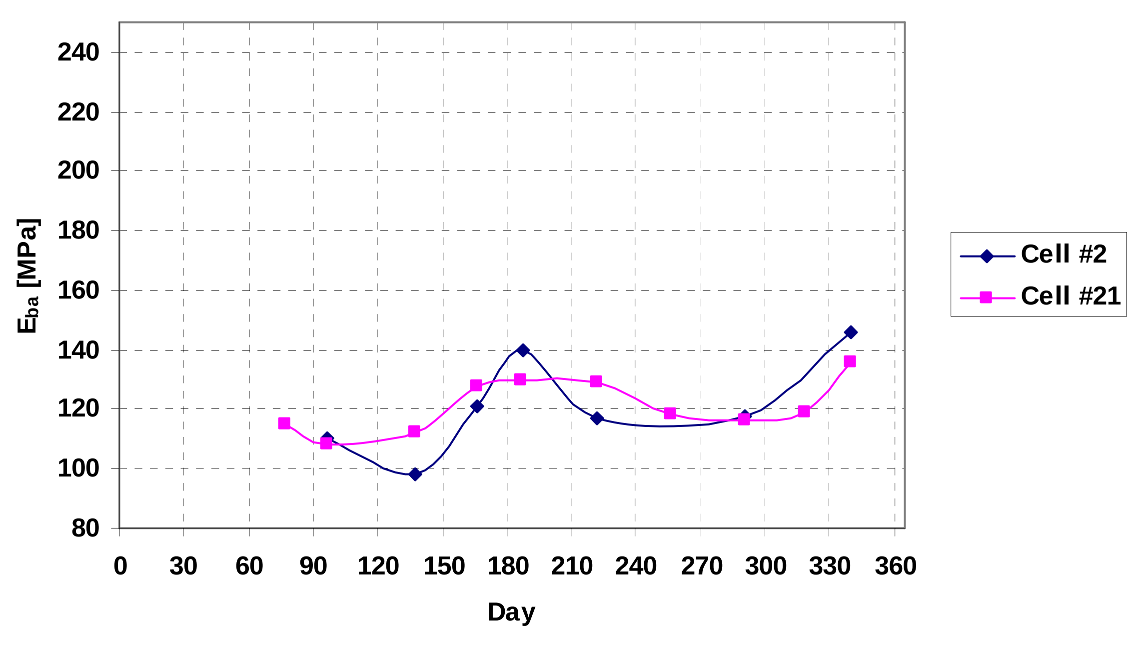

Figure 5-9 Seasonal effect on *Evercalc*-generated base modulus. Jan 1st (Day 0) – Dec 31st (Day 365), 1999.

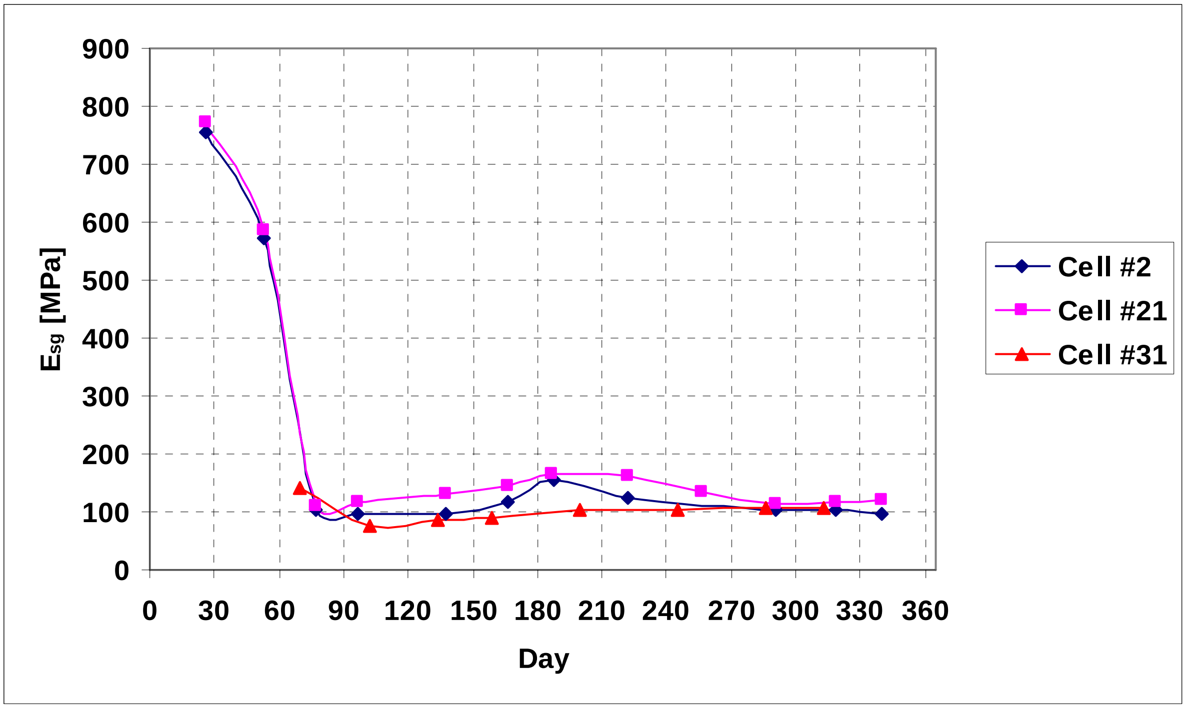

Figure 5-10 Seasonal effect on *Yonapave*-generated equivalent subgrade modulus. Jan 1st (Day 0) – Dec 31st (Day 365), 1999.

Chapter 6
Summary and Conclusions

The primary objective of this study was to quantify stiffness (resilient modulus) of aggregate base containing recycled asphalt and concrete pavements. This was accomplished by (1) reviewing other state's specifications related to implementation of the recycled materials in pavement design and (2) using the statewide (cities, counties and Mn/DOT) testing data, such as falling weight deflectometer (FWD), to develop resilient modulus values that can be used as input for Mn/PAVE and the Design Guide.

A brief survey of neighboring states, as well as states that frequently use recycled materials, revealed that the use of resilient modulus in design is limited, though considerable research is being conducted. Thus, only rehabilitation projects in the state of Minnesota were selected for study. The projects were County State Aid Highway 3, Trunk Highway 23, and Trunk Highway 200. These projects were selected based on the availability of laboratory results of resilient modulus and field measurements from FWD. Information regarding pavement thickness and actual design was also collected.

