Pavement Evaluation with a Non-Destructive Method, the Falling Weight Deflectometer

by

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Évaluation de la Chaussée avec une Méthode Non-Destructive, le Déflectomètre à Masse Tombante

Amin REZAEEZADEH

RÉSUMÉ

La détermination précise du module des couches d'enrobé à des fins de réhabilitation et de conception du revêtement d'asphalte est particulièrement importante dans l'état de la structure des chaussées souples. L'évaluation structurelle de la chaussée en service passe par la détermination en place du module d'élasticité des couches de chaussée par des essais destructifs ou non destructifs. Les tests non destructifs ont de nombreux avantages, dont un temps d'exécution plus rapide et un coût moins élevé par rapport aux tests destructifs.

Le test du déflectomètre à masse tombante (FWD) est la technique la plus largement acceptée et utilisée pour l'évaluation nondestructive des chaussées et a été largement mené au cours des dernières décennies pour évaluer les conditions structurelles et déterminer le module des couches de chaussée. L'une des applications les plus importantes des résultats des tests FWD est l'analyse et le rétrocalcul du module des couches. Le module d'élasticité des matériaux utilisés dans les chaussées est utilisé pour l'analyse de la durée de vie restante et la conception de nouvelles chaussées et revêtements. Cette valeur critique est calculée par la méthode de rétrocalcul, qui utilise des données brutes FWD. Diverses méthodes ont été développées et appliquées pour effectuer un rétrocalcul. Dans la plupart des programmes, les données FWD sont utilisées comme si elles étaient le résultat de charges statiques, tandis que les charges réelles ont un comportement dynamique. Par conséquent, les résultats peuvent varier pour les chaussées souples.

L'objectif de cette étude est de présenter les résultats et l'analyse de certaines données FWD, qui ont été obtenues par certains tests FWD effectués aux États-Unis; en particulier, pour documenter les résultats, qui rétrocalculés par le programme DBSID. Ces résultats peuvent être comparés avec les résultats du programme MODULUS, qui a été développé par le Texas Transportation Institute (TTI). Ensuite, les effets de différents paramètres tels que la température de la chaussée et les épaisseurs de couche de surface sur le module de couche FWD sont effectués. Une comparaison entre le module de couche FWD obtenu des deux programmes et les valeurs de l'indice de rugosité international (IRI) des mêmes sections de test est également effectuée. Cette étude nous permettra d'avoir des résultats plus précis et plus fiables avec le FWD.

Mots-clés: FWD, rétrocalcul, module de couche, DBSID, MODULUS, IRI

Pavement Evaluation with a Non-Destructive Method, the Falling Weight Deflectometer

Amin REZAEEZADEH

ABSTRACT

Accurate determination of the modulus of asphalt layers for rehabilitation purposes and design of asphalt coating is of particular importance in the structural condition of flexible pavements. Structural evaluation of in-service pavement involves the in-place determination of the elastic modulus of pavement layers by destructive or nondestructive testing. Nondestructive testing has many advantages, such as high speed and low cost compared to destructive testing.

The falling weight deflectometer (FWD) test is the most widely accepted and used technique for nondestructive evaluation of pavements and has been conducted extensively in the last decades to evaluate structural conditions and to determine the modulus of pavement layers. One of the most important applications of FWD test results is the analysis and backcalculation of layers modulus. The modulus of elasticity of the materials used in the pavements is used for the analysis of the remaining life and the design of new pavements and overlays. This critical value is computed through the backcalculation method, which uses FWD raw data. Various methods have been developed and applied to perform backcalculation. In most programs, the FWD data are used as if they are the results of static loads, while the real loads have the dynamic behaviour. Therefore, the results can vary for flexible pavements.

The objective of this study is to present the results and analysis of some FWD data, which have been obtained by some FWD tests carried out in the USA; in particular, to document the results, which were backcalculated by the DBSID program. These results can be compared to the results of the MODULUS program, which has been developed by the Texas Transportation Institute (TTI). Then, the effects of different parameters such as pavement temperature and the surface layer thicknesses on the FWD layer modulus are performed. A comparison between the FWD layer modulus obtained from both programs and the International Roughness Index (IRI) values of the same test sections is also done. This study will enable us to have more precise and reliable results with the FWD.

Keywords: FWD, Backcalculation, Layer Modulus, DBSID Program, MODULUS Program, IRI

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ANN	Artificial Neural Network
CV	Coefficients of Variation
DBSID	Dynamic Backcalculation Procedure with Systems Identification Method
FWD	Falling Weight Deflectometer
HMA	Hot Mixed Asphalt
HWD	High Weight Deflectometer
IFSTTAR	The French Institute of Science and Technology for Transport, Development and Networks
INDOT	Indiana Department of Transportation
IRI	International Roughness Index
LTPP	Long-Term Pavement Performance
MEPDG	Mechanistic Empirical Pavement Design Guide
MRI	Mean of International Roughness Index
NDT	Non-Destructive Test
PCC	Portland Cement Concrete
PFWD	Portable Falling Weight Deflectometer
RDD	Rolling Dynamic Deflectometer

RMS	Root Mean Square Error
SHRP	Strategic Highway Research Program
SID	Systems Identification Method
SQL	Structured Query Language
TRB	Transportation Research Board
TSD	Traffic-Speed Deflectometer
TTI	Texas Transportation Institute
TXDOT	Texas Department of Transportation
WESLEA	Waterways Experiment Station Linear Elastic Analysis

INTRODUCTION

Accurate determination of the modulus of asphalt layers for rehabilitation purposes and design of asphalt overlay is of particular importance in the structural condition of flexible pavements. Structural evaluation of in-service pavement involves the in-place determination of the elastic modulus of pavement layers by destructive or non-destructive testing. Non-destructive testing has many advantages, such as high speed and low cost compared to destructive testing. The Falling Weight Deflectometer (FWD) is one of the most essential non-destructive pavement tests that has been extensively used in recent decades to evaluate in-service pavements by road maintenance agencies in various countries. Analyzing FWD test results has been one of the major challenges for researchers over the years.

There are a range of non-destructive instruments available for research. One of these non-destructive instruments are impulsive deflection devices. In the study of non-destructive testing instruments, several summary reports have been presented that provided good comparative explanations of their relative capabilities (Anderson, 1990).

The FWD is the most common non-destructive test that measures the deflection of the pavement surface under an impulse load. The FWD test is based on raising a weight above the pavement and dropping it on a spring system that transfers the impulse to a load plate, then measuring the impulse force transmitted to the load plate as well as peak deflections at various radial distances from the impact point. A rubber buffer system and a rubber pad located under the load plate are there to help in spreading the load and simulate a passing wheel load (Anderson, 1990). The collected data from the FWD test can be analyzed and backcalculated to find the layer modulus. The different backcalculation procedures may provide different results of moduli. In this research, implementing a comparison between different backcalculation procedures have been performed. Also, the correlation of the pavement temperature, surface layer thickness, and the International Roughness Index (IRI) values to the layer modulus will be discussed.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

This chapter is a literature review that starts with an explanation of the different pavement types before concentrating on the falling weight deflectometer (FWD). More precisely, the FWD is explained with an emphasis on the different FWD data analysis methodologies that are used. In this regard, the principles of FWD data analysis are discussed first and then the various types of backcalculation are addressed in detail. Then the International Roughness Index (IRI), one of the tools to evaluate the functional properties of the pavements, is introduced. Following that, the Long-Term Pavement Performance (LTPP) program which is the largest database in the pavement industry and its database will be used in this study is presented. At the end a summary will finish this chapter.

1.2 Pavement Types

Pavements are classified into three broad categories: flexible or asphalt pavements, rigid or concrete pavements, and composite pavements (Huang, 2004). These three types of pavements are described in the following sections.

1.2.1 Flexible Pavements

A flexible pavement system is commonly composed of many layers of material, with higher-quality materials placed on top where the most intense stress from traffic occurs and lower-quality materials placed at the bottom where the least intense stress from traffic occurs (Texas Department of Transportation, 2021). A typical flexible pavement system is composed of three layers: the surface course, the base course, and the subbase course; each of these layers offers structural support and, in the ideal case, proper drainage. When Hot Mix Asphalt (HMA) is used as the surface course, it is often the stiffest layer (as measured by the elastic modulus) and may provide the pavement with the greatest strength; the underlying layers are less stiff but still contribute significantly to the pavement's strength (Texas Department of Transportation, 2021). Figure 1.1 illustrates a typical section of flexible pavements.

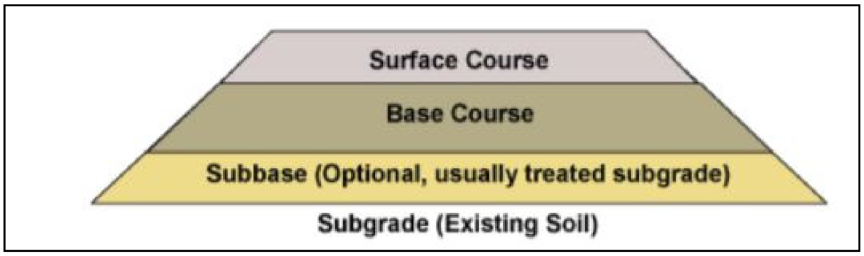

Figure 1.1 Typical section for a flexible pavement
Taken from Texas Department of Transportation. (2021, p. 12)

1.2.2 Rigid Pavements

A rigid pavement system is composed of a cement concrete surface course and, if necessary, subbase and base courses. Another word that is widely used is Portland Cement Concrete (PCC) pavement, but technically, with the addition of pozzolanic additives, cements are no longer categorized as Portland; the surface course (concrete slab) is the stiffest layer and delivers the largest share of strength (Texas Department of Transportation, 2021). Although the base or subbase layers are orders of magnitude less stiff than the PCC surface, they considerably contribute to pavement uniformity, drainage, and frost protection, in addition to providing a working platform for construction equipment. Rigid pavements are substantially stronger than flexible pavements due to the high modulus of elasticity of the PCC material, resulting in extremely minimal deflections under load. In rigid pavements, reinforcing steel can be utilized to minimize or eliminate joints and maintain narrow fracture widths (Texas Department of Transportation, 2021).

1.2.3 Composite Pavements

A composite pavement is made up of a combination of HMA and PCC. By using PCC as the base layer and HMA as the top layer, a perfect pavement with the most desirable properties is created. The PCC offers a stable foundation, while the HMA creates a smooth, nonreflective surface. However, due to the high cost of this form of pavement, it is rarely employed in new construction (Huang, 2004).

Like many things built by humans that need to be evaluated and for which a quality control process is required, pavements need to be evaluated in order to quantify their as-built, new, properties or the evolution of their properties over time under traffic in environmental loading. To do this, different tests can be performed on pavements. The tests which are performed without destructive activities and operations are called non-destructive tests (NDT) and are widely used to evaluate in-service pavements. These types of evaluation tests are described in detail in the next section.

1.3 Non-destructive Testing

One of the most reliable methods for determining the structural and functional status of a pavement is the use of NDT. These experiments have two significant advantages over destructive experiments (Shahin, 2005):

- In destructive tests, due to their nature, the layers of the pavement are tampered with, and the removal and transport of pavement materials to the laboratory become necessary for testing. While in NDT, which is in fact an on-site test, pavement is evaluated without any handling or alteration of material conditions.
- Testing is relatively quick and inexpensive, and testing is often possible because there is less disruption to traffic (Shahin, 2005).

Numerous instruments are used to conduct NDT on pavements, and these devices may be used to determine the pavement's deflections. Deflection measurements have been utilized to determine the structural capability of in situ pavements for a long period of time. They can be used to determine the elastic moduli of various pavement components by doing backcalculation (Huang, 2004). The deflection testing is described more in depth in the following section.

1.3.1 Deflection Testing

Deflection testing is used to determine the structural integrity and capacity of an existing pavement to sustain future traffic loads. As Hveem noted, there is a strong correlation between pavement deflections (an estimate for the pavement's structural strength) and the pavement's capacity to carry traffic loads at a specified minimum level of service (Smith et al., 2017). When complete deflection basins are available, backcalculation of measured pavement responses via deflection testing can provide critical pavement structure properties. The elastic modulus of each paving layer as well as the resilient modulus of the subgrade can be determined for HMA pavements. These parameters for the pavement layer and subgrade are used in pavement design techniques and performance prediction models to determine the pavement's remaining life or load-carrying capacity. Additionally, deflection data can be used in a variety of other ways to characterize the existing pavement condition. For instance, plots of deflection data along a pavement project can be inspected for nonuniformity, which may indicate areas that require additional examination using destructive methods (Smith et al., 2017).

The falling weight deflectometer (FWD) is the most widely used non-destructive testing (NDT) device used by highway agencies to assess the structural integrity and health of pavements. The FWD simulates a moving truck wheel load and evaluates the deflection basin in the pavement response. The first prototype of today's FWD was commissioned in 1964 in Denmark and became the global standard for pavement deflection testing in the 1980s (Uttamchandani, 2017). The following section goes into detail about this critical test.

1.4 Falling Weight Deflectometer

An FWD is used as a testing device for measuring the physical properties of pavement. This is a non-destructive process, and is generally preferred over other destructive testing, because tests are not only faster but also do not entail removal of pavement material (Wang & Birken, 2014). The vehicle should be brought to a stop with the loading plate positioned over the desired test location. This device is towed by a vehicle to perform the evaluation test on the different pavements. To perform the test, an FWD operator, a vehicle driver, and a traffic control person to meet the safety conditions are required. A typical FWD device is shown in Figure 1.2. The FWD test consists of a falling weight that falls from a certain height on the pavement surface; the amplitude of the applied load over the pavement by the FWD is determined by the weight of the falling weight mass and the falling height. FWD equipment is known as the most suitable tool for measuring the deflection basin of the pavement, which simulates well the motion of a moving wheel on the pavement (Shahin, 2005). The response from the load of the falling weight can be measured by some geophones located on the FWD rod near the pavement. As shown in Figure 1.3 and Figure 1.4, the mounted sensors around the load centre can measure the pavement response to the device load. The number of these sensors is usually about seven to nine. The information obtained from the deflection basin can be used to calculate the properties of each layer. The under-stress area developed by the applied load is shown in Figure 1.3 and Figure 1.4.

Figure 1.2 Typical FWD device
Taken from FWD Transtec Group Inc. (2019)

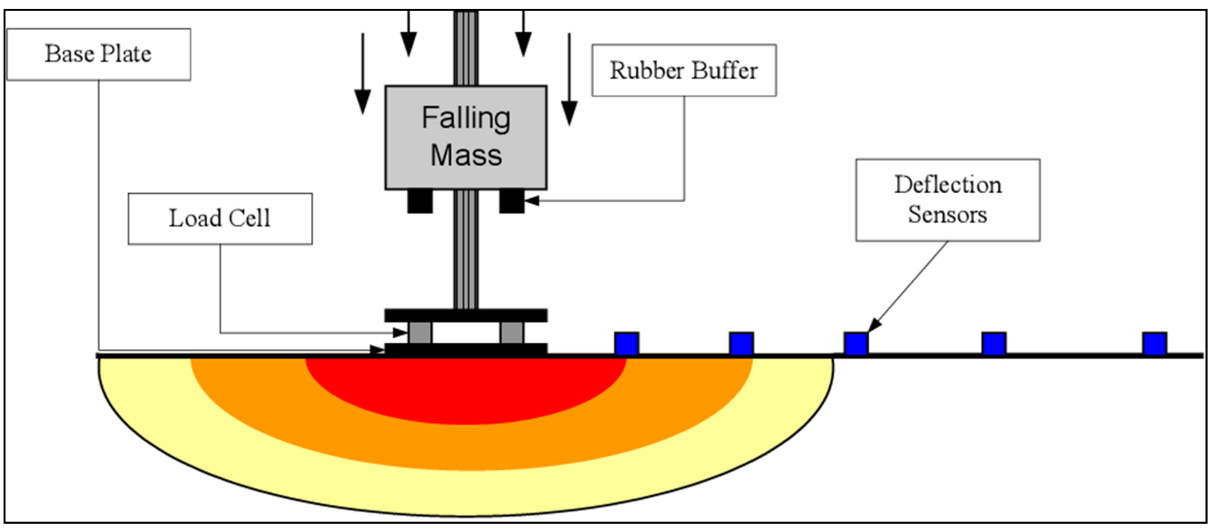

Figure 1.3 Under stress area and deflection of pavement in an FWD experiment
Taken from Chatti et al. (2017, p. 6)

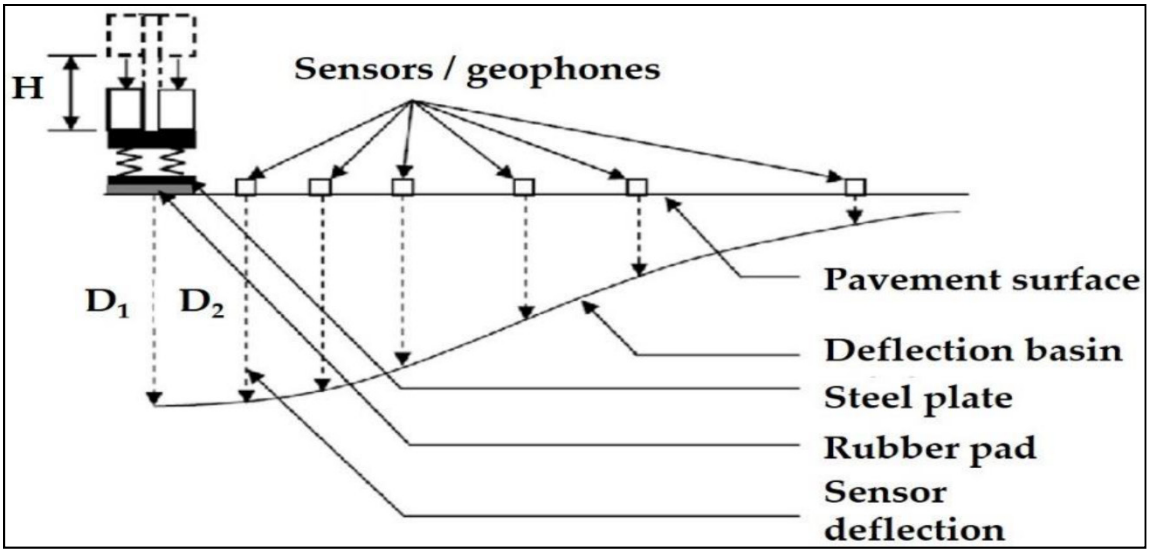

Figure 1.4 Deflections of pavement in an FWD experiment
Taken from Gkyrtis et al. (2021, p. 5)

As Figure 1.5 presents, the basic components of an FWD are **(**Alavi et al., 2008):

- An impulse-generating device with a guide system. This device allows a variable weight to be dropped from a variable height.
- Loading plate for uniform force distribution on the test layer. When the weight affects this plate, this loading plate ensures that the resulting force is applied perpendicularly to the test layer's surface, the diameter of the circular loading plate is set at 30 cm for the most commercial products.
- A load cell for measuring the actual applied impulse.
- Deflection geophones.
- A system for collecting, processing, and storing deflection data.