Based on the results of a parametric study, it was found that traditional peak-based analysis of FWD data can lead to significant errors in elastostatic backcalculation due to dynamic effects. A procedure for extracting the static response from the dynamic test data by using the frequency-response-functions (FRFs) of the pavement was formulated. The analysis was simplified by the development of a software package called *GopherCalc*.

Field measurements in the form of FWD testing on rehabilitated pavements were analyzed and compared with resilient modulus values measured in the laboratory. By using conventional (peak-based) and modified (FRF-based) elastostatic backcalculation with *Evercalc*, as well as a simplified mechanistic-empirical model called *Yonapave*, representative values of base layer moduli were determined. These values were then compared with laboratory resilient modulus values obtained from the NCHRP 1-28A protocol. The laboratory values selected were from sequences in the protocol that produced a state-of-stress similar to that imparted by FWD loading.

In addition, FWD data from the MN/Road facility was analyzed to determine the seasonal behavior of base material. Three sections (Low-volume Section 31, Mainline Sections 2 & 21) were examined for the year 1999. It was found that the base material exhibits a considerable increase in stiffness from the thawed months (approximately 120 MPa, 17,500 psi) to frozen months (approximately 760 MPa, 110,500 psi). Surface deflections in the frozen state were so small as to prevent accurate elastostatic recovery of the base moduli. For Cells 2 and 21, *Evercalc* analysis recovered a modulus of 120 MPa (17,500 psi) for both sections, while *Yonapave* returned values of 100 MPa and 130 MPa (14,500 psi and 19,000 psi), respectively. Cell 31, analyzed with *Yonapave*, predicted a base modulus of 110 MPa (16,000).

REFERENCES

[1] W. Kim, and J.F. Labuz. (2007) *Resilient Modulus and Strength of Base Course with Recycled Bituminous Material*. St. Paul, MN (Minnesota Department of Transportation, Final Report 2007-05.)

[2] T. Bennert, W.J. Papp Jr., A. Maher, and N. Gucunski. (2000). Utilization of Construction and Demolition Debris Under Traffic-Type Loading in Base and Subbase Applications. *Transportation Research Record*, *No. 1714*,. 33-39.

[3] A.A.A Molenaar, and A.A. van-Niekerk. (2002). Effects of Gradation, Composition, and Degree of Compaction on the Mechanical Characteristics of Recycled Unbound Materials. *Transportation Research Record, No. 1787,* 73-82.

[4] N. Garg, and M.R. Thompson. (1996). Lincoln Avenue Reclaimed Asphalt Pavement Base Project. *Transportation Research Record, No. 1547,* 89-95.

[5] M.S. Hoffman. (2003). Direct Method for Evaluating Structural Needs of Flexible Pavements Based on FWD Deflections. *Transportation Research Record, No. 1860 ,41-47.*

[6] B.B Guzina, and S. Nintcheu. (2002). A Study of Ground-Structure Interaction in Dynamic Plate Load Testing. *International Journal for Numerical and Analytical Methods in Geomechanics,* Vol. 26, pp 1147-1166.

[7] B.B. Guzina, and R.Y.S. Pak. (2001). On the Analysis of Wave Motions in a Multi-Layered Solid. *Quarterly Journal of Mechanics and Applied Mathematics,* Vol. 40, pp 13-37.

[8] *WSDOT Pavement Guide: EVERCALC* (1995). Seattle, WA (Washington State Department of Transportation.)

[9] R.W. Meier, and G.J. Rix. (1995). Backcalculation of Flexible Pavement Moduli From Dynamic Deflection Basins Using Artificial Neural Networks. *Transportation Research Record, No. 1473*, pp 72-81.

Appendix A

DOT Survey Responses

Michigan

Mr. Westover,

Curtis Bleech asked me to respond to your questions:

1. Resilient moduli and shear strength values used in design for virgin

aggregate bases, with seasonal adjustments;

We use a resilient modulus of 30,000 psi for dense-graded aggregate bases with no seasonal adjustment (assumed to already be seasonally adjusted). We do not have resilient modulus for our open-graded bases since AASHTO concrete design does not require it.

2. Resilient moduli and shear strength values used in design for aggregate bases containing recycled materials, again with seasonal adjustments;

We do not have separate value for bases utilizing recycled materials. They are not allowed in open-graded bases, and are restricted in dense-graded bases to areas where there is no geotextile or unfiltered underdrains.

3. Recycled material implementation guidelines and any additional information regarding successful/unsuccessful projects using recycled materials.

We do not have any implementation guidelines. We do have some success using recycled concrete as a base for concrete pavements when it is asphalt stabilized. This is a recent observation of some concrete pavements built in the late 80's/early 90's. They are performing much better (almost crack-free) than the unbound projects from the same area (that utilized virgin aggregate).

Michael Eacker
Pavement Design Engineer
Construction and Technology Support Area
Michigan Department of Transportation
(517) 322-3474
eackerm@michigan.gov

South Dakota

Responses are shown below after your questions. We do not place a shear strength value on our granular materials.

We currently do not accept Portland Cement Concrete Pavement as a portion of our salvaged bases beneath asphalt concrete pavement sections, but are currently in the middle of a research project that is studying the use of this material. Any reference in the questions below will refer to a salvaged base material consisting of a blend of granular
base & asphalt mix material.

Recycled concrete pavement is allowed beneath new concrete pavement sections provided it meets the requirements in Section 260 of our Standard Specifications for the new material specified on the project, which is usually Gravel Cushion.

Thanks and please respond if you need additional information for your survey.
Gill L Hedman
Pavement Design Engineer
605-773-5503
gill.hedman@state.sd.us

-----Original Message-----
From: Thomas Westover [mailto:west0639@umn.edu]
Sent: Tuesday, October 17, 2006 2:26 PM
To: Hedman, Gill
Subject: Resilient Modulus of Recycled Base Materials

Dear Mr. Hedman,

As a graduate student at the University of Minnesota, my research is focused on the development of seasonal resilient moduli values for aggregate bases containing recycled bituminous and concrete pavements. In addition to resilient modulus and FWD testing conducted at the University and the Minnesota Department of Transportation (MnDOT), our project requires us to ask DOT's from neighboring states how properties of recycled materials are accounted for in pavement design.

Please provide (any or all of) the following information by the end of November 2006:

1. Resilient moduli and shear strength values used in design for virgin aggregate bases, with seasonal adjustments;

We use a value of @ 21,000 psi for the Resilient Modulus (Structural Number of 0.1 per inch of material) for of a Base Material in the 1993 version of the Pavement Design Guide.

2. Resilient moduli and shear strength values used in design for aggregate bases containing recycled materials, again with seasonal adjustments;

We use a value of 30,000 psi for the Resilient Modulus

(Structural Number of 0.14 per inch of material) for of a Salvaged Base Material in the 1993 version of the Pavement Design Guide.

3. Recycled material implementation guidelines and any additional information regarding successful/unsuccessful projects using recycled materials.

We have been successfully using salvaged asphalt and granular base materials in our pavement structure for over 20 years. When we reconstruct road segments we salvage all in place asphalt and granular base for reuse as a portion of the total base structure needed on these roads. We target for a blend of 50% granular & 50% asphalt material in this base material but will accept a blend of 40% granular & 60% asphalt material in the finished product.

Section 270 of our Standard Specifications details our salvaging and stockpiling process and Section 260 details the placement and compaction for our salvaged bases.

Thank you in advance for your assistance. I would be happy to send you the final report, which should be completed by April 2007, if you are interested.

Sincerely,

Tom Westover

--
Thomas Westover
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive S.E. Rm 350A
Minneapolis, MN 55455
612.626.1538

California

Forwarded by Imad Basheer/HQ/Caltrans/CAGov on 10/23/2006 12:14 PM

Imad
Basheer/HQ/Caltra
ns/CAGov
To

10/23/2006 12:14
PM
cc
Bill
Farnbach/D03/Caltrans/CAGov@DOT,
Terrie
Bressette/HQ/Caltrans/CAGov@DOT,
Robert Hogan/HQ/Caltrans/CAGov@DOT
Subject Re:
Resilient Modulus of Recycled Base Materials(Document link: Imad Basheer)

Dear Mr. Westover,
Our response to your questions is below. Let me know if you have other questions.

Q1+Q2 (Response by Basheer). Currently, we do not use resilient modulus or shear strength. Instead, California uses an empirical method for design of new flexible pavements similar to the 1993 AASHTO method in which a gravel factor reflecting the strength of the material to be used in the pavement is used. If you would like more information about California design method check out this web link http://www.dot.ca.gov/hq/oppd/hdm/pdf/chp0630.pdf
California is currently in the process of developing M-E method in which there will be greater use of resilient modulus for characterizing the strength of various pavement materials.

Q3 (Response by Hogan). Caltrans currently allows up to 100% substitution of recycled or reclaimed materials in new aggregate base and subbase. Additionally, we have experimented with in-place material recycling in the form of pulverization and cold foam in-place recycling and are currently developing guidelines and specifications to standardized those processes. For in-place recycling projects, we typically look for structurally inadequate roadways with advanced distress, such as severe fatigue cracking, that may indicate deteriorated base or would otherwise need a thick overlay or deep milling. We have generally had good success with pulverization and cold foam, however there have been some problems with subgrade failures and concerns about the moisture susceptibility of cold foamed material. As with any in-place recycling process, material control is limited and field adjustments are required as conditions such as in-situ moisture content and pavement thickness vary. In general, we strive for a well graded mixture of 70% asphalt concrete and 30% base material with cold foam and at least 1 inch of base material for pulverization.

Dear Terrie,

As a graduate student at the University of Minnesota, my research is focused on the development of seasonal resilient moduli values for aggregate bases containing recycled bituminous and concrete pavements. In addition to resilient modulus and FWD testing conducted at the University and the Minnesota Department of Transportation (MnDOT), our project requires us to ask DOT’s from neighboring states how properties of recycled materials are accounted for in pavement design.

Please provide (any or all of) the following information by the end of November 2006:

1. Resilient moduli and shear strength values used in design for virgin aggregate bases, with seasonal adjustments;

2. Resilient moduli and shear strength values used in design for aggregate bases containing recycled materials, again with seasonal adjustments;

3. Recycled material implementation guidelines and any additional information regarding successful/unsuccessful projects using recycled materials.

Thank you in advance for your assistance. I would be happy to send you the final report, which should be completed by April 2007, if you are interested.

Sincerely,

Tom Westover

--
Thomas Westover
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive S.E. Rm 350A
Minneapolis, MN 55455
612.626.1538

Wisconsin

I'm sorry I did not respond sooner. We've done testing toward this effort,
but I don't yet have the information you are looking for.

-----Original Message-----
From: Thomas Westover [mailto:west0639@umn.edu]
Sent: Tuesday, October 17, 2006 2:21 PM
To: Fenley, Laura
Subject: Resilient Modulus of Recycled Base Materials

Dear Ms. Fenley,

As a graduate student at the University of Minnesota, my research is focused on the development of seasonal resilient moduli values for aggregate bases containing recycled bituminous and concrete pavements. In addition to resilient modulus and FWD testing conducted at the University and the Minnesota Department of Transportation (MnDOT), our project requires us to ask DOT’s from neighboring states how properties of recycled materials are accounted for in pavement design.

Please provide (any or all of) the following information by the end of November 2006:

1. Resilient moduli and shear strength values used in design for virgin aggregate bases, with seasonal adjustments;

2. Resilient moduli and shear strength values used in design for aggregate bases containing recycled materials, again with seasonal adjustments;

3. Recycled material implementation guidelines and any additional information regarding successful/unsuccessful projects using recycled materials.

Thank you in advance for your assistance. I would be happy to send you the final report, which should be completed by April 2007, if you are interested.

Sincerely,

Tom Westover

--
Thomas Westover
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive S.E. Rm 350A
Minneapolis, MN 55455
612.626.1538

North Dakota

We do not perform resilient moduli testing on bases in our pavement designs.

-----Original Message-----
From: Thomas Westover [mailto:west0639@umn.edu]
Sent: Tuesday, October 17, 2006 2:24 PM
To: Horner, Ron J.
Subject: Resilient Modulus of Recycled Base Materials

Dear Mr. Horner,

As a graduate student at the University of Minnesota, my research is focused on the development of seasonal resilient moduli values for aggregate bases containing recycled bituminous and concrete pavements. In addition to resilient modulus and FWD testing conducted at the University and the Minnesota Department of Transportation (MnDOT), our project requires us to ask DOT's from neighboring states how properties of recycled materials are accounted for in pavement design.