The FWD test can be used to monitor the health of a pavement and to identify locations with significant deflections, as well as to detect variations along the length of a specific project. Additionally, this test is capable of performing inverse analysis (i.e., backcalculation of pavement mechanical properties). Among these, the FWD is particularly well-known for its application in backcalculation to calculate the modulus of the pavement layer (Uttamchandani, 2017). The FWD procedure simulates the amount and duration of a single heavy moving wheel load by applying dynamic loads to the pavement surface. As illustrated in Figures 1.4 and 1.5, the deflections at each measured point are measured in micrometers. The procedure determines the vertical deflection response of the pavement surface to an impulse load applied to it (Wang & Birken, 2014). When adopting FWD technology, the primary elements affecting pavement deflection are the layer material types, material quality, subgrade support, environmental conditions, pavement discontinuities, and variability within the pavement structure (Wang & Birken, 2014).

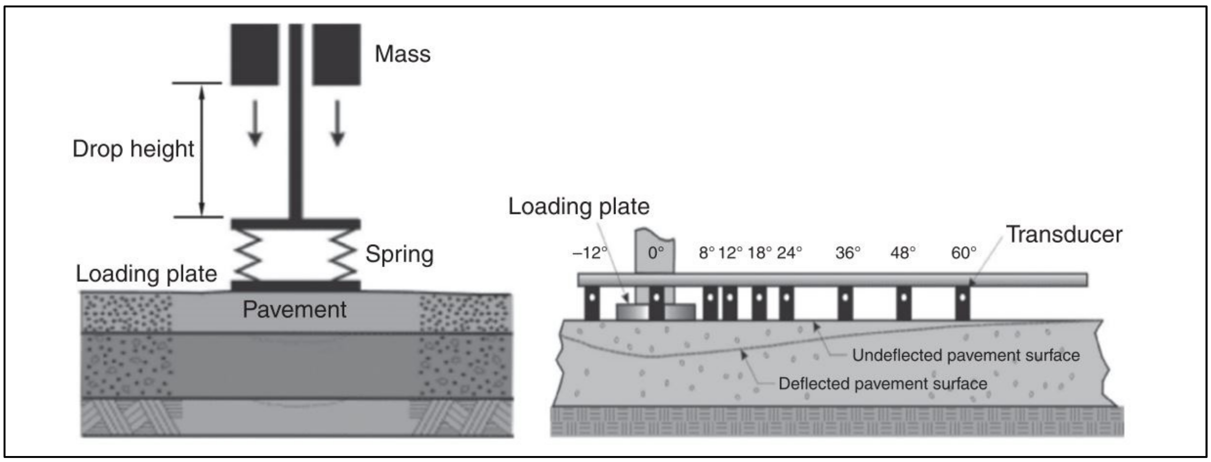

Figure 1.5 Diagram of the FWD testing
Taken from Wang and Birken. (2014, p. 9)

In addition to FWD, other types of equipment of deflection-based evaluation of pavement, such as Rolling Dynamic Deflectometer (RDD) and Traffic-Speed Deflectometer (TSD), have also been used to evaluate the structural condition of pavements on a continuous (non-stop) basis at the network-level of pavement management. Furthermore, there are two main FWD variations that were developed to address unique field-testing requirements. The first is the light weight deflectometer, which is basically a portable FWD with a lower load magnitude. It is typically utilized for quality control testing of unbound pavement materials and in locations where conventional FWD is ineffective. The other FWD type is the high weight deflectometer (HWD), which is a heavier load FWD that is used to evaluate the structural performance of airport pavements. The HWD models the wheel load of a moving aircraft (such as a Boeing 777 or an Airbus 380), with loading magnitudes ranging from 40 to 320 kN (Uttamchandani, 2017). The Portable Falling Weight Deflectometer (PFWD) has been extensively utilized in the evaluation of unbound pavement layers and for quality control purposes (Solatifar et al., 2017). The following section explains more precisely the PFWD device.

1.5 Portable Falling Weight Deflectometer

The PFWD is a light, portable device which has been developed to calculate construction layer rigidity, including subgrades, base courses, and pavements. As a result of the effect of a weight that is falling, the PFWD produces a non-destructive shock wave through the soil. To assess surface motion, from which deflection is determined, sensors such as velocity transducers or accelerometers are utilized. To measure the impact force of the falling weight, a load cell is used (Steinert et al., 2005). PFWDs have been investigated as a tool for determining the appropriate time to impose weight restrictions on low-volume roads during the spring thaw, as well as for controlling the compaction quality of aggregate base courses and other soils. PFWDs operate similarly to conventional FWDs, in that a falling weight exerts force on a plate, and the resulting deflection is measured using one or more deflection sensors. A PFWD has a significant cost advantage over an FWD in terms of purchasing and operating. Additionally, PFWDs assess the stiffness of pavement systems and compacted layers directly, which is critical for mechanistic pavement design. Numerous studies have compared the modulus values determined by PFWDs and FWDs for paved roads and found that the PFWD typically generates larger modulus values than the FWD, possibly due to the PFWDs thinner depth of influence, resulting in a greater influence of the stiff pavement on the resulting modulus. According to some researchers, the PFWD is better suited to roads with thin pavements, and only a few studies have been undertaken to assess the PFWDs utility for tracking seasonal stiffness variations. For thin pavement sections, the PFWD adequately followed seasonal stiffness variations (Steinert et al., 2005). A schematic of a PFWD is shown in Figure 1.6.

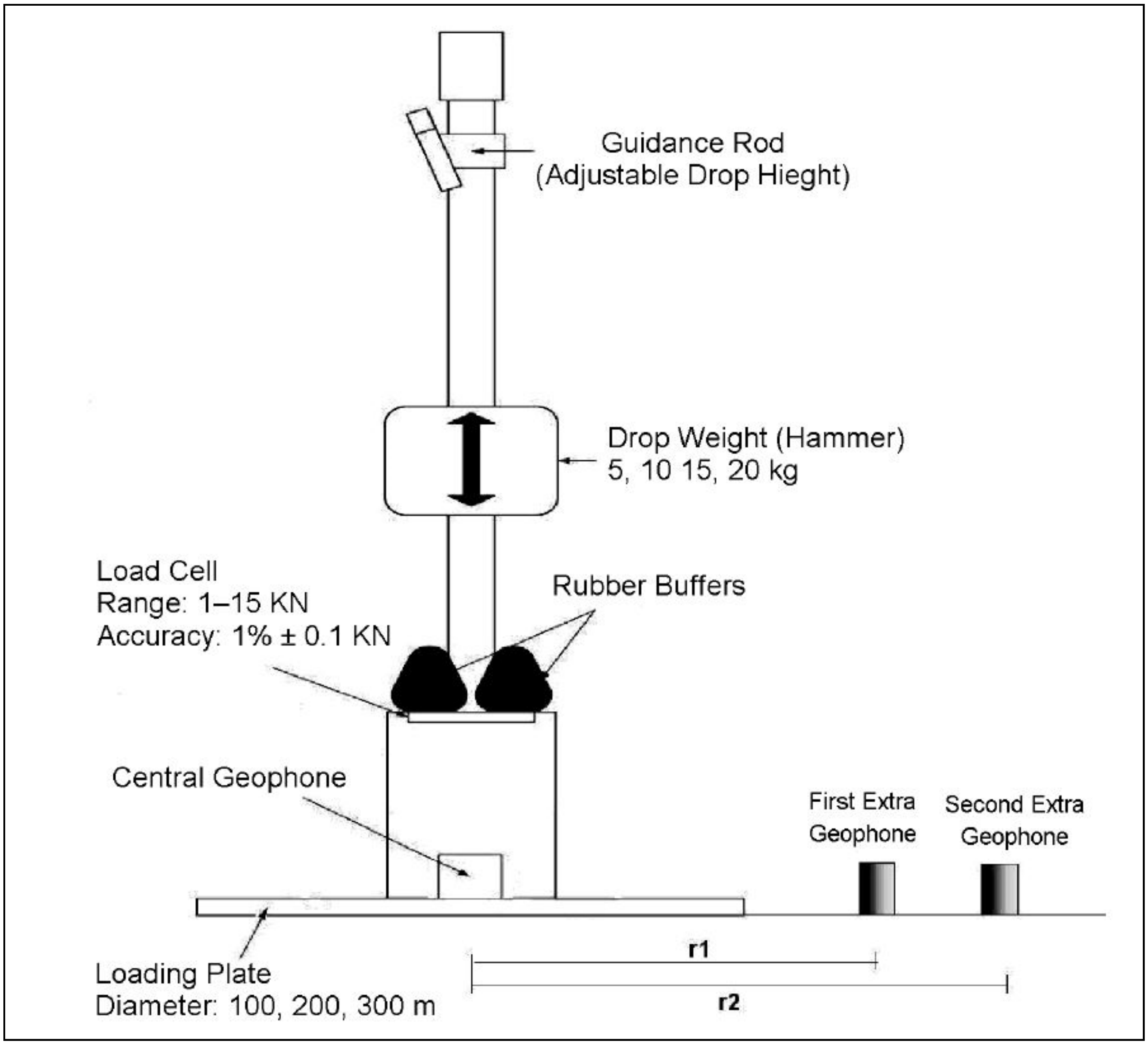

Figure 1.6 Schematic of a PFWD
Taken from Kavussi et al. (2010, p. 124)

Like all the engineering fields which in utilizing and implementing a device must follow the needed instructions that have been created under the supervision of the official agencies, organizations, administrations, etc., FWD testing procedures as a non-destructive testing follows the guides and instructions given by Mechanistic-Empirical Pavement Design Guide (MEPDG). MEPDG is introduced in the following section, and the relationship between FWD and MEPDG is also described.

1.6 Mechanistic-Empirical Pavement Design Guide and FWD Correlation

The MEPDG was published in 2004 for further evaluation and research on pavement analysis and design methods by researchers (Li et al., 2011). The MEPDG approach consists of the mechanistic part and the empirical part. The mechanistic section involves applying the basic principles of mechanical properties of materials to calculate pavement response (stress, strain, and deformation) to predict pavement performance. The empirical section of MEPDG also includes the adaptation of developed laboratory models of pavement performance with the observed performance measurements (distresses) in operating pavements (Applied Research Associates Inc, 2004). The guide takes into account the input characteristics that affect pavement performance, such as traffic, climate, pavement structure, and material properties, and applies engineering mechanics concepts to forecast crucial pavement responses. MEPDG poses numerous research tasks and problems for the pavement community due to the incorporation of hundreds of additional variables, the addition of new characteristics to characterize materials, and the complexity of the implementation (Li et al., 2011). The increasing development of mechanistic-empirical thickness design processes, most notably the publication of the MEPDG, has raised the necessity to precisely describe the structural condition of existing pavements. The MEPDG estimates the performance of the newly constructed pavement by simulating the projected cumulative damage throughout the selected design term on a monthly or semi-monthly basis. Due to the detailed consideration of the effects of prevailing climatic conditions, changes in material qualities, and traffic loading, the amount of incremental damage occurring throughout each computing interval varies. Finally, the incremental damage sustained throughout each computation period is translated into physical pavement distresses and anticipated roughness levels using calibrated performance models (Pierce et al., 2017). FWD data is one of the parameters which is influenced by MEPDG. The FWD testing procedure as a non-destructive testing follows the guides and instructions given by MEPDG; also, as a non-destructive pavement testing devices, using FWD data is a common activity to calibrate the MEPDG. A study was conducted in 2020 to subdivide pavement portions into smaller parts based on FWD data for use in the local calibration of

MEDPG. FWD tests were conducted along 12 asphalt concrete pavement sections, and the modulus was backcalculated using three analytical algorithms. The pavement sections can be used to calibrate MEDPG on a local level (Islam et al., 2020).

Like all the devices, FWD must be calibrated in certain time intervals to have better performance and more accurate results. It is important to regularly maintain and service FWDs; this will improve equipment performance, longevity, and the quality of acquired data (Wang & Birken, 2014). The importance of FWD devices calibration is presented in the following section.

1.7 FWD Calibration

An important part of the maintenance of the existing pavements is the accurate characterization of material parameters of each layer in the pavement structure. To characterize the parameters of the paving layers, the deflection data obtained by the FWD can be used by backcalculation and these data must be accurate. The effects may be financially important if FWDs are not calibrated. The overestimation of a deflection by 0.0254 mm resulted in 26% more undercoating area, according to a study by the Indiana DOT (INDOT). This mistake resulted in excessive drilling at 20,000 US dollars and additional asphaltic materials at 29,000 US dollars (Alavi et al., 2008). By modelling a 0.0508 mm deflection overestimate, 37,000 USD in further drilling and 54,000 USD in additional asphaltic materials were thought necessary, despite the fact that they were unnecessary. On an asphalt concrete (AC) overlay project, similar trends were observed; additional deflections of 0.0254 mm resulted in an additional 11,187.50 US dollars per lane-kilometer for asphaltic materials, while 0.0508 mm errors resulted in an additional 23,625 US dollars per lane-kilometer for materials. On the other hand, overestimated deflections resulted in a significantly lower design life for the pavement. Underestimating deflections by 0.0254 mm resulted in a 25.4 mm thinner AC layer than was required, leading to a 2.8 million equivalent single axle load reduction in pavement life.

Calibration should be performed in accordance with the manufacturer's recommendations for impulse loading type devices (Alavi et al., 2008).

Obviously, with a calibrated FWD device, the more accurate FWD raw data and more accurate deflection basin will be obtained. Once FWD data are collected from the field, multiple analysis tools are available to the pavements. These software packages typically calculate pavement layer modulus, a material parameter that is essential for pavement layer design. According to survey data, 90% of state highway agencies use FWD data for pavement layer modulus estimation (Alavi et al., 2008). As previously mentioned, to find the modulus, FWD data analysis is needed. The following section explores FWD data analysis.

1.8 FWD Data Analysis

The most frequently used method for determining the effective elastic modulus of pavement structural layers and subgrade is backcalculation using measured surface deflections (Smith et al., 2017). The stiffness of the pavement layers is determined through backcalculation using deflection data and an assuming pavement cross section. The examination of pavement deflection data has grown increasingly complex over the years, owing mostly to the need to move toward more mechanistic pavement analysis and the developing capacity of today's sophisticated computers. Numerous concepts and methods for backcalculating deflection data have been developed, which vary principally according to the type of pavement being investigated (Smith et al., 2017). This section presents an overview of backcalculation. As illustrated in Figure 1.7, the process can be described using the example of a simply supported beam.

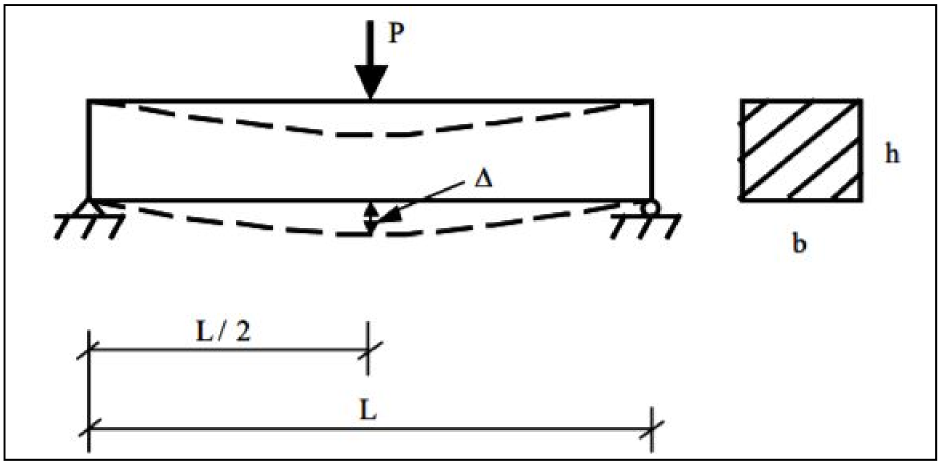

Figure 1.7 Simply supported beam with a concentrated midspan
Taken from Smith et al. (2017, p. 31)

Where:

P = Load.

b = Width.

L = Length.

h = Height.

Δ = Maximum deflection.

From fundamental engineering mechanics, the maximum deflection occurs under the load (i.e., in the middle of the beam) and is calculated in Equation 1.1 (Smith et al., 2017).

$$\Delta = \frac{PL^3}{48EI} \quad (1.1)$$

Δ = Midspan deflection of the beam.

P = Load applied to the surface.

L = Beam span.

E = Elastic modulus of the beam.

I = Moment of inertia for a rectangular beam.

The moment of inertia for a rectangular beam, I, can be determined from the width and height of the beam, as shown in Equation 1.2.

$$I = \frac{bh^3}{12} \quad (1.2)$$

Finally, by substituting known values of P, L, b, and h in equation 1.1, the elastic modulus of the beam (E) may be computed (Smith et al., 2017).