Please provide (any or all of) the following information by the end of November 2006:

1. Resilient moduli and shear strength values used in design for virgin aggregate bases, with seasonal adjustments;

2. Resilient moduli and shear strength values used in design for aggregate bases containing recycled materials, again with seasonal adjustments;

3. Recycled material implementation guidelines and any additional information regarding successful/unsuccessful projects using recycled materials.

Thank you in advance for your assistance. I would be happy to send you the final report, which should be completed by April 2007, if you are interested.

Sincerely,

Tom Westover

--
Thomas Westover
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive S.E. Rm 350A
Minneapolis, MN 55455
612.626.1538

Appendix B

SDOF Initial Conditions

In a typical backcalculation procedure, it is assumed that the layered pavement system is laterally homogeneous over the length of the FWD sensor array. As a result, the geophone records from a single FWD test will have similar characteristics in both frequency- and time-domain signatures. Features of the record, such as resonance peaks in the frequency record, will be less pronounced for distances further away from the load. It is therefore necessary to fit each geophone record individually to ensure accurate extrapolation with the single-degree-of-freedom (SDOF) model. To ensure a reliable and efficient fit, a procedure is outlined for selecting the initial conditions from each geophone.

Initial Spring Stiffness

To determine the initial spring stiffness, k_i, recall the SDOF fitting equation used:

$$FRF_{SDOF}(f_m) = \frac{1/k}{\sqrt{\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(2\xi\frac{\omega}{\omega_0}\right)}}, \qquad \omega_0 = \sqrt{\frac{k}{m}},\ \xi = \frac{c}{2\sqrt{km}} \tag{B.1}$$

The denominator of this equation approaches one as the circular frequency $\omega \to 0$ so the static value approaches $1/k$. Selecting the initial value for k using the value of the FRF at 10Hz provides a reasonable approximation while avoiding the noise dominated behavior typical of the lower frequencies. The expression for the initial spring constant then becomes

$$k_i = \frac{1}{FRF(10Hz)} \tag{B.2}$$

Initial Damping

Using the results of numerical simulations, it was determined that the ability of a SDOF system to adequately capture the low-frequency resonance peak, if any, is primarily dependent upon the proper choice of damping ratio. For records where a resonant peak is prominent in the fit range, the SDOF system is highly sensitive to the choice of damping ratio, and the half-power method provides a methodology for determining an initial value. Let

$$FRF^{reduced} = \frac{FRF^{\max}}{\sqrt{2}} \tag{B.3}$$

where FRF^{max} is the maximum value of the geophone record. Let f_L and f_R be the frequencies to the left and right of the maximum whose value is $FRF^{reduced}$. An equivalent damping ratio can then be approximated as

$$\xi_i = \frac{f_R - f_L}{2f_{\max}} \tag{B.4}$$

This approximation will not yield reasonable values for peaks where f_L and f_R can not be readily determined. Based on experience, for peaks within the fit range that are not as pronounced, a damping ratio of 0.3 was found to provide reliable convergence. In the case where there is no peak or the function varies monotonically over the fit range, a damping ratio of 0.8 is recommended. The effect of damping ratio on the SDOF system can be seen in Figure B-1

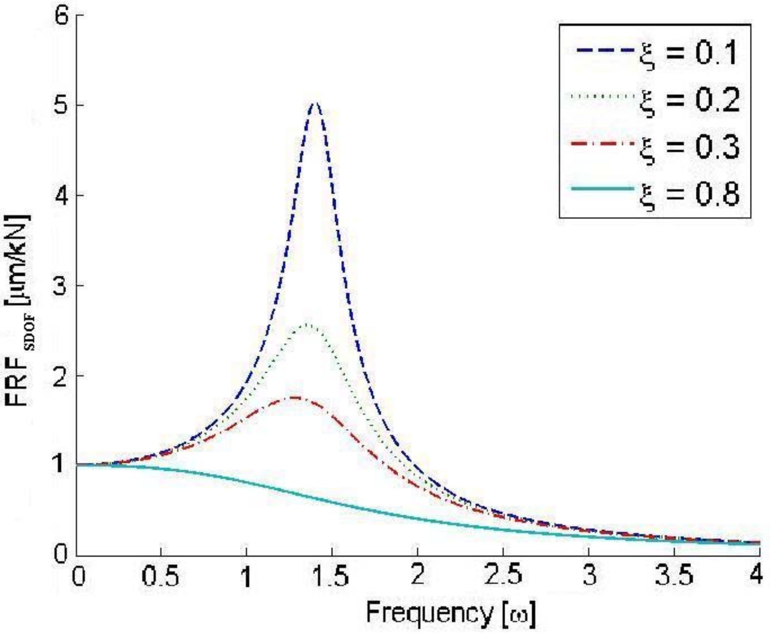

Figure B-1 Effect of damping ratio on a SDOF system response.

Initial Mass

Following the proper selection of spring and damping parameters, an value for the initial mass can be determined. Using the expression

$$m_i = \frac{k_i\left(1-2\left(\xi_i\right)^2\right)}{2\pi f_{\max}}, \qquad \xi_i < \sqrt{2} \tag{B.5}$$

ensures the location of the SDOF peak and field peak are located at the same frequency. For values of $\xi i>\sqrt{2}$, experience suggests that a value for mi that is sufficiently small (e.g. 1*10^-5) will provide reasonable fits for the suggested fit range around 10-20 Hz.

Implementation in GopherCalc

All of the initial condition selection procedures outlined here are implemented automatically in *GopherCalc*. The procedure should be applied to each geophone record individually to ensure that the SDOF system will fit each geophones particular character.

Appendix C

Additional Project Selection

Using information contained in the 808 Database, a short survey of the projects was performed. The purpose was to locate projects within the database which could provide a further basis for comparison. The projects listed in this table were chosen based on the amount of data available.

Table C.1 Minnesota recycling projects selected for further review.