While backcalculating the elastic modulus of pavements is comparable to backcalculating the modulus of beams, it is more challenging since numerous unknowns (i.e., the modulus of the various pavement layers and their interaction) affect the overall deflection observed on the surface. Researchers and practitioners have created a variety of ways for backcalculating the pavement layer and subgrade modulus throughout the years, as well as a variety of programs for performing the computations (Smith et al., 2017). The term modulus is utilized in this research multiple times; therefore, this parameter needs to be described.

1.8.1 Modulus of Elasticity

The term modulus is derived from the Latin root term *modus*, which means measure. The modulus of elasticity in tension or compression is a mechanical property that indicates the stiffness of a solid material under tensile or compressive loads. It quantifies the relationship between tensile/compressive stress (force per unit area) and axial strain (proportional deformation) in a material’s linear elastic region via the following equation (Jastrzebski, 1959):

$$E = \frac{\sigma}{\varepsilon} \tag{1.3}$$

The elastic modulus indicates the relative stiffness or rigidity of a material, that is, a stiff material will have a high modulus of elasticity, whereas a flexible material will have a low modulus of elasticity (Vaidya & Pathak, 2019). Elasticity modulus or the Young's modulus was named after the 19th century British scientist Thomas Young (Truesdell, 1960).

1.8.2 Bituminous Materials Stiffness

The modulus of elasticity concept can be applied to the granular materials in the pavement because they are not sensitive to a change of temperature or a change in loading frequency. However, the bituminous materials used in the pavements are viscoelastic materials, which means that their stiffness, characterize by the modulus, changes according to the temperature and loading frequency (Widyatmoko, 2016). Since in FWD tests the pavement deflections are measured at various pavement temperatures, the backcalculated moduli of asphalt layers, estimated based on testing pavement temperatures, can be converted to moduli at a reference temperature by applying temperature correction factors (Akbarzadeh et al., 2012). Estimating the HMA modulus at temperatures other than testing temperature can be performed by developing temperature correction models and equations. Several research studies have investigated the influence of pavement temperatures on backcalculated asphalt pavement moduli and have proposed models for the adjustment of asphalt moduli to a reference temperature (Kim et al., 1995; Stubstad et al., 1994). The Equation 1.4 and Equation 1.5 represent two temperature correction models at the reference temperature of 68 °F.

Kim et al. (1995):
$$\frac{E_{68}}{E_T} = 10^{-0.0153(68-T)} \quad (1.4)$$

E_{68} = Asphalt modulus at temperature 68 °F

E_T = Backcalculated asphalt modulus at temperature T (F)

T = Test temperature of asphalt (F)

Stubstad et al. (1994):
$$\frac{E_{ref}}{E_{AC}} = \frac{1}{1-2.2\log\left(\frac{T_{AC}}{T_{ref}}\right)} \quad (1.5)$$

E_{ref} = Asphalt modulus at temperature 20 °C

E_{AC} = Backcalculated asphalt modulus

T_{AC} = Test temperature of asphalt (°C)

T_{ref} = Reference temperature of asphalt (20°C)

1.9 Description of the Pavement Backcalculation Process

Considering the Figure 1.8, which depicts a three-layer system with surface deflections measured by sensors at five different points, assists to explain the principle of backcalculation for flexible pavements. In practice, the deflection at any specific sensor is influenced by the moduli of all layers, each of which has a different impact. However, the following general principle always applies to a three-layer system: The modulus of the bottom layer is adjusted to match the deflections of sensors located far from the load while the modulus of the middle layer is adjusted to match the deflections of sensors located at intermediate distances from the load, and the modulus of the top layer is adjusted to match the deflections of sensors located near the load (Huang, 2004). When a load is applied, it propagates through a segment of the pavement system, as indicated by the conical zone in Figure 1.8. The angle of the sides of this zone, which varies between layers, is proportional to the relative stiffness or modulus of the material in each layer (AASHTO, 1993). Stress is distributed over a broader region in stiffer materials (larger modulus). Surface deflection at or beyond the contact between the subbase and subgrade layer is entirely due to stresses (deformations) within the subgrade. As a result, the deflection basin's outer readings primarily reflect the in-situ modulus characteristics of the lower (subgrade) soil (AASHTO, 1993; Malla & Joshi, 2006).

As shown in Figure1.8, the deflections observed by sensors 4 and 5, which are located outside the stress zones of the HMA and base layers, are solely dependent on the subgrade. To begin, any suitable modulus can be assumed for the HMA and granular base, while the subgrade modulus is adjusted until the computed deflections at sensors 4 and 5 match the measured deflections. Following that, the moduli of the granular base and subgrade, which are independent of the HMA modulus, determine the deflection at sensor 3. Thus, until the estimated and measured deflections at sensor 3 match well, the modulus of the granular base is modified. Finally, the modulus of the HMA layer is computed by repeating the procedure with sensors 1 and 2 (Huang, 2004).

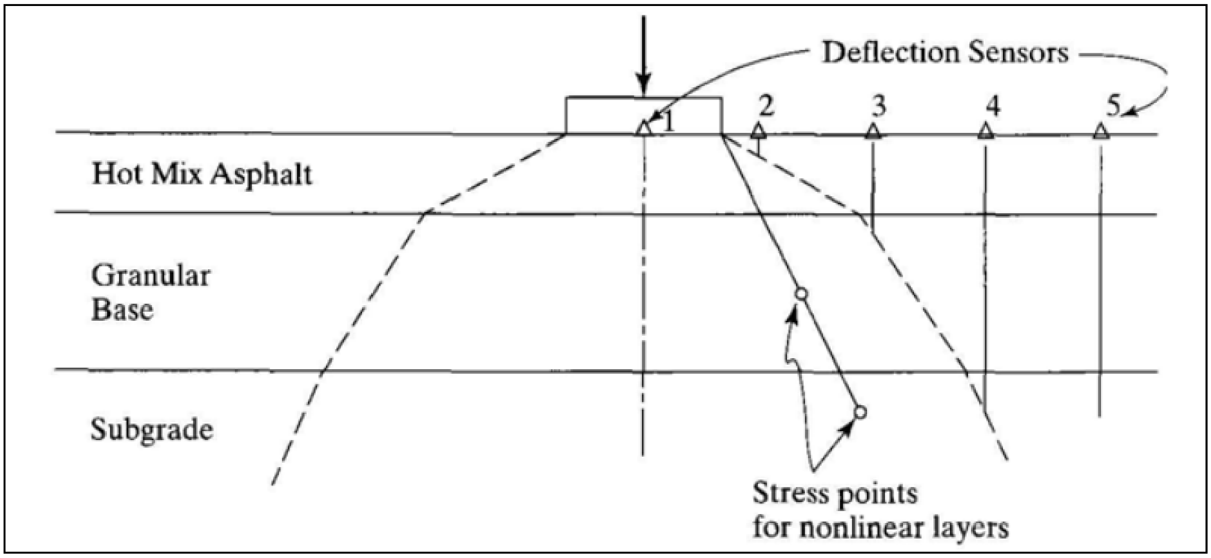

Figure 1.8 Stress zone under the FWD load
Taken from Huang (2004, p. 416)

Numerous backcalculation procedures (and associated programs) for flexible pavements are similar, but the results obtained from the programs vary because of the programs' intrinsic assumptions, iteration techniques, and forward and backcalculation schemes. Existing backcalculation algorithms can be categorized based on the solution methodology used. One of these groups is based on iterative approaches that use the forward analysis method iteratively. The moduli of the layer are changed frequently until a good match between the calculated and measured deflection basins is obtained. The other group is tasked with optimizing and searching a database of deflection basins. A forward calculating scheme is utilized to construct a database, which is then searched for the best match to the measured deflection basin (Smith et al., 2017). The following sections provide an overview of the iterative and the optimization methods for backcalculating flexible pavements.

1.9.1 Iterative Method

The most frequently used method of backcalculation is an iterative mathematical process. The technique presupposes that the FWD deflections are caused by a unique set of layer moduli.

The data analyst chooses the seed modulus for deflection calculations based on experience and judgment. These predicted deflections are compared to those obtained from measurement. The seed moduli are modified and the calculation is repeated following the initial calculation. The iteration ends when a predefined level of tolerance between the measured and estimated deflections is attained. The layer modulus is estimated during this iteration (Alavi et al., 2008). As shown in Figures 1.9 and 1.10, this technique entails continually adjusting the layer modulus until the computed deflection basin matches the measured deflection basin within a specified tolerance. The primary challenge in backcalculating the elastic modulus of a layered pavement system is that the equations used to compute the pavement surface deflection are not closed-form solutions (i.e., the unknowns cannot be solved directly). As a result, a rigorous iterative approach with some decision and convergence criteria is required. Figure 1.10 illustrates the technique (Smith et al., 2017).

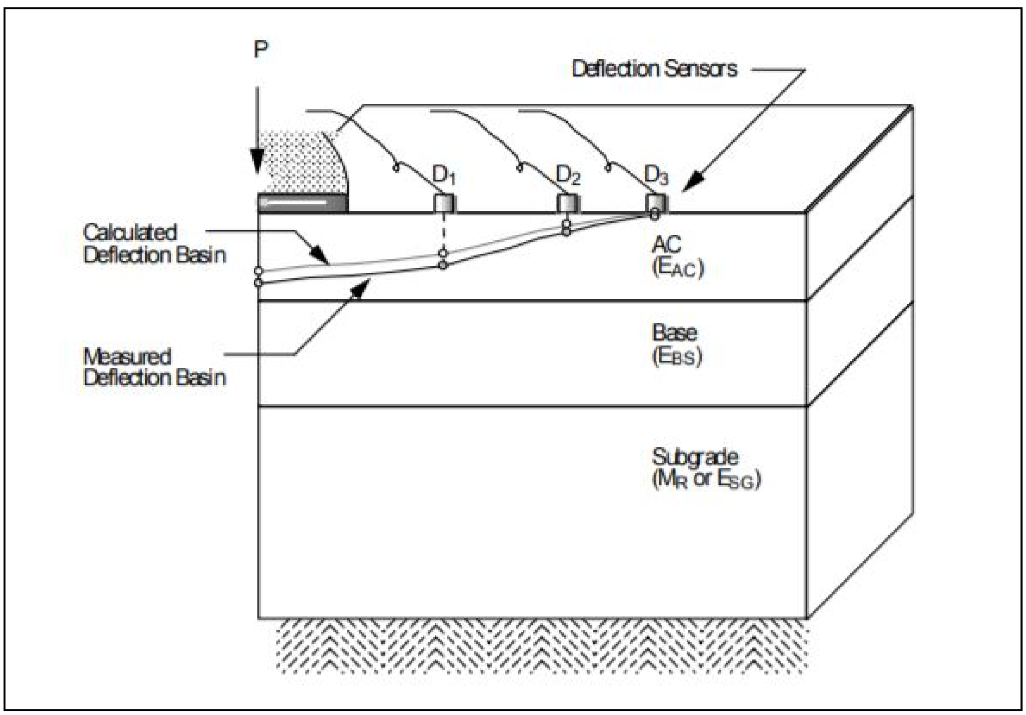

Figure 1.9 Matching measured and calculated deflection basins
Taken from Washington State Department of Transportation. (2005, p. 14)

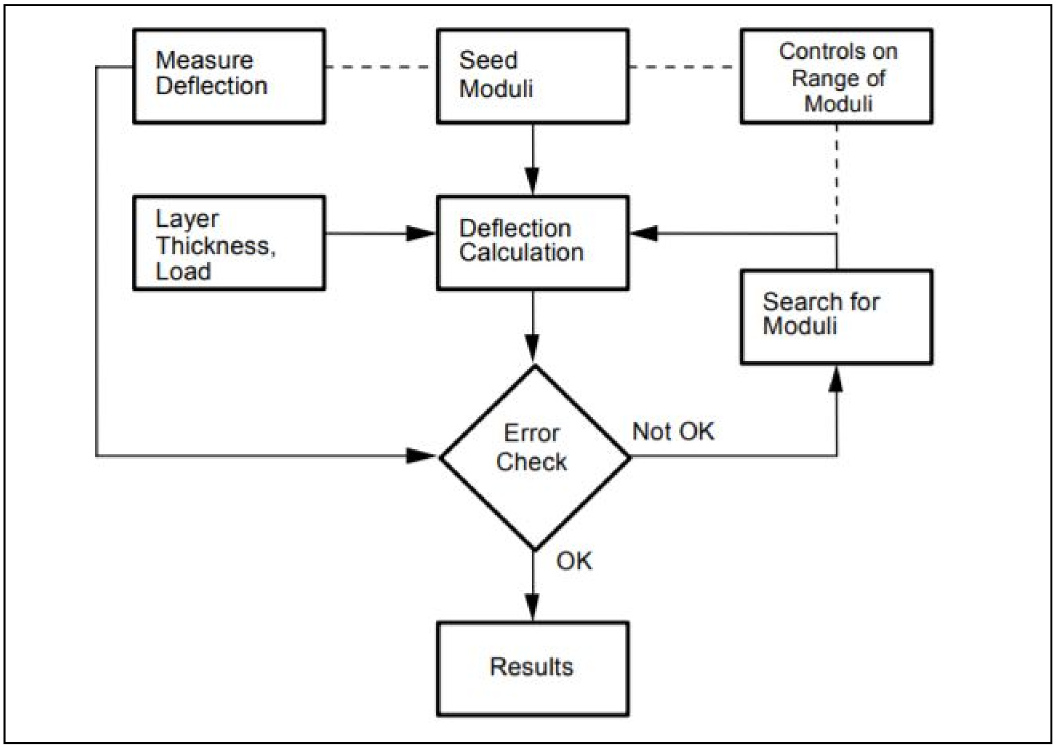

Figure 1.10 Iterative backcalculation flow chart
Taken from Washington State Department of Transportation. (2005, p. 15)

Typically, the search algorithm is accomplished by minimizing an objective function composed of any number of independent variables (i.e., layer moduli, thicknesses, etc.), which is commonly defined as the weighted sum of squares of the differences between calculated and measured surface deflections, as shown in Equation 1.6 (Smith et al., 2017).

$$f = \sum_{j=1}^{m} a_j \left(w_{jm} - w_{jc} \right)^2 \tag{1.6}$$

w_{jm} = Measured deflection at sensor j, (inches).

w_{jc} = Calculated deflection at sensor j, (inches).

a_j = Weighing factor for sensor j, (inches).

One issue with this approach is that the convergence can be very slow, requiring numerous iterations of the forward calculation program (Smith et al., 2017). An example of an iterative program is DBSID, which will be used in this research.

The main steps of the iteration process are as follows (Van Cauwelaert et al., 1989):

• Step 1: Determine the surface deflections at known radial distances from the loaded area centre.

• Step 2: For each layer, enter layer thicknesses, load application characteristics, and Poisson's ratios.

• Step 3: Begin the forward calculation procedure by inputting the initially assumed layer modulus values (seed moduli). In some cases, the computer generates seed moduli automatically using measured deflections and regression equations; in others, the user must define them. At this stage, some algorithms obtain seed moduli via a database strategy.

• Step 4: Calculate surface deflections at the same radial offsets as those measured in step 2 using the data supplied in step 2 and the most recent set of layer moduli.

• Step 5: Conduct an error check to ensure that the surface deflections measured and calculated are within the given tolerance limits. Repeat steps 4 and 5 until the objective function's value becomes sufficiently short.

1.9.2 Optimization Method

In this method, a forward calculation program is utilized to generate a database of deflection basins for various layer moduli, specified layer thicknesses, material characteristics, pavement types, and loading conditions (sometimes referred to as a basin search method). The measured deflection basin is compared to the database deflection basins using a search algorithm, and a set of moduli is interpolated from the layer moduli that provide the database's nearest estimated deflection basins. MODULUS backcalculation software, which makes use of databases generated by the WESLEA program, is an example of a program that employs this strategy (Rohde & Scullion, 1990; Van Cauwelaert et al., 1989). The number of basins required to generate a suitable database is determined by the number of layers and the modulus ranges given by the user (i.e., wide ranges require a generation of a greater number of basins than narrow ones). The moduli are then interpolated using an algorithm that searches for newly created deflection basins. The program optimizes the solution by minimizing the ratio of measured and calculated surface deflections. While convergence to a local minimum cannot be ruled out entirely, the program always converges (Baladi et al., 1994). After creating the deflection basins, an algorithm is used to search for them, and the moduli values are interpolated between the various deflection basins using a method. The software's objective is to identify a collection of moduli that minimizes the ratio of the measured and calculated surface deflections. When testing a large number of pavements with identical setups in a succession, backcalculation using a database search is highly useful. In these circumstances, the database may be used repeatedly to backcalculate the moduli of the various pavement layers for all similar pavements, significantly lowering the time required to build the database. This method can be applied to any database created by a linear or nonlinear program (Baladi et al., 1994).

There are numerous techniques for analyzing and interpreting FWD data. These can be classified as follows:

• The methods of analysis for calculating pavement response (forward analysis).
• The methods for interpretation of pavement response (backcalculation).

The backcalculation methods, like iteration method and optimization method are normally used to calculate the modulus of the different layers in the pavement. Calculating pavement response under a load with known modulus values (forward calculation) approaches include layered elastic solutions based on Burmister's original two- and three-layer solutions (Burmister, 1945), which are by far the most frequently employed of all forward analysis methods.

1.10 Burmister Model

Burmister model is a general theory of stresses and displacements in layered soil systems, developed by Burmister in 1944. For most structural methods of pavement design, strains and stresses in the layers are determined using linear elastic theory with multi-layer programs based on the Burmister model. Layered elastic solutions based on Burmister's original two- and three-layer solutions are generally limited to linear elastostatic analysis and have been demonstrated to yield satisfactory results when material behaviour stays linear. The following are the fundamental assumptions underlying this category of solutions (Smith et al., 2017):

• Surface load is uniformly distributed over a circular area.
• All layers are homogeneous, isotropic, and linearly elastic.
• Upper layers extend horizontally to infinity.
• Bottom layer is a semi-infinite halfspace.

One of the programs that use this method is MODULUS program. This program will be used in this research and is described in the following sections.

As mentioned earlier, one of the most important applications of the FWD test results is the analysis and backcalculation of layers modulus. Various methods have been developed and applied to perform backcalculation. These methods are often based on linear elastic theory and employ different approaches to adjust the theoretical-deflection basin to the obtained deflection basin by the FWD device. The conventional approach for interpreting FWD data in order to backcalculate structural pavement parameters entails extracting the peak deflection from each sensor displacement trace (deflection basin) and matching it to the deflections predicted by a static model of the pavement. This process is computationally efficient, and when the layer depths are known and their properties are mostly uniform with depth, it is effective in backcalculating layer properties. The static backcalculation approach, on the other hand, may not produce reliable results (Turkiyyah, 2005). This procedure is detailed in the next section.

1.11 Types of Backcalculation Methods

The FWD load is usually assumed as a static load, for ease and acceleration of calculation. In the static analysis, only the maximum load values and maximum deflection recorded in the sensors are used for backcalculation, while the applied load by the FWD is dynamic in nature and is of a time history type. On the other hand, the asphalt layer has viscoelastic behaviour. Accordingly, the application of dynamic analysis which makes use of load time history and deflection that is easily recorded by the FWD is very limited. The FWD load ranges from zero in the period of 20 to 95 milliseconds (depending on the FWD device type), during a half-sinusoidal curve, firstly reach a maximum value and then again to zero. If the applied load is static, at the same time with the load peak occurrence, the deflection peak will also occur, but the FWD results do not support such phenomena. As shown in Figure 1.11, the points farther from the load centre reach their maximum values with some delay; this time delay is known as the deflection phase difference and due to the wave propagation speed, a shock has also emerged (Kutay et al., 2011). FWD devices manufactured by different manufacturers usually have different loading time durations. Since FWD testing is a dynamic process, these differences may affect its results. For this purpose, Matsui et al. have studied the results of backcalculations obtained from experiments with three different loading time durations using numerical static and dynamic analysis methods. The results show that the results of the static and dynamic analysis in the numerical study are different (Matsui et al., 2000).

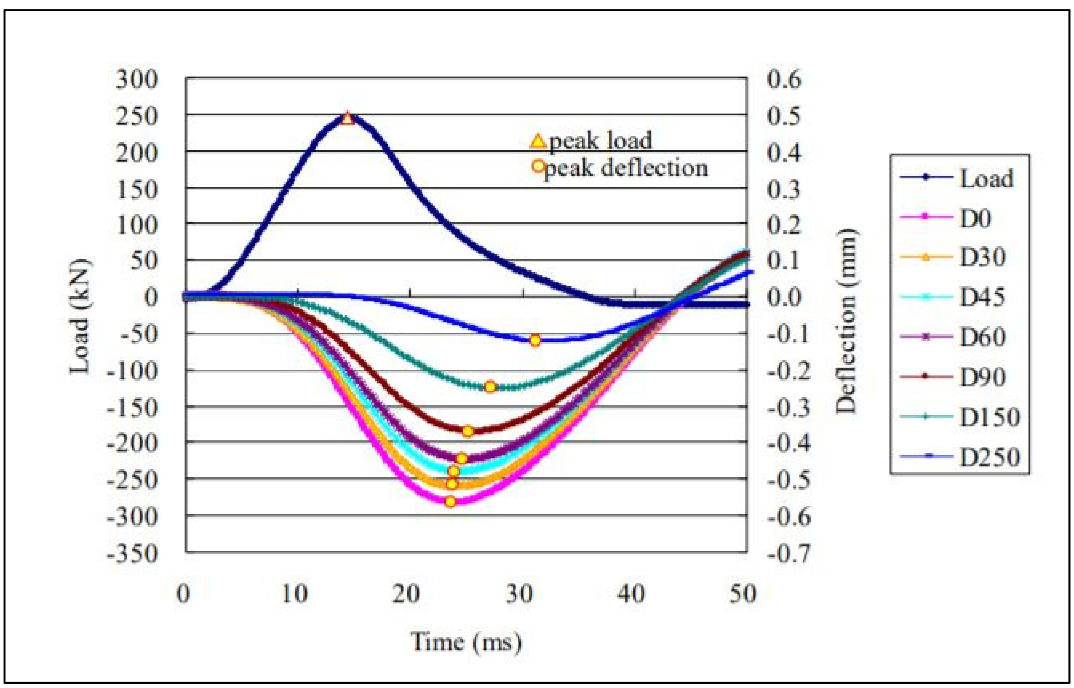

Figure 1.11 Deflection and loading time history
Taken from Matsui et al. (2006, p. 18)

To perform the backcalculation, there are many computer programs which can help to find the layer modulus using FWD data. One of the most widely used software for the backcalculation of pavement layer modulus is ELMOD, which is provided by Dynatest company. Dynatest is one of the companies in the pavement engineering equipment and services. Different pavement testing equipment and devices are manufactured in Dynatest and the FWD is one of its manufactured devices. The ELMOD uses an iterative method for backcalculation and at most can analyze up to four layers with unknown modulus. The initial range for the elasticity modulus (including upper and lower bound of each layer modulus) is determined by the software, and Poisson’s ratio is considered as 0.35. The main assumption of the software is that the pavement layers are homogenous and have linear elastic behaviour (Dynatest, 2014). There are multiple programs that perform static and dynamic backcalculation and it is not known which approach, or which software has the better performance. In this matter and to introduce and describe both approaches, the following sections are listed.

1.11.1 Backcalculation with Static Analysis Approach

Numerous studies have been conducted over the last few decades to examine various aspects of the interpretation and backcalculation of FWD test results. Numerous papers summarized several conclusions from these investigations. The available backcalculation processes can be roughly classified as static or dynamic, depending on the type of model employed to evaluate the pavement's theoretical reaction. The theoretical static response of a pavement model under the highest value of the applied impulse load is matched to the maximum measured deflection of the pavement at each geophone position using static backcalculation processes. Static backcalculation processes are frequently utilized in engineering practice because of their simplicity and speed of calculation (Hadidi & Gucunski, 2010). There are several programs available that implement this approach such as ELMOD, Alize-LCPC, EVERCALC, MODULUS, etc.

Traditionally, to analyze FWD data, static backcalculation techniques based on the layered elastic theory are used. However, the dynamic effects of the impulse loading produced in the

FWD test, as well as the viscoelastic behaviour of asphalt concrete, cannot be considered in the static process. The backcalculated layer properties from the static approach and the pavement responses calculated using these layer properties are therefore questionable (Cao et al., 2019). The most common method used in this technique for determining the layer modulus is performed by simplifying the model to a statically applied load. Given its widespread use, because of the assumptions implicit in its use, it creates unsatisfactory results. Only the peak deflections are used in the static backcalculation. To find the layer modulus, the deflections are iteratively matched to computed deflections. Deflections, whether peak or time series, depend on each layer thickness and elastic modulus, and so the modulus can be backcalculated if the layer thicknesses are known (Maina et al., 2013). MODULUS is a computer program which has been used in our study to implement the static backcalculation; therefore, it should be introduced and explained.

1.11.1.1 Introducing MODULUS Program

MODULUS software is one of the most used and known programs in the pavement industry to backcalculate the FWD data to find the layer modulus. This program was developed by the Texas Transportation Institute (TTI) for Texas Department of Transportation (TXDOT) and has been used since the early 1990's to perform structural evaluation of the pavements and to provide layer modulus values for structural design. Since the 1990s, it has been updated several times. MODULUS program performs the backcalculation in the type of static one and can evaluate a maximum of four layers of pavement.

MODULUS program uses the Waterways Experiment Station Linear Elastic Analysis (WESLEA) method for forward calculation of moduli. WESLEA is a multilayer elasto-static theory-based system. WESLEA is used to create a database of deflection basins for various modular ratios. It uses a pattern search technique to select the set of layer moduli that provides the deflection basin with the best match to the measured deflection in the field (William 1999; Ahmed, 2010). The MODULUS program uses the multi-layered elastic theory in its computations, which is described in detail in the following paragraph.

As discussed earlier, flexible pavement is a multi-layer structure with stronger elements on top, and it is accurately represented by a homogeneous mass (Huang, 2004). Burmister initially proposed solutions for a two-layer system before expanding them to a three-layer system in order to characterize the pavement reaction under load (Burmister, 1945). It can be applied to any number of layers due to advancements in computation efficiency (Huang, 2004). The following are the assumptions supporting the layered theory (Ahmed, 2010):

- The pavement system consists of several members, each made of a different material.
- Each member is of uniform thickness and infinite dimensions in all horizontal directions (Burmister layer), resting on a semi-infinite elastic and isotropic domain.
- Each member consists of a homogenous, isotropic, linear, and elastic material whose constitutive equation is governed by Hooke's law.
- The system is free of any stress and deformations before application of external traffic loading.

1.11.2 Backcalculation with Dynamic Analysis Approach

Field studies have indicated that deflections of the FWD correlate closely with pavement deflections induced by moving wheels loads. However, interpretation of FWD deflection data remains somewhat problematic. A point of discrepancy arises because FWD measurements are interpreted as static deflections in many studies, thus ignoring the fact that the load of the FWD is dynamic (Sebaaly et al., 1986). The nature of the applied load delivered by the FWD is impulsive, which is suitable in closely simulating the effect of a moving wheel on the pavement surface. The dynamic analysis of FWD data therefore logically yields results which are more accurate than those obtained from the static approach, in which the theoretical model is considerably more simplified and thus effectively more unrealistic. In backcalculation of the FWD results using the dynamic analysis approach, the deflection data has been presented as a time history with the time domain (Maina et al., 2013). To use this data in dynamic analysis, several computer programs can be used. Currently, there are some computer programs that do dynamic backcalculation. DYNAMIC, FEDPAN, PAVE-SID, PDAP, FWD-DYN, BKGREEN, DBALM, LAMDA, DYNABACK, EVECALC II, and DBSID are some of the available dynamic backcalculation programs (Grenier et al., 2009). Dynamic Backcalculation Procedure with Systems Identification method (DBSID) is a computer program that have been employed to implement the dynamic backcalculation in our study; therefore, it is required to introduce and describe this program.

1.11.2.1 Introducing DBSID Program

DBSID is a computer program which has been developed at Texas Transportation Institute (TTI) for backcalculation of pavement material properties using FWD full-time load and deflection histories. Based on the knowledge and the experience on the dynamic backcalculation, the pavement structure is limited to three layers pavement and because the backcalculation procedure needs to call the forward model frequently, different with the static backcalculation program like MODULUS, each run of dynamic forward model needs intensive of calculations. The faster the computer runs, the less time is needed to wait. With normal home computers, it takes about two hours to calculate the layer modulus. The System Identification (SID) technique is an iterative process that continues the iteration process until the desired convergence condition is achieved or the maximum iteration number is out of range (Liu, 2002). The big difference between dynamic backcalculation and static backcalculation is using the time history data in the dynamic backcalculation and using the peak deflections in the static backcalculation.

Figure 1.12 is a typical of 7 sensors deflection time history and the load time history. The load time history curve describes how the FWD dropping weight load changes with the time, also under this dynamic loading, how the induced deflection changes with the time. Because the dynamic load induced wave travels from the loading centre to the radial direction with the attenuation style, the peak location changes with the increase of the distance to the centre of the load. Normally, each curve of time history data needs 300 data points to define it, while in static backcalculation method, only 1 value is used which is known as the peak value.

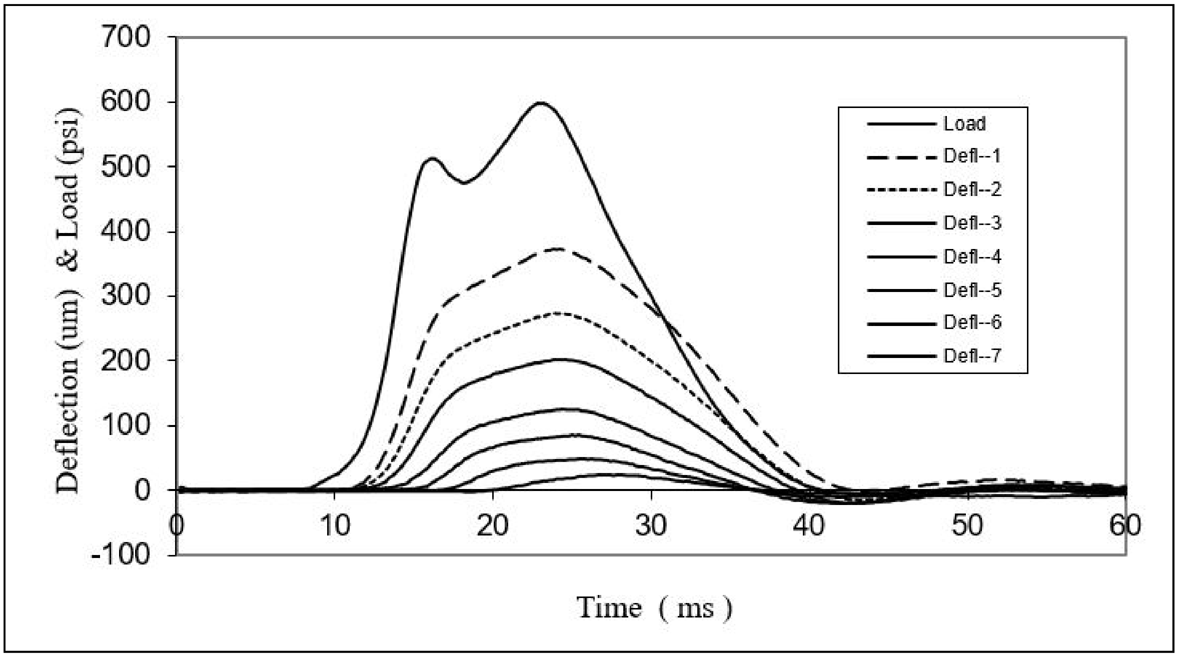

Figure 1.12 Typical FWD load and deflection time history
Taken from Liu (2002, p. 4)

Because in most FWD tests the default setup is only to collect the peak information, if we want to collect time history data to do dynamic backcalculation analysis, setup must be changed to let the FWD, collect time history data. Collecting time history data really does not increase too much usage to the FWD system and does not increase much running time. It is because when the FWD system only collects peaks, the FWD hardware and software really collect the whole time history, only does not write it to the file to keep it. Therefore, if in the future some dynamic backcalculation software is developed, it is how regret when we find that the old data file does not keep time history data. Therefore, it is good and smart to collect time history data (Liu, 2002).

Beside the pavement evaluation tests like FWD, there are a lot of other ways to evaluate the pavements. One of the key functions required for a pavement management system is its ability to evaluate and predict future pavement conditions within an analysis period. This evaluation involves the use of pavement performance indicators and performance prediction models (Ningyuan et al., 2011). International Roughness Index (IRI) is one of these indicators that is extensively utilized and will be studied in this research. The following section is the explanation of this index.

1.12 International Roughness Index

Road roughness is gaining importance as a measure of road condition, both in terms of pavement performance and as a significant predictor of road user costs. This requirement for roughness measurement has resulted in the development of a multitude of equipment, ranging from quite simple devices to fairly complex systems. A thorough description of road roughness in a longitudinal road profile is essential for road maintenance and to ensure the ride safety and comfort of a vehicle fleet, as well as to reduce the dynamic load on a vehicle and pavement. The IRI is the most often used index worldwide for longitudinal road roughness measurement in order to manage road infrastructure. The IRI is a performance and ride quality measure for pavements. IRI is highly associated with both the overall amount of ride vibration and the overall level of pavement loading vibration (Mucka, 2017). Since its inception in 1986, the IRI has become the most widely used road roughness index for analyzing and maintaining road systems globally. IRI is a computer-based virtual response system that is based on the mathematical response of a quarter-car vehicle model to a road profile. IRI is calculated using a simulation of the roughness response of a car travelling at 80 kilometers per hour; it is the reference average rectified slope, which is a ratio of a vehicle's accumulated suspension vertical motion divided by the distance travelled during the test. IRI is a numeric value that summarizes the roughness characteristics that affect vehicle reaction. In pavement management systems and in the transportation/highway engineering field, IRI is frequently employed as a performance measure for pavement condition (Mucka, 2017).

1.12.1 IRI and Layer Modulus Correlation

Pavements are evaluated and determined by their functional properties and structural properties. As part of pavement assessment, monitoring and measurement of the functional and structural properties of the pavement are necessary in order to determine the remaining life of the pavement before any rehabilitation work is undertaken. In many cases, the layer modulus is utilized to evaluate the structural properties of the pavement and the IRI is used to evaluate the functional properties of the pavement. The residual life of a pavement is calculated using the FWD backcalculated layer modulus, and a reduction in modulus correlates with an increase in damage, hence a reduction in the pavement's residual life. A lower modulus may result in more damage and more damage may result in pavement degradation which may result in an increase in the IRI values. However, the influence of external factors on the pavement may not reveal the relationship between the layer modulus and the IRI value. Limited research has been performed to find a correlation between the layer modulus and the IRI values. For example, a study published in 2019 concluded that there was no correlation between the structural properties and the functional properties of flexible pavements (Barudin et al., 2019).

Thus far, many aspects have been introduced and explained that will be evaluated in this study, but we need data in order to evaluate and analyze these subjects. Long-Term Pavement Performance (LTPP) program is the largest databases in the pavement industry, which helped us tremendously during this study. It is for this reason that the next section is devoted to describing this database in detail.