Project #	Project Information		Original Design		
	City/County/State	Hwy	Year of Const	AASHTO Class Soil Type	R-Value
0114-09	Duluth, MN	TH 18			
0912-23	Duluth, MN	TH 73		slpl SL; swamps	
6928-22	Duluth, MN	TH 73	1977	Silt Loam	29
3107-27	TH6 to Effie	TH1	1955	clay/silty clay	10
5803-34	Askov to Nickerson	TH 23			
0901-72	S.Carlton Co Line to Duluth	TH 23		clay	
0901-66	.9 mi N of CSAH 8 to 0.1 mi N of CSAH	TH 23		clay	
5804-49	Pine County: CSAH15 to state line	TH 48	1976	loamy fine sand	na
5804-51	Pine County	TH 48		loamy fine sand	na
5804-52	Pine County	TH 48			
0110-29	0.1 mi S of CSAH 2 to 0.1 mi N of CSAH 4	TH 65	1939	loamy sand and gravel	20
3609-29		TH 65	1939	loamy sand and gravel	
0903-26	W of Moose Lake to Kettle River	TH 27			
6927-17	Prairie Lake to Floodwood	TH 73		silty loam, sandy loam	
6935-85		TH 169			

Project #	Pre-Rehab Analysis				Rehab Information				
	Date	PSR (Ride)	SR	PQI	Year of Rehab	CIR/ FDR/ M&O/ Ov	Depth of Mill/Reclaim	Emulsion %	Oil Type
0114-09					1995	CIR			
0912-23	1994	2	2.3	2.1		CIR	4	3	
6928-22	1993	2.3	2.6	2.4	1995	CIR	4		N/A
3107-27	1995	1.9	1.5	1.7	1997	FDR	6.5		58-28
5803-34	1994	2.2-2.4	2.4-2.5	2.3-2.4	1998	FDR	12 to 14		
0901-72	2000	1.5-3.4	1.9-4.0	1.7-3.6	2002	FDR	12 to 14		
0901-66	2000	1.5-3.4	1.9-4.0	1.7-3.6	2001	FDR	8 to 12		
5804-49	1996	2.3	3.2	2.7	1998	FDR	12		52-34
5804-51	1998	2.1	3	2.5	1999	FDR	12		
5804-52					2000	FDR			
0110-29	2003	2.2	2	2.1	2005	FDR	14		
3609-29					2000	FDR	6		52-34
0903-26	1998	1.9	2.2	2	2000	FDR			
6927-17	1996	2.4	2.5	2.4	2000	FDR	12		52-34

Appendix D

FWD Parametric Study

To investigate the conditions where peak-based (P2P) backcalculated pavement and base layer elastic moduli differ significantly from their frequency-based (FRF) counterparts, a parametric study was performed. The study used an elastodynamic FWD forward model [6] that utilizes the method of propagator matrices, the Fourier transform, and the Hankel integral transform [7]. A set of six synthetic test profiles were used to examine the behavior of three and four layer layered systems. See Table D.1 for a description of the inputs to the forward calculation process. Using noise-polluted time-histories and the corresponding frequency-domain representations, deflection basins were computed. As shown in Figure D-1, the contribution of dynamic effects produces a decidedly larger deflection at most geophone locations, particularly close to the load plate.

Table D.1 Information on Synthetic Layer Profiles.

Case Number	Young's Modulus [MPa]				Thickness [m]			
	AC	Base	Subbase	Stiff	AC	Base	Subbase	Stiff
1	2700	216	112	N/A	0.1	0.3	N/A	∞
2	2700	54	28	N/A	0.1	0.3	N/A	∞
3	2700	216	112	1160	0.1	0.3	5	∞
4	2700	54	28	580	0.1	0.3	5	∞
5	2700	28	N/A	580	0.15	3	N/A	∞
6	2700	270	112	N/A	0.1	0.3	N/A	∞
Case Number	**Mass [kg/m3]**				**Poisson's ratio**			
	AC	Base	Subbase	Stiff	AC	Base	Subbase	Stiff
1	2335	2027	1865	N/A	0.35	0.35	0.4	N/A
2	2335	2027	1865	N/A	0.35	0.35	0.4	N/A
3	2335	2027	1865	2160	0.35	0.35	0.4	0.45
4	2335	2027	1865	2160	0.35	0.35	0.4	0.45
5	2335	1865	N/A	2160	0.35	0.4	N/A	0.45
6	2335	2027	1865	N/A	0.35	0.35	0.4	N/A

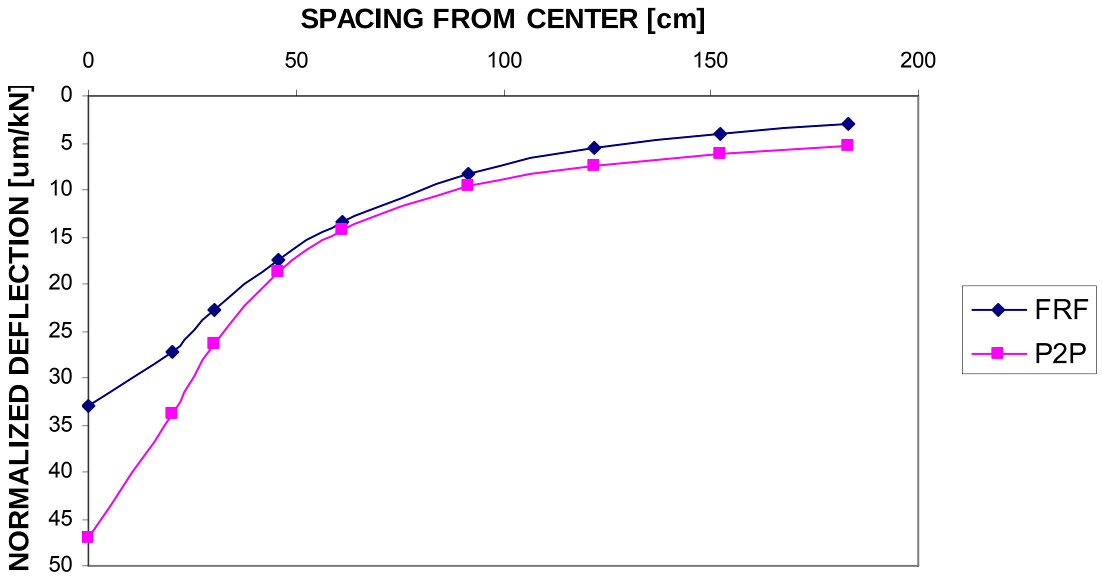

Figure D-1 Comparison of static (FRF) and dynamic (P2P) deflection basins, Case 4.