1.13 Long-Term Pavement Performance Program

The Transportation Research Board (TRB) conducted a Strategic Transportation Research Study of the nation's highway and bridge infrastructure deterioration in the early 1980s. The study advocated the establishment of a Strategic Highway Research Program (SHRP) to concentrate research and development efforts on highway transportation improvement. The study report, published in 1984 as TRB Special Report 202, America’s Highways, accelerating the search for innovation, recommended six strategic research areas. The LTPP program was one of these areas. Independent contractors produced specific research proposals for SHRP in

1985 and 1986. The TRB published the comprehensive study plans in May 1986 as a TRB paper titled Strategic Highway Research Program Research Plans (Elkins et al., 2003).

The LTPP program was designed to be a comprehensive solution for a wide range of pavement information requirements. It tries to construct models that will better describe how pavements perform based on current technical knowledge of pavements. It also aims to learn more about the effects of various design features, traffic and the environment, materials, construction quality, and maintenance procedures on pavement performance. As more data becomes available, analyses are carried out to produce better performance prediction models for use in pavement design and management, better understanding of the effects of many variables on pavement performance, and new techniques for pavement design, construction, and rehabilitation (Elkins et al., 2003).

The LTPP program's strategy constitutes a substantial departure from conventional research methods. Traditionally, pavement performance studies have been divided into discrete themes with limited scope and duration, beginning with data collection and concluding with recommendations based on the data analysis. The LTPP initiative was conceived as a long-term national effort to overcome some of the challenges inherent in short-term pavement behaviour studies. In the LTPP paradigm, data collection occurs prior to the establishment of numerous specific data analysis objectives. Due to the fact that many critical data analyses are performed by individuals who are not involved in data collection, the LTPP program has invested in the construction of a publicly accessible database and database use tools (Elkins et al., 2003).

Extracting data from the LTPP database requires special knowledge and takes time to learn it to be able to find the correct and related data. Reading the LTPP book and the LTPP user guide is helpful to be able to extract data from the LTPP database. The following section provides information to aid in understanding and using the LTPP database.

1.13.1 LTPP Database Description

The LTPP program collects research quality pavement performance data from in service test sections located throughout the United States and Canada. The LTPP database is a relational database made of distinct but connected data tables. The significance of a relational database is that all data is kept in tables in a straightforward row/column format (rows are referred to as records and columns are referred to as fields). Each row of data is recognized individually by the values contained in a primary key column or a combination of columns (most of the tables in the LTPP database use multicolumn key fields). Additionally, relationships exist between the database's tables, which are represented by similar data values contained in several tables. For instance, many data tables contain STATE_CODE and SHRP_ID columns, which are used to uniquely identify test sections or projects. These fields can be used to locate data for a particular area of a test in a variety of tables. The LTPP database is self-describing, which means that it contains information about its structure. Modern relational database management systems offer Structured Query Language (SQL), the industry-standard language for operating and communicating with relational databases. One of the most essential characteristics of SQL for data consumers is its ability to obtain and integrate data pieces stored in different tables based on user-defined constraints. SQL can be used to extract, combine, count, and perform basic mathematical operations on data stored in database format. To fully utilize the LTPP database's capability and simplicity, users should become comfortable with SQL (Elkins & Ostrom, 2021).

To be able to read and understand LTPP data, it is essential to learn many of the codes, acronyms, and abbreviations. The following table represents a small portion of these abbreviations and codes.

Table 1.1 LTPP database abbreviations and acronyms
Adapted from Elkins & Ostrom (2021)

Acronyms	**Meaning**
Bakcal	Backcalculation
MON	Monitoring
DEFL	Deflection
LOC	Location
TST	Test
RHB	Rehabilitation
MNT	Maintenance
TRF	Traffic

One of the most common steps in conducting research in the engineering subjects is to perform statistical analysis on the data contained in the research. The subjects in this research are no exception to this rule and statistical methods are used to analyze the data. Following that, we will examine some of the previous research in this area in the next section.

1.14 Statistical Analysis of FWD data

There are several research that perform the statistical analysis on FWD data some of which are mentioned in this section. A study in 2010 was conducted to evaluate the consistency and accuracy of three backcalculation software. To examine consistency a statistical analysis was performed using three sets of FWD deflection data (Ahmed, 2010). One of the tools that is utilized in the statistical analysis is performing correlation. Researchers usually utilize this method to find the relationship between different variables among their data. Some studies were implemented to find a correlation between the AC moduli determined from laboratory tests and the FWD field tests (Oh et al., 2012; Hossain & Scofield, 1992). In our study, we also use various statistical methods to analyze the data, which are discussed in detail in Chapters 3 and 4.

1.15 Summary

Pavement construction is a very costly process, and the pavements are usually designed for a long period of time. Understanding pavement properties may help the pavement engineers to reduce these costs. The layer modulus is one of the most important pavement parameters that can help to achieve this goal. As this literature review shows, existing research has mainly focused on the prediction of the layer modulus with the help of different methods. Very little attention in contrast, has been paid to do the comparison of the existing methods and existing computer programs to find the best method. Very few statistical analyses to compare the static and dynamic backcalculation methods have been performed in the previous literature; therefore, it is appropriate to consider this subject in this study. Also, lack of doing research to discover the effect of different parameters including the surface layer thickness and the pavement temperature that may influence the results of backcalculation is observed. The layer modulus is a parameter to measure the structural properties of the pavements; on the other hand, to measure the functional properties of the pavements like roughness, the IRI is widely utilized. Therefore, it is very helpful to try to discover a relationship between the layer modulus and the IRI value of the same test section.

CHAPTER 2

RESEARCH FOCUS AND OBJECTIVES

2.1 Problem Statement

The FWD device is one of the most recognized and utilized devices in the road and pavement industry. The pavement can be evaluated using this device. Since FWD is a non-destructive testing device, meaning that the test can be performed without any destruction, coring, drilling, etc., it is very useful for the roads and pavements that are in service. One of the major problems and challenges that the pavement engineers have experienced over the years is the analyzing of the FWD data. The FWD data is usually assumed as if they are the results of a static load, while in reality, the nature of the load is dynamic. Accordingly, the results may vary for the flexible pavements. One of the most important applications of FWD test results is the analysis and backcalculation of the layers modulus. In the evaluation of the remaining life and in the design of new pavements and overlays, the modulus is a crucial parameter. The backcalculation process, which uses FWD raw data, can compute this crucial value. The precision of the modulus obtained with FWD does have a major effect on the pavement design. The variation of the modulus obtained from FWD can lead to a variation of the number of estimated years of residual pavement life. To backcalculate the layer modulus, two approaches are utilized, dynamic and static backcalculation. Until now, many computer programs have been developed to perform the static and dynamic backcalculation, but each approach provides a different value of modulus after ending the calculation and running procedure. It is not known which program and method provide the most accurate results and what parameters (e.g., pavement temperature, layers thicknesses etc.) influence the backcalculation process. Also, there is a lack of research done on linking and comparing the modulus obtained from FWD data backcalculation and the pavement quality indexes such as International Roughness Index (IRI) values.

2.2 Research Objectives

The main objective of this research is to evaluate the pavement properties, particularly, the modulus obtained from the FWD device and to compare the available FWD data backcalculation methods (dynamic and static backcalculation) and to analyze the effect of the pavement parameters including temperature and the layer thickness on the backcalculation results. Another objective is to better understand the link between the modulus obtained from the FWD data backcalculation and the International Roughness Index (IRI) values of the same tested pavement.

Since the accurate determination of the modulus of asphalt layers for rehabilitation purposes and design of asphalt resurfacing is of particular importance in the structural condition of flexible pavements, the specific objectives of this research are:

- To present various FWD test data, carried out on the different pavements and highways (10 test sections), to have the test data documented and recorded to help the researchers access the ready and complete FWD test data, conducted in different locations and regions, in a single document.
- To perform the static backcalculation using the MODULUS computer program to be able to evaluate the static backcalculation approach and the MODULUS software.
- To perform dynamic backcalculation using the DBSID computer program and to find the probable similarities and differences between the results of two methods (static and dynamic).
- To evaluate the effects of pavement temperature and the pavement layers thickness on the results of backcalculation process.
- To present the IRI values of the related test sections and to find the probable correlation of the IRI values and the modulus obtained from the backcalculation.

2.3 Outline of Thesis

This thesis is separated into different sections plus an introduction. In this regard, Chapter 1 covers the literature review on this research with emphasis on the FWD device and its testing procedure and the data analysis. The problem statement, the objectives and the outline of the research are explained in Chapter 2. Chapter 3 presents the data and methodology utilized in this research. Chapter 4 demonstrates the results and outputs of the study and chapter 5 represents the research conclusions and the recommendations for the future studies.

CHAPTER 3

DATA AND METHODOLOGY

3.1 Introduction

In this chapter, the different types of FWD data backcalculation to be used in this study are presented, then the comparison of static and dynamic backcalculation by describing the MODULUS computer program and the DBSID software are demonstrated. The way of working and the using procedures of both programs are discussed precisely. The FWD raw data and all the used data in this study are introduced and the Long-Term Pavement Performance (LTPP) Program whose database has been utilized in this research is also represented. Unlike most studies in this field, in which only one or two test sections are examined, in this study, we examined 10 test sections in different locations with different geographical conditions throughout North America to obtain sufficient and reliable data. The test sections in this study, all in the USA, include different highways and roads in Alabama, Florida, Kentucky, Michigan, Missouri, New Jersey, New York, Pennsylvania, Texas, and Washington. The type of pavement structure including their layers and the thickness of layers and the material of the pavements and other parameters including the pavement temperature at the time of the test are also presented. With these data, the two methods of backcalculation (static and dynamic) can be performed and then compared and the effect of pavement temperature and layers thickness on the modulus obtained from FWD data backcalculation can be discussed. International Roughness Index (IRI) values of the same studied sections are also illustrated. The IRI values are compared with the layer modulus obtained from FWD data backcalculation. As one of the objectives of our study is performing the backcalculation, it is necessary to explain this subject further. In this regard, the different types of backcalculation that are employed in this study are presented in the following sections; then, further details are demonstrated.

3.2 Types of Backcalculation Analysis

As mentioned earlier in chapter 1, three major groups have been developed to do backcalculation; these three groups are categorized based on the techniques which are used to solve the problem. The first group is based on iteration techniques, which repeatedly uses a forward analysis method in an iterative process. The layer modulus is over and again balanced until a reasonable match between the calculated and measured deflection basins is obtained. The second one depends on looking through a database of deflection basins. A forward calculating plan is utilized to create a database, which is then searched to locate a best match for the watched deflection basin. Regression equations are used for the third group, and they are fitted to a deflection basins database obtained by a forward calculation scheme (Smith et al., 2017). The static and the dynamic backcalculation methods which are studied in this research can utilize these groups and processes to perform backcalculation. The comparison between these two types of backcalculation is presented in the following section.

3.3 Comparison of Static and Dynamic Backcalculation

FWD data is typically processed via backcalculation software for computing the pavement layer modulus. Though there is currently a lot of backcalculation software available, it is not known which software produces the most reliable and accurate results. Inconsistent and unreliable backcalculation software can take a major toll on pavements overlay and rehabilitation design as the modulus is the inputs for these construction calculations (Tarefder & Ahmed, 2013). Most of the backcalculation programs are based on simplified assumptions such as pavement elastic behaviour and static load. These algorithms use the FWD sensors reported peak values of loads and deflections. On the contrary, the dynamic approach accounts for the dynamic nature of the load, and factors such as inertia and damping of material. In these algorithms, load and deflection time-histories measured by FWD are used as inputs (Ameri et al., 2009). In this research, the MODULUS software and DBSID computer program are employed to do the backcalculation. The MODULUS software performs the static backcalculation and the DBSID program does the dynamic backcalculation. The results have been compared, the performance of each program has been evaluated and the advantages and disadvantages of each approach have been clarified. This comparison will enable us to have more precise and reliable results with the FWD.

Throughout the remaining life analysis and throughout the design of new pavements and overlays, the modulus is the key parameter. This critical value is determined using the backcalculation process, using raw data from the FWD (Tawfiq, 2003). Most common backcalculation algorithms, which use the load and deflection peak values at each sensor during each drop, assume the FWD load will be applied statically. The pavement system with linear or nonlinear (stress-dependent) materials is modelled as a layered elastic system. For the estimation of the theoretical deflections under the established load a forward analysis subroutine is used. Such determined deflections are attempted to converge to the measured ones. In other words, the modulus is estimated by reducing the error in each iteration step between the measured and determined deflections (Lytton, 1989). In dynamic backcalculation, the full-time history data of both load and deflections during the FWD test are measured, depending on the type of FWD system the loading time usually ranges from 20-95 milliseconds. When completely used the FWD provides excellent structural details. It is apparent from a review of the sensor peak values for each position of the measurement that points further from the centre of the load plate attain their peak values later than positions closer to the plate. This time difference known as phase difference of deflections is a function of shock wave propagation velocity (Ameri et al., 2009). Such types of time history data provide valuable knowledge that would lead to enhanced accuracy of the structural pavement evaluation if well utilized. The use of peak values only discards this potentially incredibly valuable knowledge (Matsui et al., 2006). In the DBSID program, which has been employed for dynamic backcalculation, the time history deflection data of FWD is needed. On the other hand, in the MODULUS software only the peak deflections are utilized to perform backcalculation. These programs are discussed in the following sections.

3.4 Implementing Static Backcalculation with MODULUS Program

In MODULUS program, the needed inputs to perform backcalculation are the FWD raw deflection file, number of the pavement layers and their thicknesses, the pavement layers Poisson's ratios, the initial layer modulus ranges, asphalt temperatures at the time of testing, the number of the geophones and their distances from the centre of the load plate, the peak deflections obtained from the FWD geophones at the different stations, the FWD load plate radius, and the FWD load amplitude. A likely range of probable layer moduli provided by the program user simplifies the procedure by providing as the basis for a small internal database against which mathematically generated deflection basins are compared to the software's actual measured deflection basin. Once an acceptable match is established, the modulus required to achieve this match is presented as the individual layer modulus.

Backcalculation is the main computation model in the MODULUS program. The data from the FWD tests have been used in the MODULUS software for backcalculation the layer modulus. As mentioned earlier, the pavement structure data, loading data and measured deflections have been entered into the program before proceeding to perform backcalculation. It is activated by selecting the icon from the main screen, which will display the screen shown in Figure 3.1. In the structural data, we have defined the number of layers and the thickness of them. The Poisson's coefficients of each layer have also been defined. Based on the MODULUS program user manual, and the suggested values mentioned in the table 3.1, 0.35 has been considered for the hot mixed asphalt (HMA) pavements by the software default. In the MODULUS program, the layer thickness unit, the modulus unit, the pavement deflection unit, and the load unit are inches, ksi, mil and lb., respectively. The difference value when making the adjustment between the measured deflection values and those calculated by the software is called the root mean square error (RMS).

Table 3.1 Typical Poisson's ratio values for backcalculation
Taken from Pierce et al. (2017, p. 32)

Material Type	Poisson's Ratio
HMA	0.35
PCC	0.15–0.20
Stabilized base or subbase	0.25–0.35
Granular base or subbase	0.35
Cohesive (fine grain) subgrade soils	0.45
Cohesion less (coarse grain) subgrade soils	0.35–0.40
Stiff layer	0.35 or less

Figure 3.1 is a screen shot of the MODULUS program that shows the geophone distances from the load plate centre, layers thickness, initial modulus range, and the Poisson's ratio for each layer. This figure belongs to the Washington state test section, which is one of the 10 states, utilized in this study. In this figure, the surface thickness is shown as 4.60 inches, the base thickness is 8.0 inches and the subgrade thickness is 66.0 inches. The geophone distances from the load plate are 0, 8, 12, 18, 24, 36 and 60 inches. For base and subgrade layers, the modulus range and the Poisson's ratio have been also assigned. When one material type is selected, a recommended modulus value is put into the range field. However, these values can be changed or adjusted. For the subgrade, only the most probable value is needed to do the backcalculation. For normal operations, a starting value of 10 ksi works well in most cases. If the calculated modulus is significantly different from the input value, the system will be re-run with a more appropriate initial subgrade value. Since our raw FWD data file has valid pavement temperature measurements, the program automatically put the average pavement temperature into the asphalt temperature field, and the modulus range is changed based on the temperature. The FWD measured temperature that belongs to Washington state, are shown in Figure 3.2.

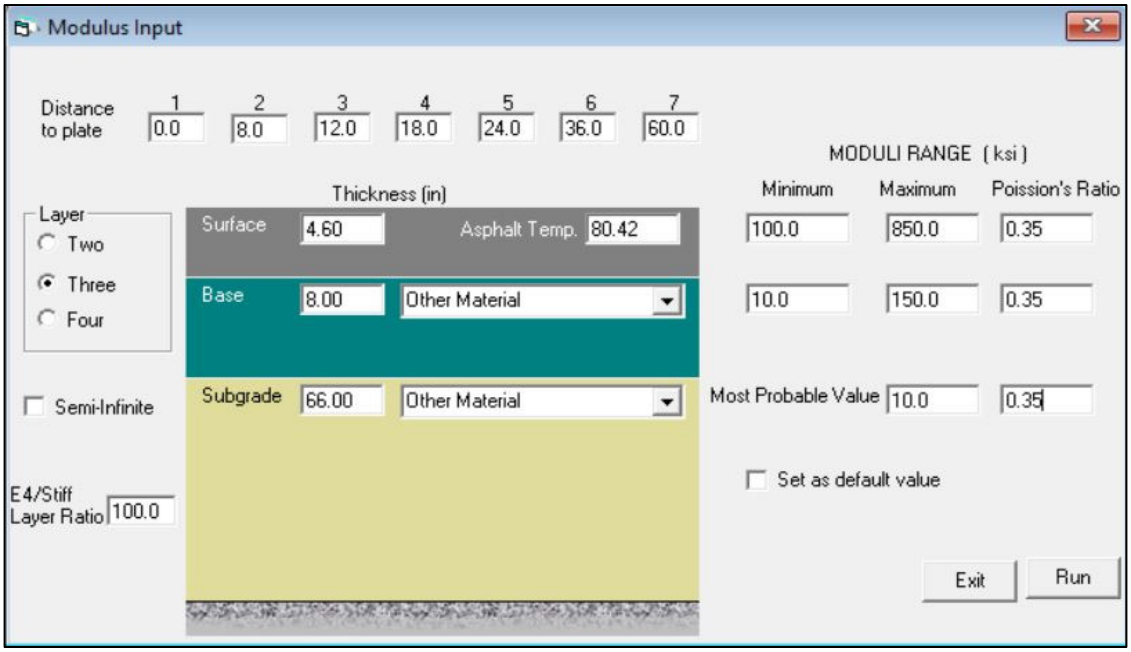

Figure 3.1 MODULUS backcalculation input dialogue box

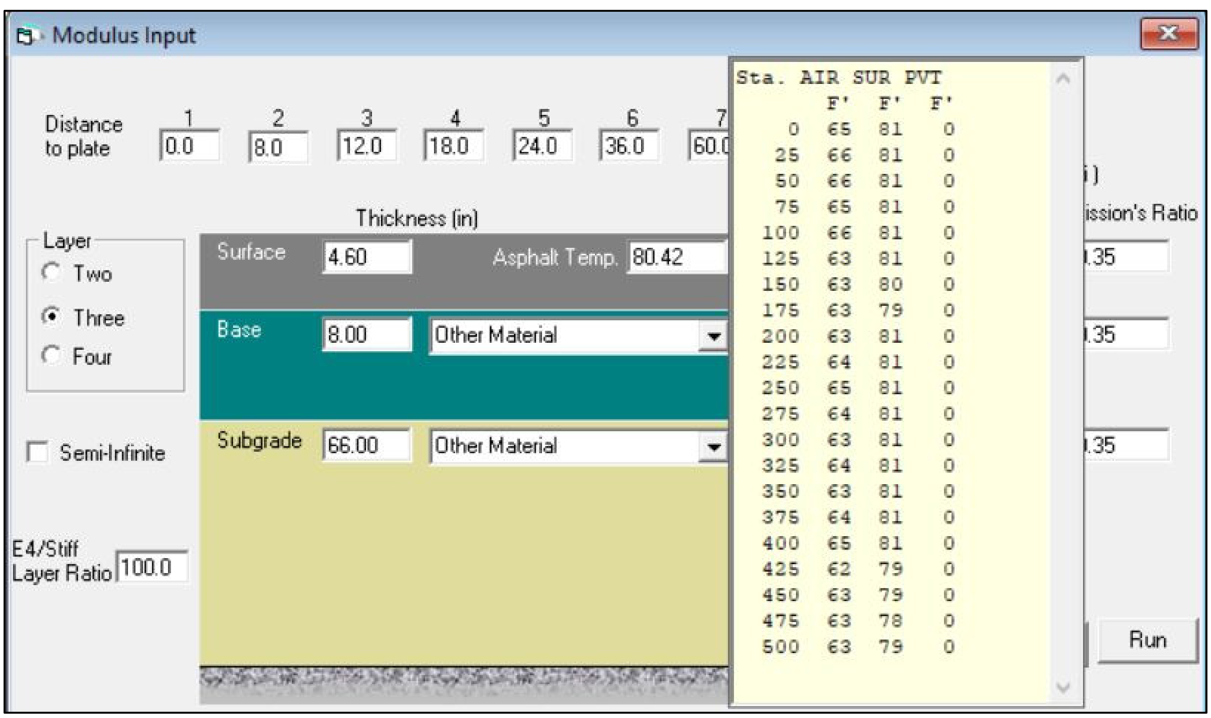

Figure 3.2 Measured temperature and other parameters in MODULUS program

3.5 Implementing Dynamic Backcalculation with DBSID Program

In this research, 10 different time history data files that have been obtained from 10 different pavements in 10 states of the USA have been utilized to perform dynamic backcalculation with DBSID program. Each time history data file contains a large amount of numbers, as if we put them in a Microsoft Word file with a font of 12, it will occupy about 500 pages. A little part of one of these 10-time history data files is listed in the Appendix I; this file information is related to Alabama state.

To start the backcalculation process using the DBISD program, it requires a run of MODULUS static program and saving the result file to ASC format. This ASC file is read by the DBSID program and since the DBSID can only analyze three layers pavement system, it is strongly recommended that the static backcalculation also models the pavement to three layers system and has the same thickness and Poisson's Ratio (Liu, 2002). A typical ASC summary result file of MODULUS program is listed in Appendix III. Also, a typical output file of the DBSID program results is listed in Appendix II.

3.5.1 DBSID Program Working Procedure

In this section, the details on some of the steps of the DBSID running procedure are presented. In DBSID program, the needed inputs to perform backcalculation are the FWD time history deflection file, number of the pavement layers and their thicknesses, the pavement layers Poisson's ratios, asphalt temperatures at the time of testing, the number of the geophones and their distances from the centre of the load plate, the peak deflections obtained from the FWD geophones at the different stations, the FWD load plate radius, the FWD load amplitude and the summary result file of the MODULUS program.

When doing the FWD tests, the FWD device moves on the pavement, stops, and does the test, then it goes through some meters ahead and stops again and performs the test on the next stop point. This procedure continues for normally 21 stop points. These stop points are called stations. In DBSID program, we need to select which stations will be used to do the dynamic analysis. In our raw data, there are 21 stations which the FWD tests were done on them, only in Alabama test site, there are 20 stations and in Florida and New York test sites, there are 11 stations. In all other test sections, there are 21 stations. Figure 3.3 is a screen shot of one of the stages in the DBSID program. In this figure, there are three group controls. The first is choosing the station method, two choices are listed: by the serial number of stations or by milepost. The second one is input the range of the stations. If selecting by station number, we must input the starting, ending and step of the station's range, otherwise we need to input the starting, ending milepost. The third group shows some information about the test file to select the stations.

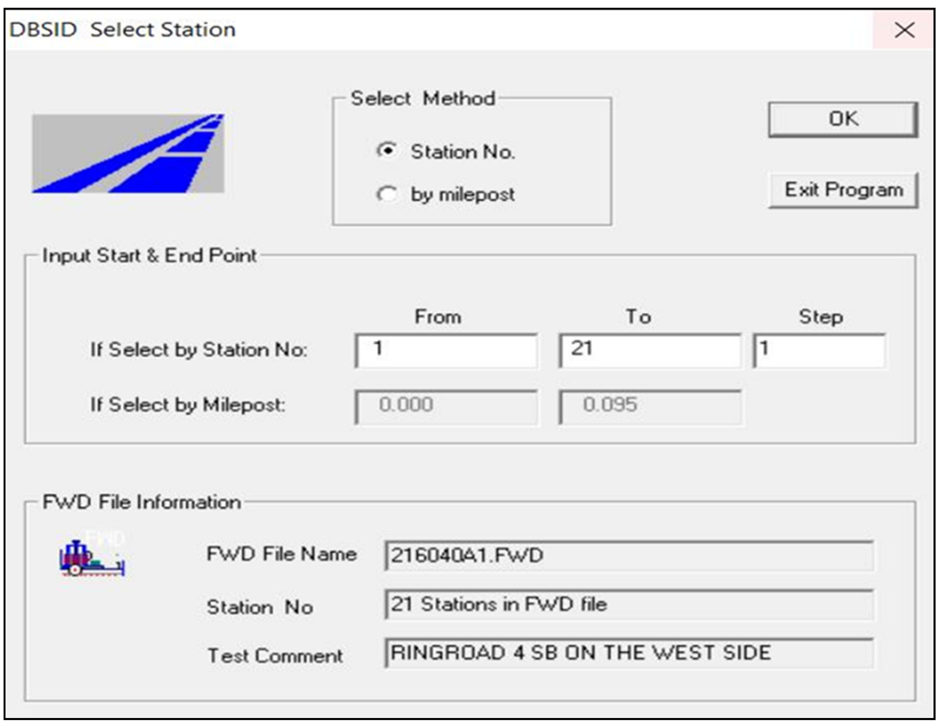

Figure 3.3 Selecting the stations in DBSID program

Figure 3.4 shows the MODULUS summary result read by the DBSID program from the ASC file. DBSID program only uses this result to set the initial and the range of each backcalculation parameter. The buttons in this screen allow us to browse each station MODULUS result.

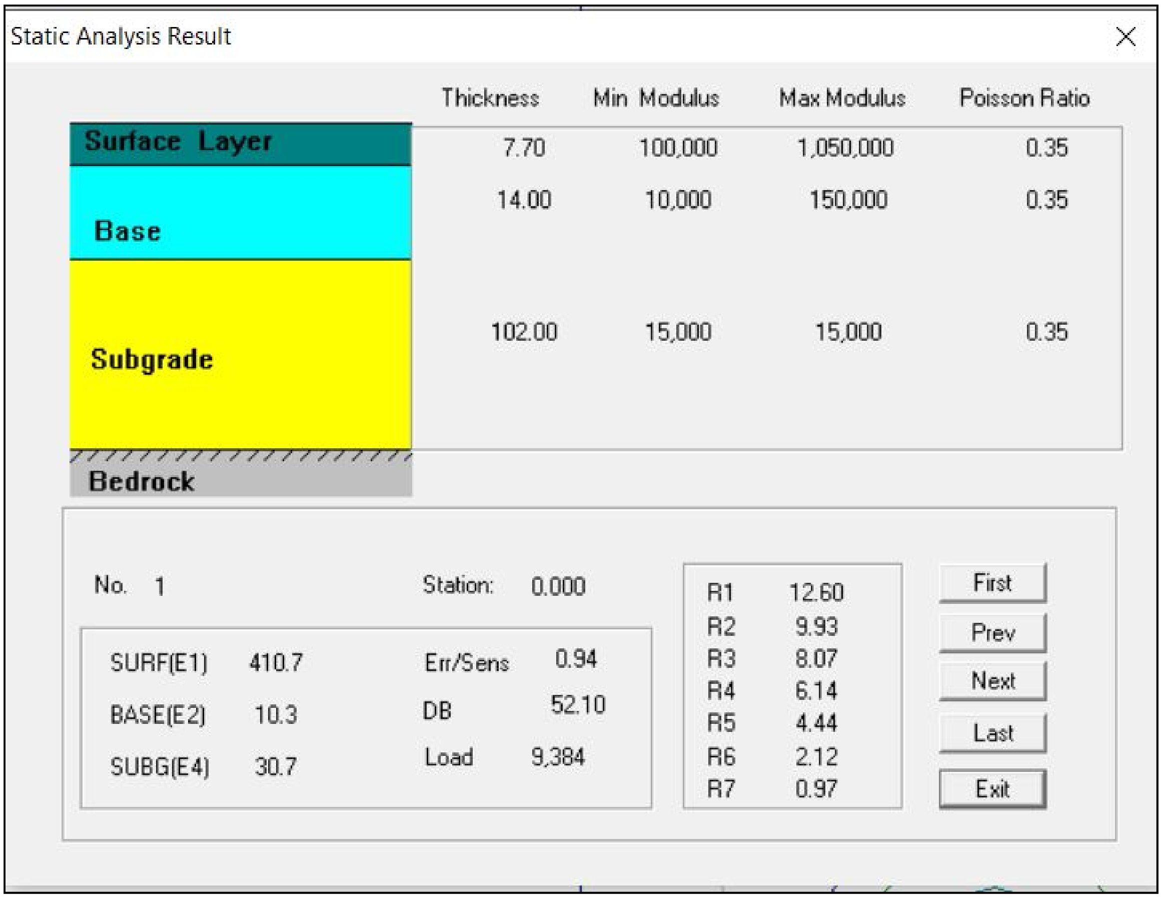

Figure 3.4 Static backcalculation MODULUS result screen in DBSID program

As the DBSID program performs the dynamic backcalculation based on the iterative process, the iteration will repeat until the iteration times larger than the maximum iteration number (program sets it to 40). It means that for each station, the iteration process is implemented for 40 times, for example in Washington test section that we have 21 stations of the FWD test, 840 iterations have been performed to find the layer modulus. The DBSID program will select the best result from each iteration result. The range and limit value are determined by the static MODULUS result, read from ASC file obtained by MODULUS software.

3.5.1.1 Iteration Process

After inputting the needed parameters, the iteration process begins. Figure 3.5 shows the iteration plot screens. Because only four squares are available for display time history comparison, when the iteration number is larger than four, the latest four are always displayed. When the convergence conditions are satisfied, the iteration processing will be ended, and the result of the last iteration will be the final result for this station. If the input parameters are far from the real value or the initial and the parameters range are not set correctly, the iteration is never ended by the satisfied convergence conditions until the iteration number or loop number is larger than 40. In this case, the DBSID program automatically selects the best result within all 40 results by the smallest root error between tested and calculated deflection time history. When one station iteration processing is finished, next station will begin until all the stations are ended, the DBSID will exit and the backcalculation result is stored in the result file (Liu, 2002).

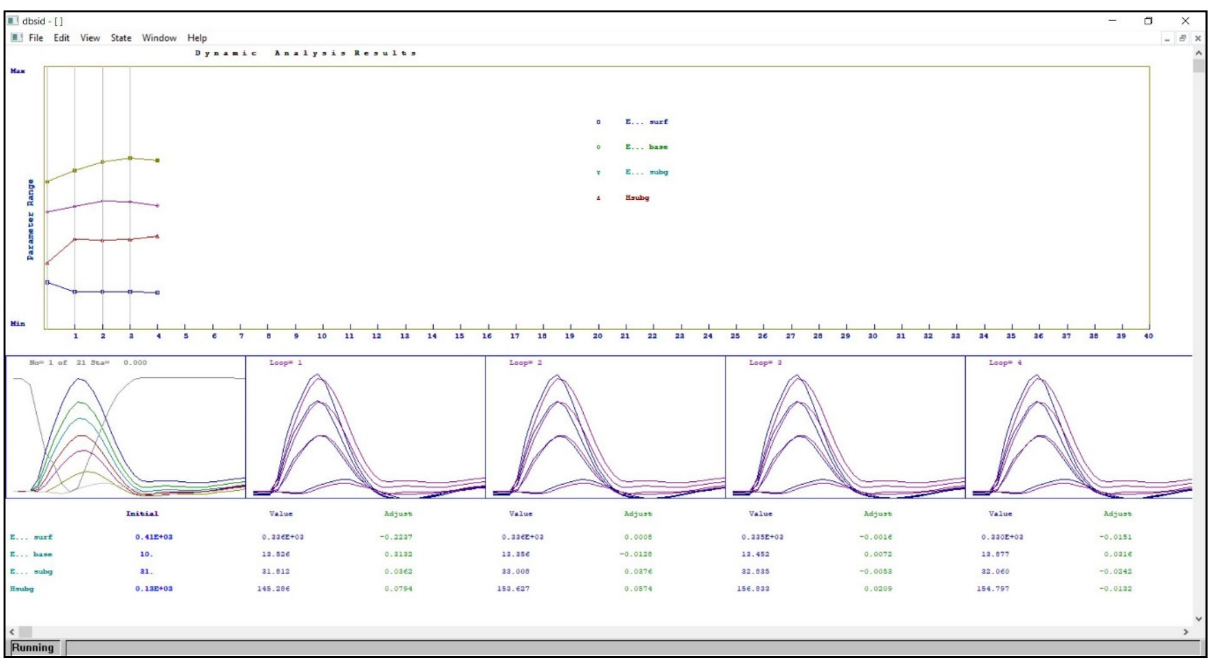

Figure 3.5 DBSID iteration processing

3.6 Statistical Analysis

In this research, to be able to make a comparison between our data, some statistical tests and analysis including correlation and T-test are conducted. The following sections describe these tests and in the next chapter, the results and interpretation of the results are performed.

3.6.1 Correlation

Correlation means association; more precisely, it is a quantitative measure of the degree to which two variables are related. Three probable outcomes of a correlational analysis are listed below (McLeod, 2018):

- A positive correlation exists when two variables move in the same direction. Thus, when one variable increases as the other variable increases, or one variable decreases while the other decreases.
- A negative correlation exists when an increase in one measure is accompanied by a drop in the other.
- When there is no association between two variables, there is zero correlation.

3.6.2 Paired Sample T-Test

There are many statistical techniques to conduct the comparison between various data. One of these techniques is conducting a T-test. A T-test is a type of inferential statistic used to determine if there is a significant difference between the means of two groups, which may be related in certain features (Hayes, 2022).

The paired sample T-test is a statistical test that is used to evaluate if the mean difference between two sets of observations is equal to zero. Each subject or entity is measured twice in a paired sample T-test, resulting in pairs of observations. The paired sample T-test is frequently used in case-control studies and repeated-measures designs ("Paired Sample T-Test, 2022").

This type of T-test is very appropriate to our study since a comparison between two methods (static and dynamic backcalculation), carried out on the same test section, is required. In this study, to perform the T-test on the data, the SPSS 26 software has been utilized.

3.6.2.1 Hypotheses

As is the case with many statistical procedures, the paired sample T-test has two competing hypotheses, the null and the alternative. The null hypothesis states that the true mean difference between pairs of samples is equal to zero. The alternative hypothesis, on the other hand, assumes that the true mean difference between the paired samples is greater than zero. The paired sample T-test hypotheses are formally defined below ("Paired Sample T-Test, 2022"):

• The null hypothesis (H_0) assumes that the true mean difference is equal to zero.

• The alternative hypothesis (H_1) assumes that the true mean difference is not equal to zero.

3.6.2.2 Normality

Numerous methods exist for testing the assumption of normality, but the simplest is to visually inspect the data using a tool such as a histogram. Given that real-world data are almost never perfectly normal, this assumption can be considered reasonable if the shape appears to be roughly symmetrical and bell-shaped ("Paired Sample T-Test, 2022"). In general, as long as the sample is based on 30 or more observations, the sampling distribution of the mean can be safely assumed to be normal (Mordkoff, 2016).