Using these deflection basins as an input, backcalculation was performed using *Evercalc*. In the procedure, the layer thickness, Poisson's' ratios, and seed moduli were identical for both P2P and FRF deflection basins. With the true (input) modulus for reference, the results of backcalculation are shown in Figure D-2a-d. The dynamic effects of the FWD test are evident in the backcalculated moduli. In particular, a well-known shortcoming of P2P data interpretation is faulty results in the presence of a shallow stiff layer. As demonstrated in Cases 3, 4, and 5, the backcalculation compensates for the dynamic effects by overestimating the modulus of the AC layer, while leaving the stiff layer virtually undetected. In contrast, the FRF method consistently provides a more accurate representation of the pavement moduli. In Case 4, the FRF method fails to fully recover the stiff layer moduli with the same consistency as other layers in other cases. This may be a limitation of the FWD testing configuration, as FWD deflection basins are not significantly affected by stiff layers located at depths greater than 3 meters [9].

While further field study would be necessary to further validate the results from synthetic data, the FRF analysis method presented produces an input that is more consistent with the fundamental assumptions underlying elastostatic backcalculation. Using this simple but effective modification has the potential to elevate the accuracy and reliability of current backcalculation schemes in a significant way. The frequency domain analysis requires no modification to existing FWD test procedure, as long as the full 120 ms time-history of the test is collected.

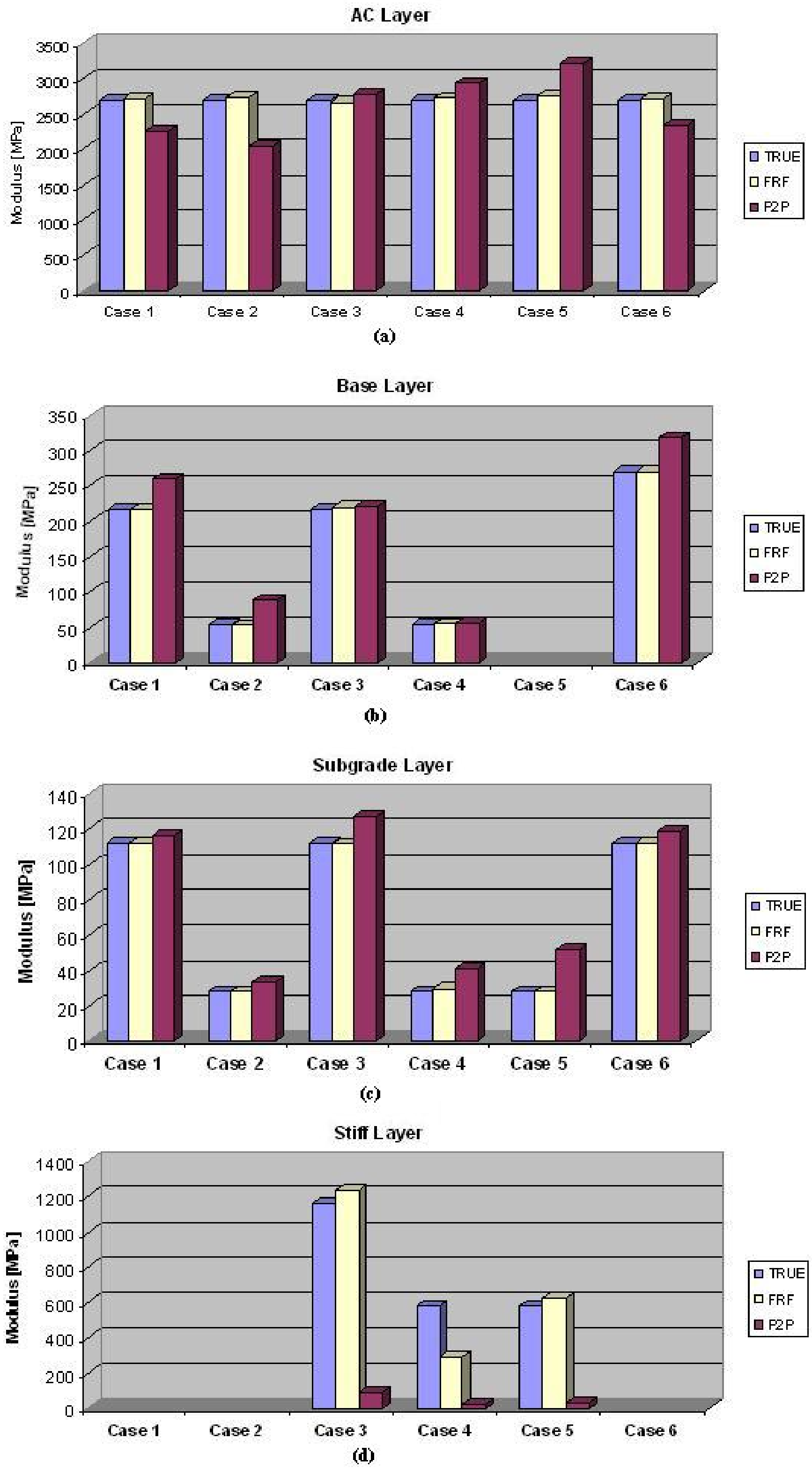

Figure D-2 Results of *Evercalc* backcalculation for the a) AC layer, b) base layer, c) subgrade layer, d) stiff layer (if present).

Appendix E

Seasonal Effects

This section will present the results of the two backcalculation procedures in more detail. Each value for each location is an average of the backcalculated moduli from each of the three drop heights at that location.