3.6.2.3 Interpretation

The P-value is used to determine statistical significance. The P-value indicates the likelihood of observing the test results if the null hypothesis is correct. The smaller the P-value, the less likely it is that a result similar to the one observed would occur if the null hypothesis were true. Thus, a low P-value indicates that the null hypothesis has less support. The P-value is typically set to 0.1 or less. This equates to a 10% (or less) probability of obtaining the observed result if the null hypothesis is true ("Paired Sample T-Test, 2022").

3.7 Data Collection

In this study, a lot of effort has been made to collect data as well as to access the software. Hundreds of researchers and scientists have been contacted from all over the world, and this has taken us a long time. The table-A IV-1 in Appendix IV lists some of the people and organizations that have been contacted to collect the data and software required. I would like to thank all these people and organizations. My special thanks go to ltppinfo@dot.gov to help me in the way of providing some portions of my data. To find the related test sections to this research, all the 50 states in the U.S. and all the provinces in Canada were investigated and finally, 10 appropriate test sections were chosen to come into the analysis. To establish a more confident comparison, we limited all the test sections to flexible pavements consisting of three layers of HMA at the top and a base layer and subgrade at the bottom. Layers thickness information was also required. IRI data should also be included in all of the test sections. This investigation and searching for data took a lot of time, since the LTPP database was so large. As mentioned earlier, our data to perform backcalculation have been obtained from the LTPP database; the following section describes the utilizing of this database more.

3.7.1 Long-Term Pavement Performance

It can be seen from the previous academic studies that different researchers have published a large number of papers and studies with using of LTPP database, showing the importance, prevalence and efficiency of this database. The LTPP database was utilized in this study because it is a comprehensive database that has a lot of information about pavements across the United States and Canada from the 1980s until now and is free and easily reachable. Moreover, finding the test sections that have all the data needed to perform static and dynamic backcalculation, as well as IRI data in the same test section, made it difficult for us to find the related data. Following that, being the FWD raw file in the time history format that is needed to perform dynamic backcalculation and being the FWD raw file in the R80 format to be read by both MODULUS and DBSID programs limits us more to find the appropriate data. To extract the correct and related data to our study, the LTPP book and LTPP user guide were read and the LTPP contact page and helping centre through email were communicated.

3.8 Introducing Raw Data

The raw data, which have been inputted into the programs, are obtained from the FWD tests executed in 10 states of the USA. The required data to do the backcalculation are:

- The number of the pavement layers and their thicknesses;
- The Poisson's ratio of each layer;
- The initial layer modulus ranges;
- The air and asphalt layer temperatures at the time of FWD testing;
- The number of the geophones and their distances from the centre of the load plate;
- The deflections obtained from the FWD geophones at the different stations;
- The load plate radius; and
- The FWD load amplitude.

The seven geophones distance from the centre of the load cell are 0, 8, 12, 18, 24, 36 and 60 inches. The first geophone is located at the centre of the load. For each drop, the height of the hammer is different, so the load amplitude that is transferred to the pavement is different. These data have been employed in this research as the inputs of the MODULUS software and DBSID program. The radius of the loading plate of the FWD devices that have been used in this study is 15 cm. The number of layers in all the tested sections in this study are 3 layers; surface layer, base layer, and the subgrade. The thickness of each layer in all the test sections in 10 states is shown in Appendix VII. The surface layer material in all the test sections is hot mixed asphalt (HMA). As an example, the pavement cross-section of the Michigan location is shown in Figure 3.6. The surface deflections are recorded from the FWD data under a certain amount of load application. These data are called deflection basin. The detailed information of the layers can be recorded from the bore log and construction history. Also, the FWD device records the pavement surface temperature at each station during the test in the site.

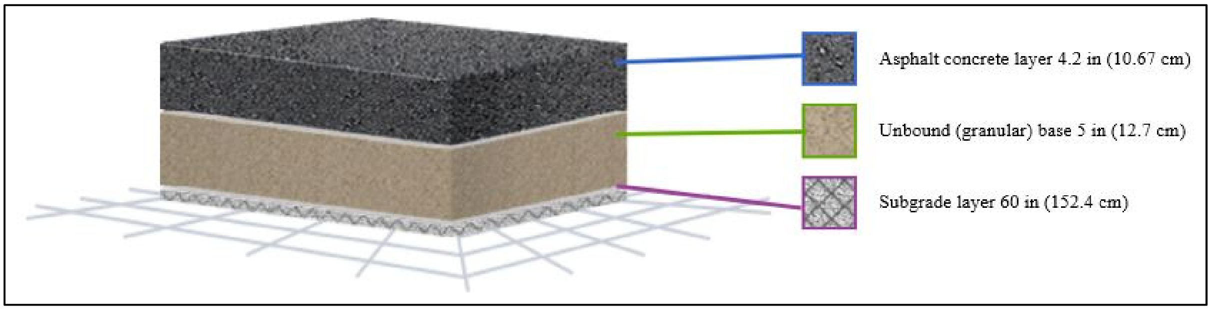

Figure 3.6 Pavement Cross-Section of the Michigan location
Taken from LTPP

As mentioned before in section 1.8.2, asphalt concrete is extremely sensitive to temperature changes. In the summer, the strength of the surface course is diminished, whereas in the winter, the strength of the surface course is increased. As a result, the temperature has a significant impact on the backcalculation process. Therefore, in this research the correlation between the layer modulus obtained from FWD and the pavement temperature will be evaluated. The temperature of all the test sections at the time of the FWD test is available in Appendix VII. Since we have various test sections which are taken from different geographical regions with different environmental conditions, it is a good idea to illustrate these locations on the map to have a more precise perspective of the locations. Figure 3.7 illustrates the test sections locations on the map.

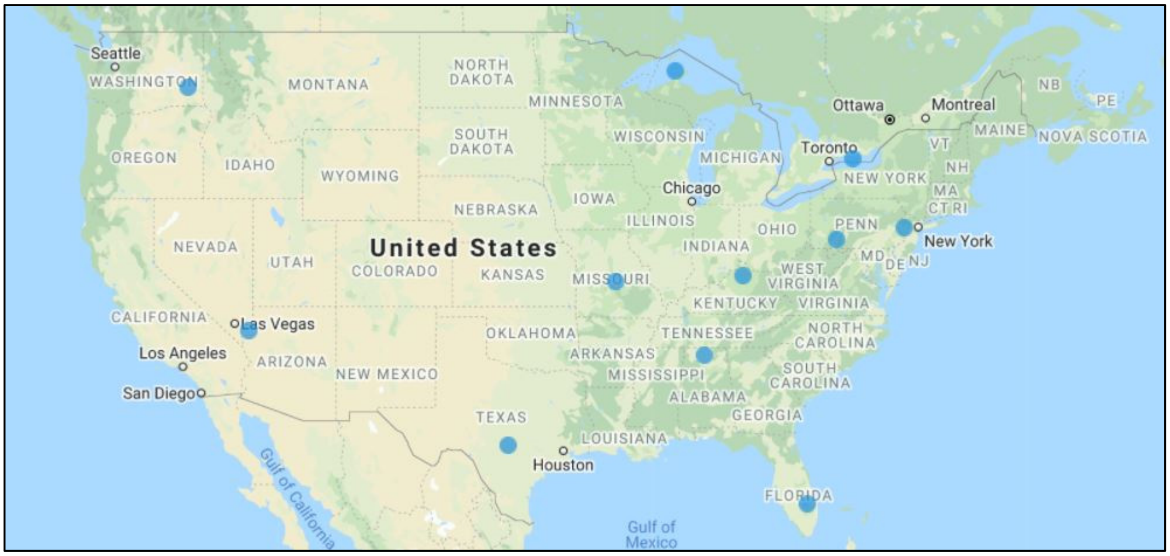

Figure 3.7 Test sections locations on the map
Taken from LTPP

The layers thicknesses and the temperature of the air and the pavement in all the test sections are presented in the Appendix VII. The surface layer thicknesses in different states are illustrated in Figure 3.8, and the average pavement temperature in the test sections are available in Figure 3.9.

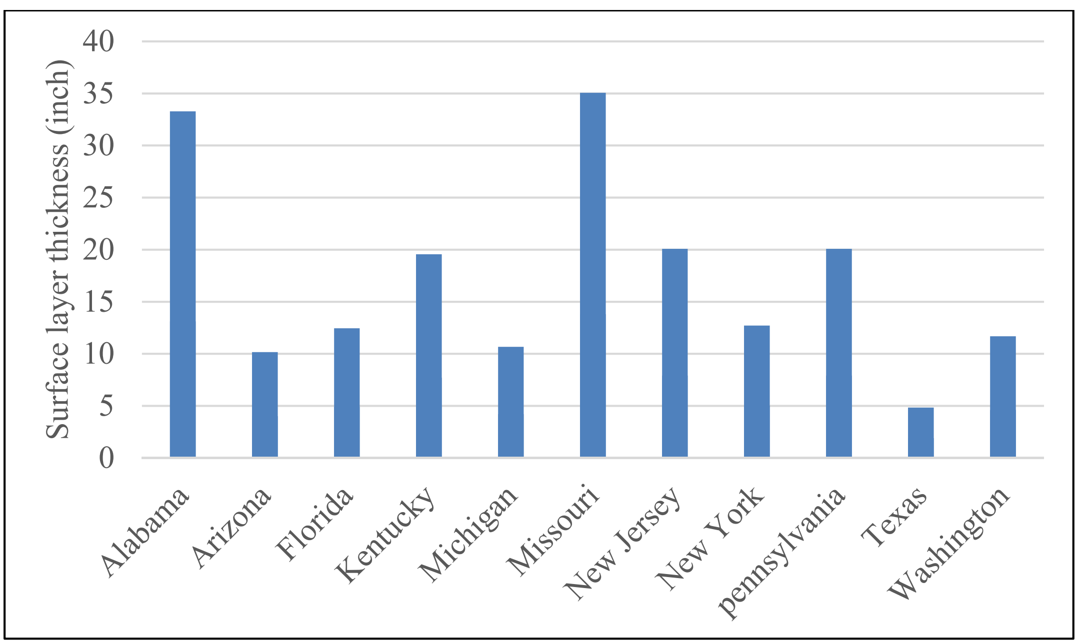

Figure 3.8 Surface layer thicknesses in different states

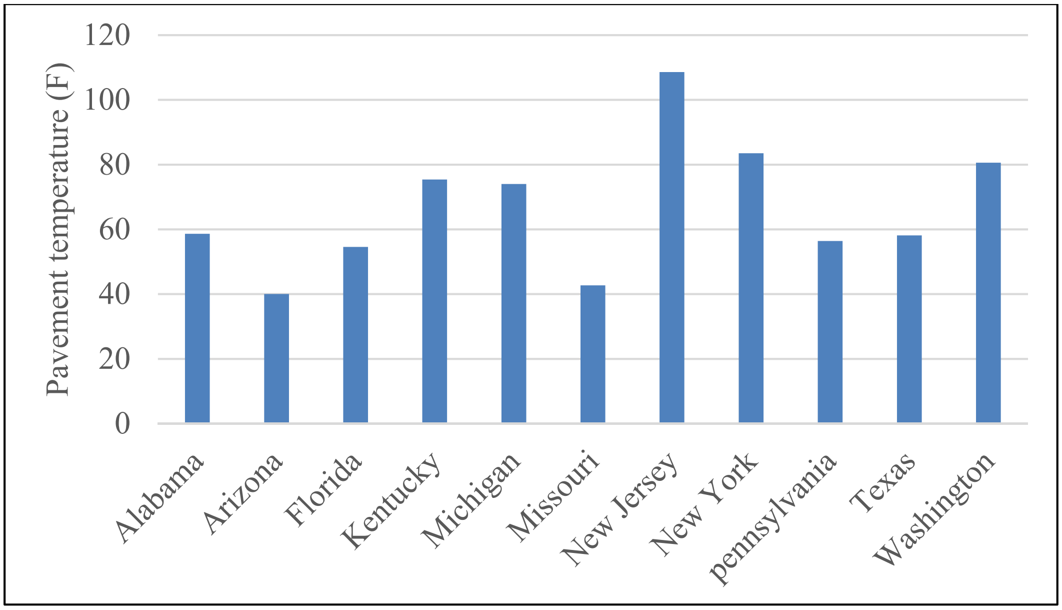

Figure 3.9 Average pavement temperature in different states

Beside the FWD data, the International Roughness Index (IRI) data of the same FWD test sections are obtained from LTPP database. The IRI is described in the following section.

3.9 International Roughness Index (IRI)

As explained earlier in Chapter 1, the International Roughness Index (IRI) has emerged as the most widely used road roughness index for analyzing and managing road networks around the world. Surface elevation data gathered by either a topographic survey or a mechanical profilometer are used to compute the IRI, which describes the longitudinal surface profile in the wheelpath. It is defined by the average rectified slope, which is a ratio of the accumulated suspension vertical motion to the distance (horizontal) travelled obtained from a mathematical model of a standard quarter car travelling at a speed of 80 km/h (Huang, 2004). The lower values of IRI means the better quality of pavement and the pavements with the less quality have the bigger IRI values. Table 3.2 represents the IRI data in Alabama test section that have been used in this study; the other IRI data for the rest of the test sections are illustrated in Appendix V. They have been collected from 10 states in the USA from the LTPP database.

They include IRI left wheel path, IRI right wheel path and mean IRI (MRI) data, which is the mean of right and left wheel paths. Figure 3.10 shows the IRI values in different test sections as a bar chart.

Table 3.2 Alabama IRI data

State Name	**Run Number**	**IRI Left Wheel Path in/mi**	**IRI Right Wheel Path in/mi**	**MRI in/mi**
Alabama	1	73.18	51.07	62.09
	2	66.65	59.88	63.23
	3	68.18	61.27	64.69
	4	63.04	62.09	62.6
	5	67.16	59.94	63.55
Mean				63.23

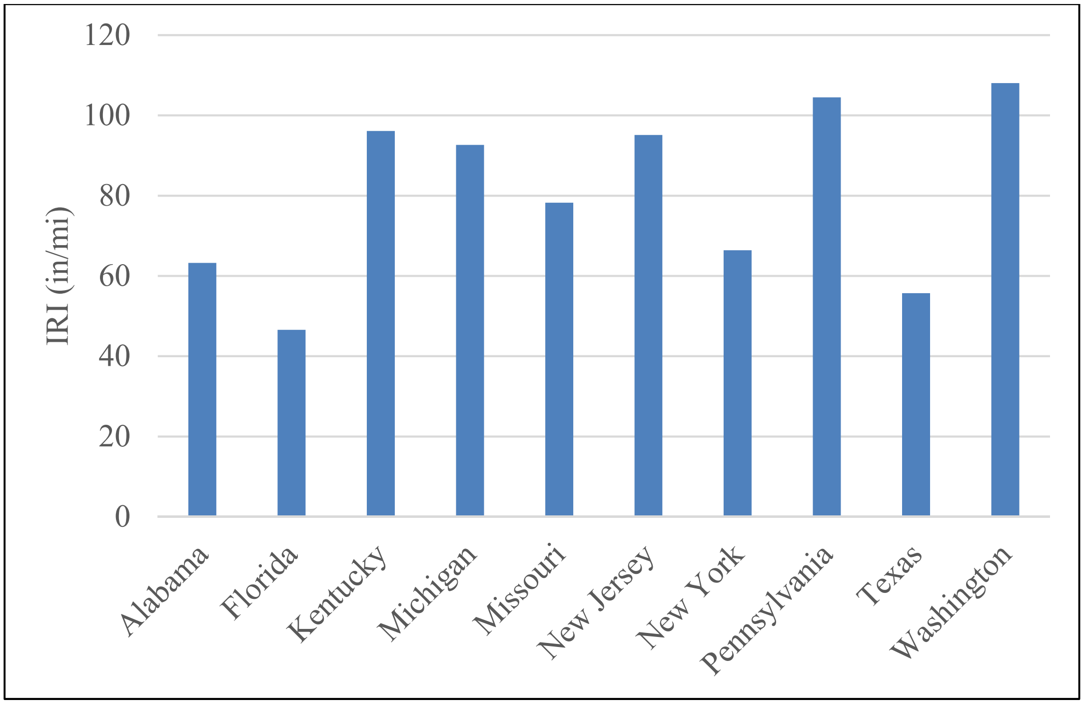

Figure 3.10 IRI values in different states

In the next chapter, the results of this research are presented. More particularly, the results of static backcalculation and dynamic backcalculation will be presented and compared; then these results will be correlated to the significant factors in a pavement, including the temperature of the pavement and the layer thickness. Consequently, the effects of these factors on the layer modulus obtained from FWD data backcalculation will be determined. Last but not the least, the existence or non-existence of a correlation between the IRI values and the layer modulus obtained from FWD data backcalculation at the same test sections will be examined.

CHAPTER 4

RESULTS

4.1 Introduction

In this chapter, the results of different types of FWD data backcalculation are presented, then the comparison of static and dynamic backcalculation by choosing the MODULUS computer program and DBSID software, will be demonstrated. Then the two methods of backcalculation (static and dynamic) are compared using a statistical method, called T-Test. T-Test is a test which is utilized in the statistics analysis to find the probable differences and similarities of two groups of data; the results of this test are presented in detail in this chapter. The effect of pavement temperature and layers thickness on the layer modulus obtained from FWD data backcalculation is carried out using correlation analysis. International Roughness Index (IRI) values of the same understudy sections are also compared with the layer modulus obtained from FWD data backcalculation using the regression analysis. At the end, to establish a more confident comparison, the adjusted layer modulus to a reference temperature ant the IRI values are compared in the pavements with the same age.

4.2 Results of Static Backcalculation Using MODULUS Program

Upon backcalculation process completion the results are displayed. The results of all the test sections are presented in Appendix VI in different tables; the results of the static backcalculation in the state of Alabama test section are presented as an example in the table 4.1. In this table, the first column shows the stations on which the FWD test is performed continuously. In fact, this test has been performed in 20 points or stations in the Alabama test section. The second column shows the amplitude of the load, applied to the pavement. The next seven columns represent the deflection measurements by the seven geophones installed on the rod of the FWD device. The next three columns show the layer modulus obtained from static backcalculation of the different layers of the pavement structure, including the surface, base and subgrade layers. The statistical parameters including mean, standard deviation, and coefficient of variation are also documented.