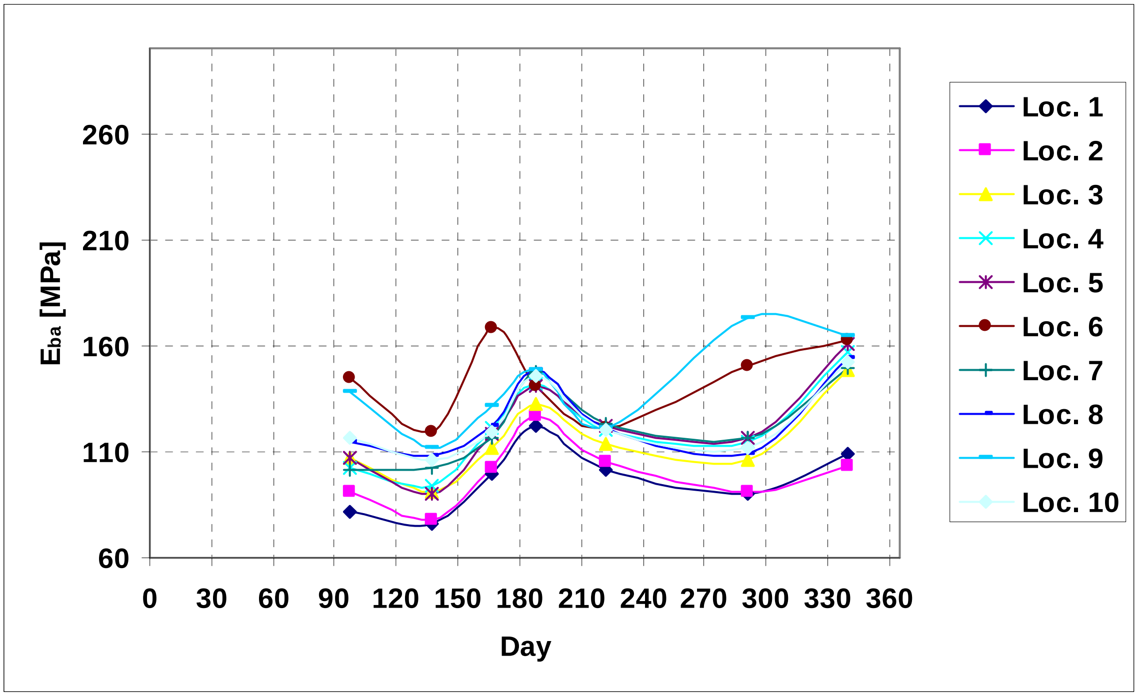

Figure E-1 Mn/ROAD Mainline Cell #2. Seasonal effect on *Evercalc* -generated base modulus Jan 1st (Day 0) – Dec 31st (Day 365), 1999.

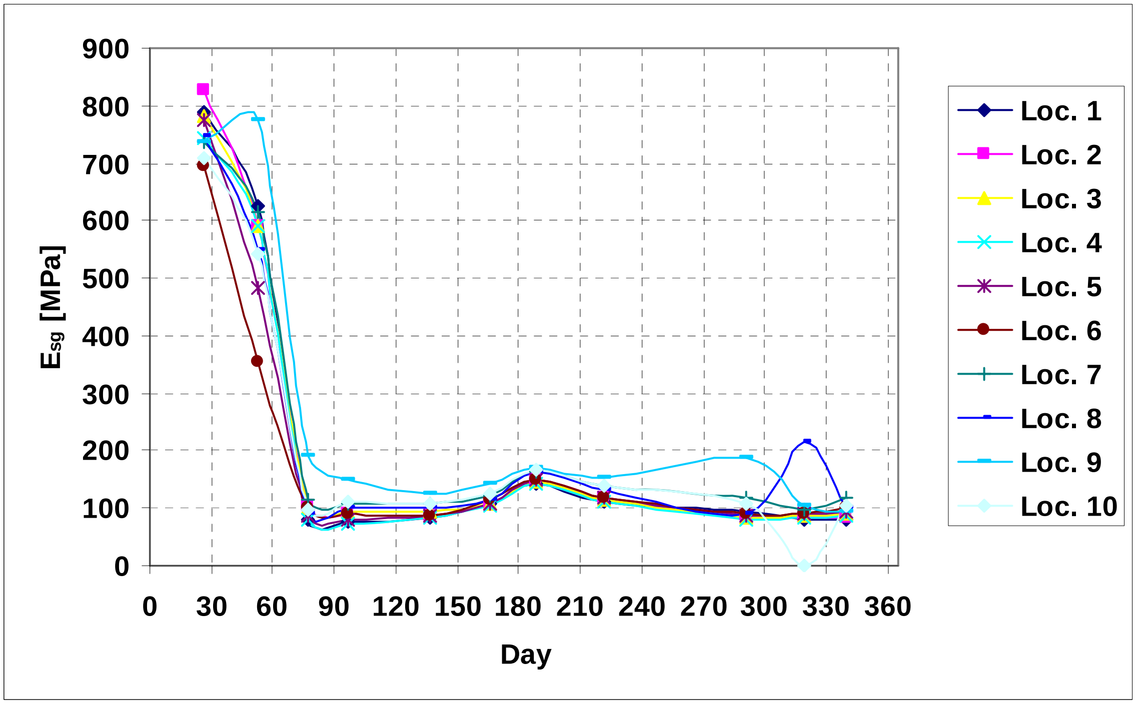

Figure E-2 Mn/ROAD Mainline Cell #2. Seasonal effect on *Yonapave*-generated equivalent subgrade modulus. Jan 1st (Day 0) – Dec 31st (Day 365), 1999.

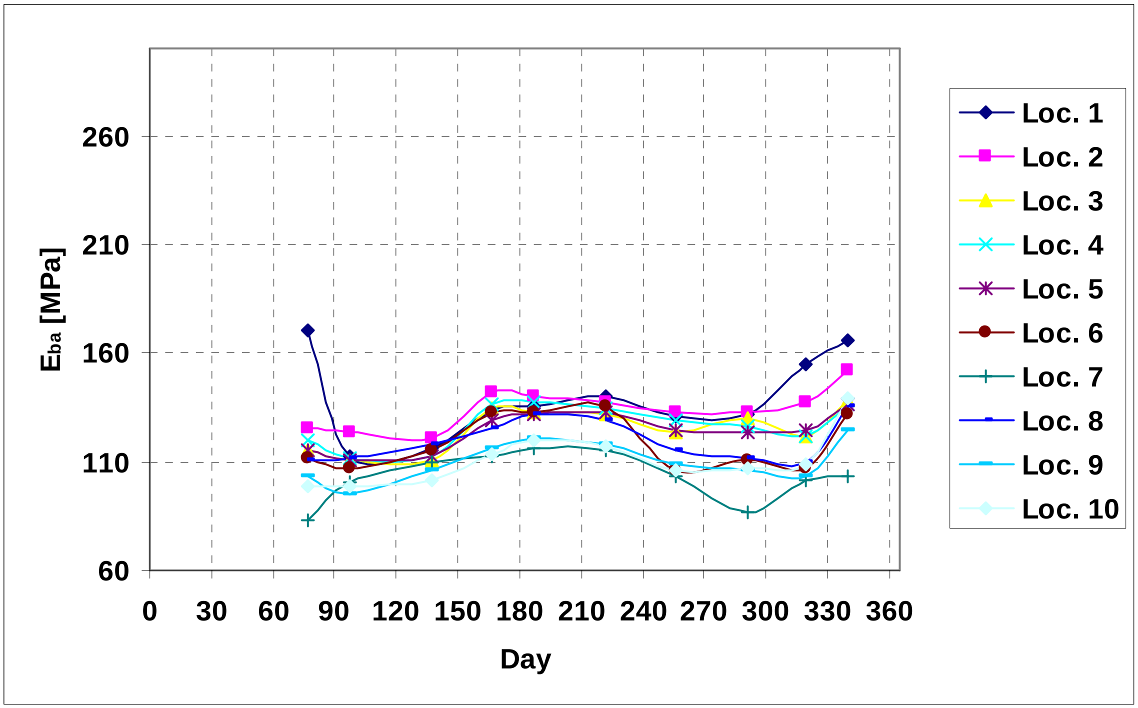

Figure E-3 Mn/ROAD Mainline Cell #21. Seasonal effect on *Evercalc*-generated base modulus Jan 1st (Day 0) – Dec 31st (Day 365), 1999.

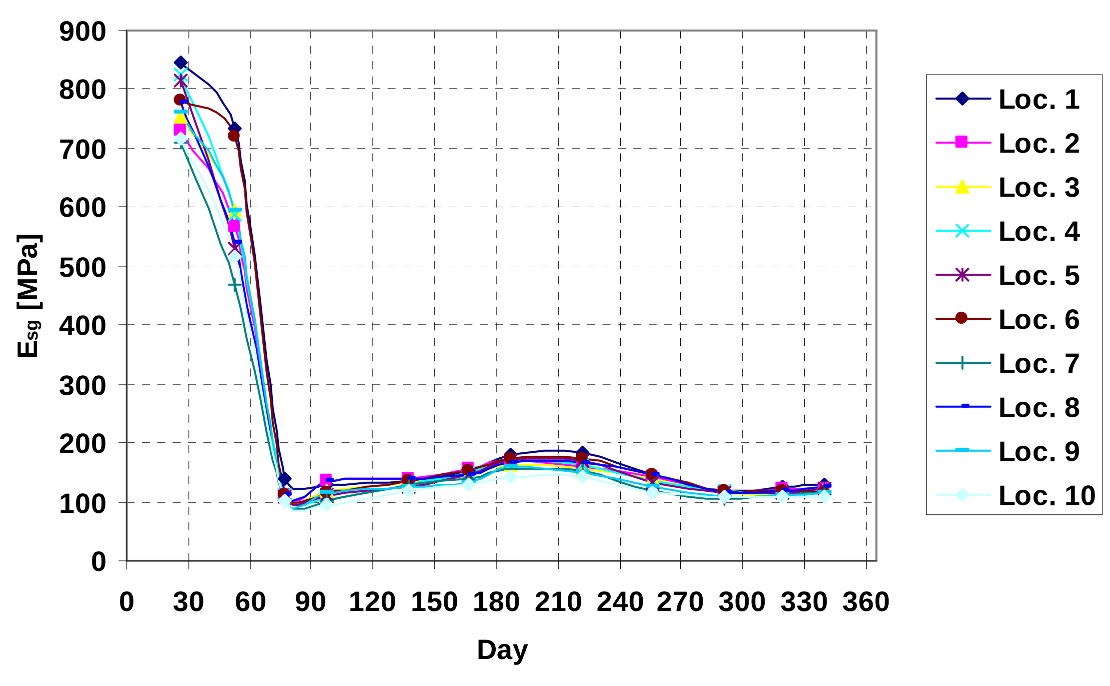

Figure E-4 Mn/ROAD Mainline Cell #21. Seasonal effect on *Yonapave*-generated equivalent subgrade modulus. Jan 1st (Day 0) – Dec 31st (Day 365), 1999.

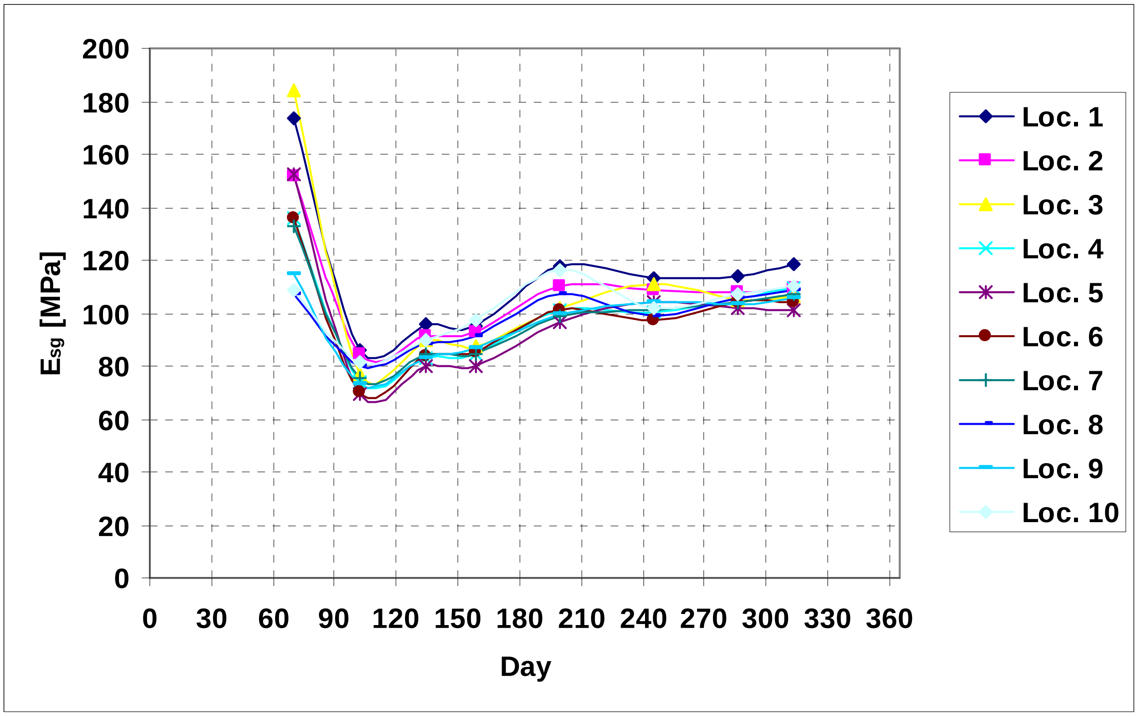

Figure E-5 Mn/ROAD Low-volume road Cell #31. Seasonal effect on *Yonapave*-generated equivalent subgrade modulus. Jan 1st (Day 0) – Dec 31st (Day 365), 1999.