Table 4.1 Alabama MODULUS results

	Load	**Measured Deflection (mils)**							**Backcalculated Modulus (ksi)**		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9915	4.92	3.56	3.30	2.90	2.45	1.80	0.94	553.4	87.5	25.0
25	9669	4.39	3.48	3.17	2.76	2.39	1.75	0.94	786.1	49.1	28.7
50	9709	5.30	4.31	3.87	3.36	2.85	2.09	1.11	692.0	26.9	27.8
75	9788	4.14	3.41	3.09	2.75	2.41	1.81	1.02	967.2	48.5	27.4
100	9645	5.50	4.37	3.92	3.40	2.93	2.15	1.15	604.9	39.0	23.8
125	9554	5.09	4.15	3.87	3.47	3.00	2.27	1.22	839.7	31.0	22.3
150	9594	5.34	4.49	4.10	3.63	3.18	2.38	1.32	897.3	13.1	29.0
175	9526	6.29	5.15	4.67	4.04	3.46	2.49	1.27	597.5	18.9	23.9
200	9558	4.74	3.84	3.51	3.08	2.68	2.02	1.13	774.9	45.8	23.8
225	9526	4.52	3.66	3.28	2.89	2.53	1.93	1.09	746.4	64.5	23.1
250	9614	4.61	3.81	3.52	3.17	2.78	2.15	1.21	921.9	48.9	21.2
300	9610	3.92	3.14	2.89	2.62	2.35	1.83	1.03	932.1	105.8	21.5
325	9530	3.59	2.87	2.68	2.37	2.06	1.54	0.91	1066.2	57.6	31.0
350	9387	3.70	2.96	2.72	2.41	2.07	1.59	0.89	924.9	74.9	27.7
375	9427	4.09	3.38	3.16	2.87	2.53	1.97	1.19	1120.7	46.8	23.1
400	9554	3.89	3.38	3.13	2.84	2.54	2.02	1.23	1308.4	53.8	21.1
425	9375	3.66	3.19	3.01	2.74	2.45	1.95	1.18	1466.6	52.8	21.0
450	9411	3.73	3.07	2.86	2.61	2.32	1.84	1.17	1109.2	91.4	21.2
475	9431	4.00	3.30	3.07	2.75	2.41	1.87	1.11	1042.3	56.1	23.8
500	9546	4.00	2.93	2.73	2.46	2.19	1.73	1.05	703.7	150.0	21.8
Mean		4.47	3.62	3.33	2.96	2.58	1.96	1.11	902.8	58.1	24.4
Std.Dev		0.74	0.61	0.53	0.44	0.36	0.25	0.12	237.4	31.8	3.1
Var Coeff (%)		16.56	16.73	15.85	14.79	14.05	12.55	11.11	26.3	54.7	12.7
		Adjusted Mean Modulus (ksi)							848.9	48	22.9

4.3 Results of Dynamic Backcalculation Using DBSID Program

In this section, the results of dynamic backcalculation obtained from the DBSID program are presented. These results are from the same test sections in 10 states, including Alabama, Florida, Kentucky, Michigan, Missouri, New Jersey, New York, Pennsylvania, Texas and Washington, which have previously been used for performing the static backcalculation. Therefore, the inputs in both programs remain the same, while the outputs may be different. In Appendix VII, different tables show the results of the dynamic backcalculation in the various test sections and the results of dynamic backcalculation in the test section in Kentucky are presented as an example in the table 4.2. In this table, the first column shows the State name and the second column shows the station number, which was explained in the previous section. The third column shows the surface layer modulus which is obtained from dynamic backcalculation using the DBSID program. The fourth and the fifth columns illustrate the temperature of the pavement and air at the time of the FWD test. The last column shows the thickness of different layers of the pavement structure, which are the surface, base and subgrade layers. The statistical parameters such as mean, standard deviation and the coefficient of variation have been documented at the bottom of the table. The structure of the tables that are in Appendix VII is the same as the table 4.2.

Table 4.2 Kentucky DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
Kentucky	1(0.000)	330.30	66.2	60.8	Surface=7.70 Base=14.00 Subgrade=102.00
	2(25.000)	354.46	68.0	62.6	
	3(50.000)	287.87	68.0	62.6	
	4(75.000)	239.09	68.0	62.6	
	5(100.000)	260.83	69.8	62.6	
	6(125.000)	241.67	69.8	62.6	
	7(150.000)	279.70	71.6	64.4	
	8(175.000)	390.64	75.2	64.4	
	9(200.000)	390.97	75.2	62.6	
	10(225.000)	244.79	75.2	66.2	
	11(250.000)	255.25	75.2	64.4	
	12(275.000)	273.55	77.0	64.4	
	13(300.000)	390.18	77.0	66.2	
	14(325.000)	349.25	80.6	64.4	
	15(350.000)	318.10	78.8	66.2	
	16(375.000)	314.80	78.8	66.2	
	17(400.000)	340.44	82.4	66.2	
	18(425.000)	321.47	82.4	64.4	
	19(450.000)	303.79	82.4	64.4	
	20(475.000)	342.14	80.6	66.2	
	21(500.000)	303.29	80.6	64.4	
Mean		311.07	75.4	64.2	
Std Dev		48.9	5.4	1.6	
Var Coeff (%)		15.71	7.16	2.49	

4.4 Static and Dynamic Backcalculation Results Comparison

In this section, the static backcalculated layer modulus obtained from MODULUS program and dynamic backcalculated layer modulus obtained from DBSID program collected from 10 different test sections are compared and analyzed.

According to the tables 4.1 and 4.2 and all the other 18 tables in Appendix VI and Appendix VII, coefficients of variation (CV), which is computed by dividing the standard deviation by the mean value, for the predicted modulus of the MODULUS program are lower than that of the DBSID program in the most test sections. In order to be able to have the results of both static and dynamic backcalculated layer modulus together in one place to be capable of comparing them visually, the Figures 4.1 to 4.10 have been drawn. Figures 4.1 to 4.10 show the modulus of the surface layer, backcalculated from the MODULUS and the DBSID programs in different stations; each point shows the backcalculated layer modulus in a station. The blue colour represents the MODULUS program results and the red colour indicates the DBSID ones. More details about the Figures 4.1 to 4.10 are provided at the end of these figures.

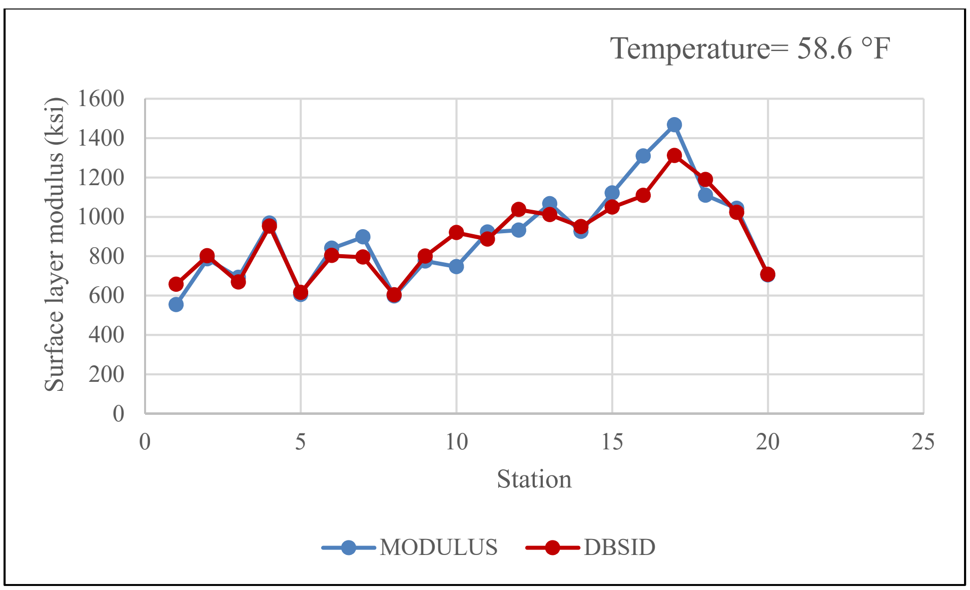

Figure 4.1 Surface layer modulus comparison using MODULUS and DBSID in Alabama

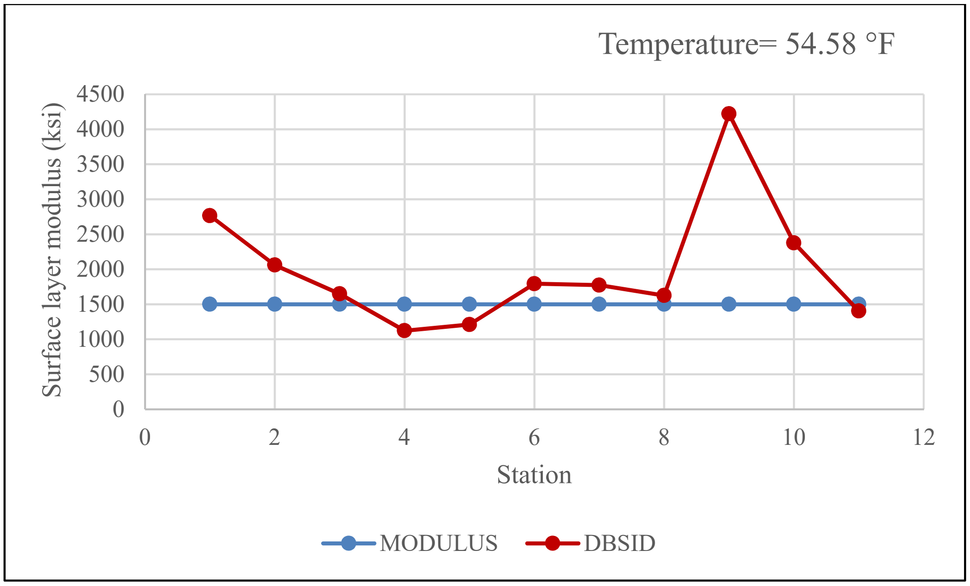

Figure 4.2 Surface layer modulus comparison using MODULUS and DBSID in Florida

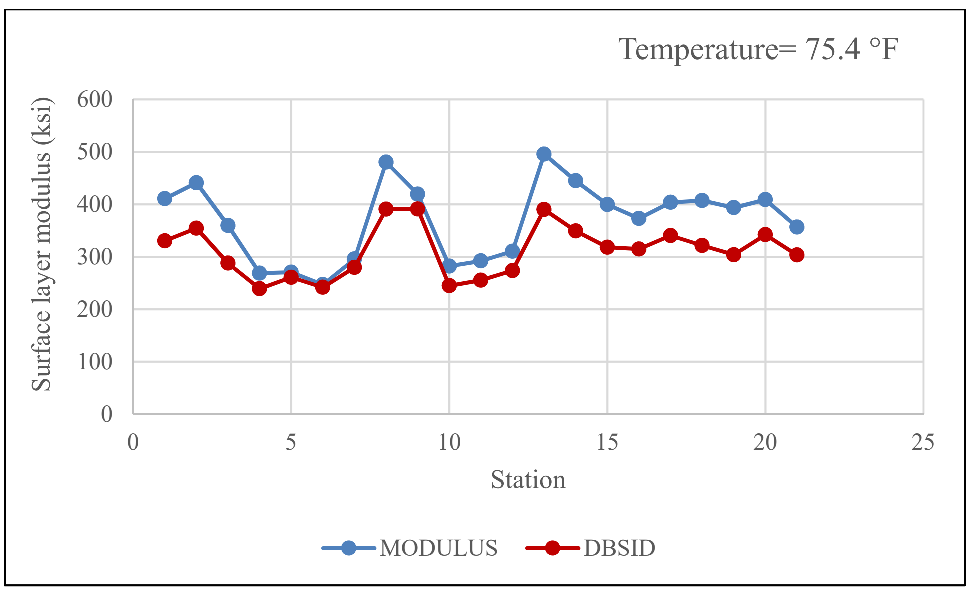

Figure 4.3 Surface layer modulus comparison using MODULUS and DBSID in Kentucky

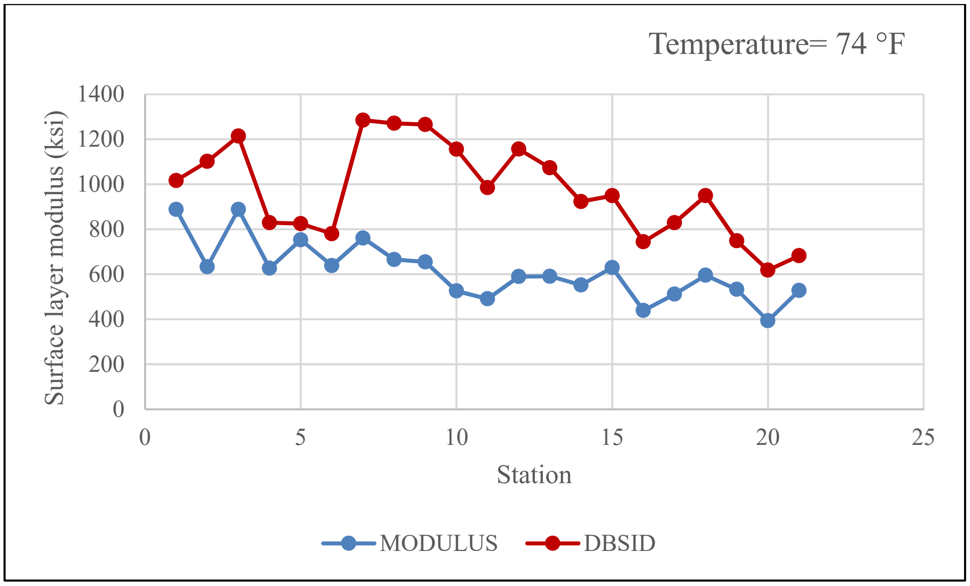

Figure 4.4 Surface layer modulus comparison using MODULUS and DBSID in Michigan

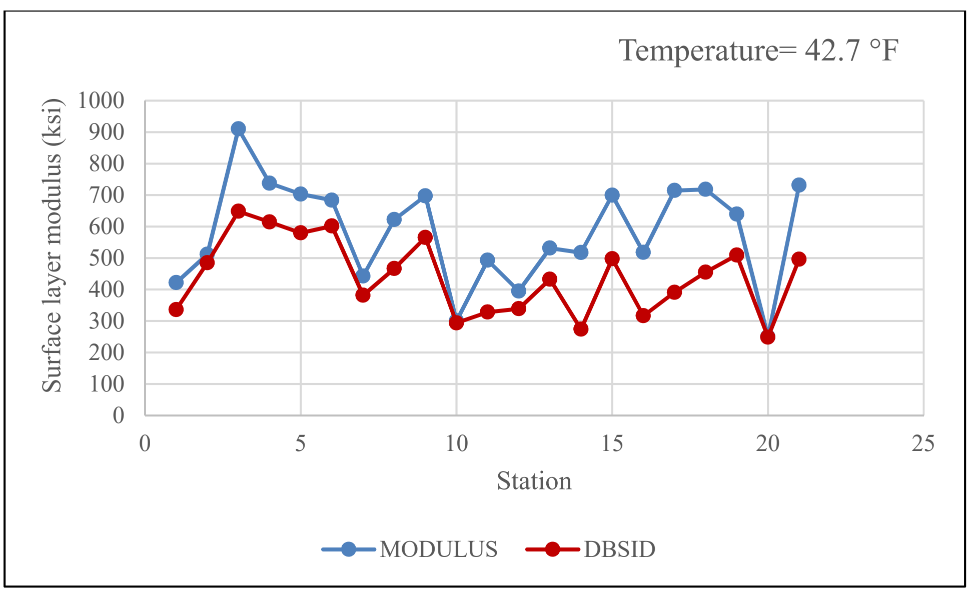

Figure 4.5 Surface layer modulus comparison using MODULUS and DBSID in Missouri

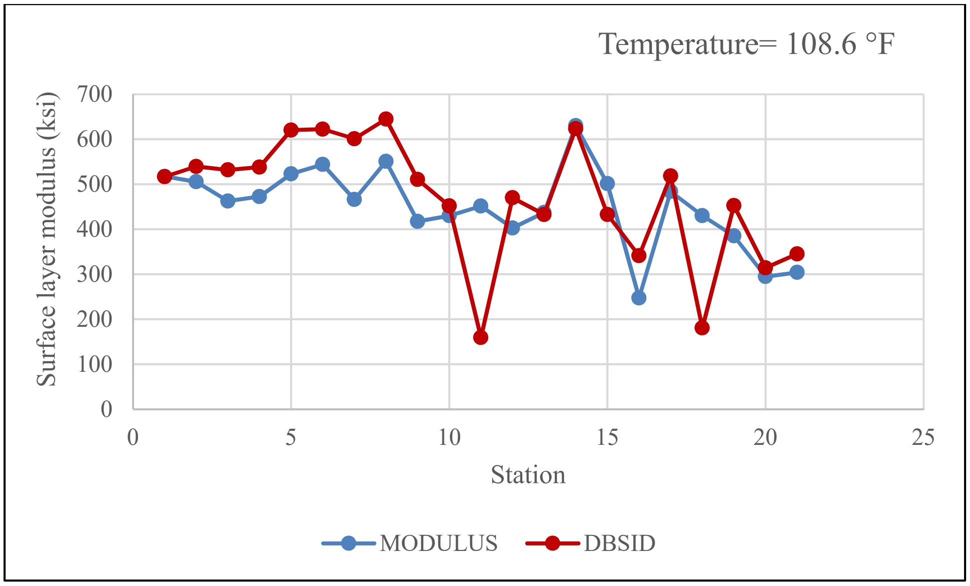

Figure 4.6 Surface layer modulus comparison using MODULUS and DBSID in New Jersey

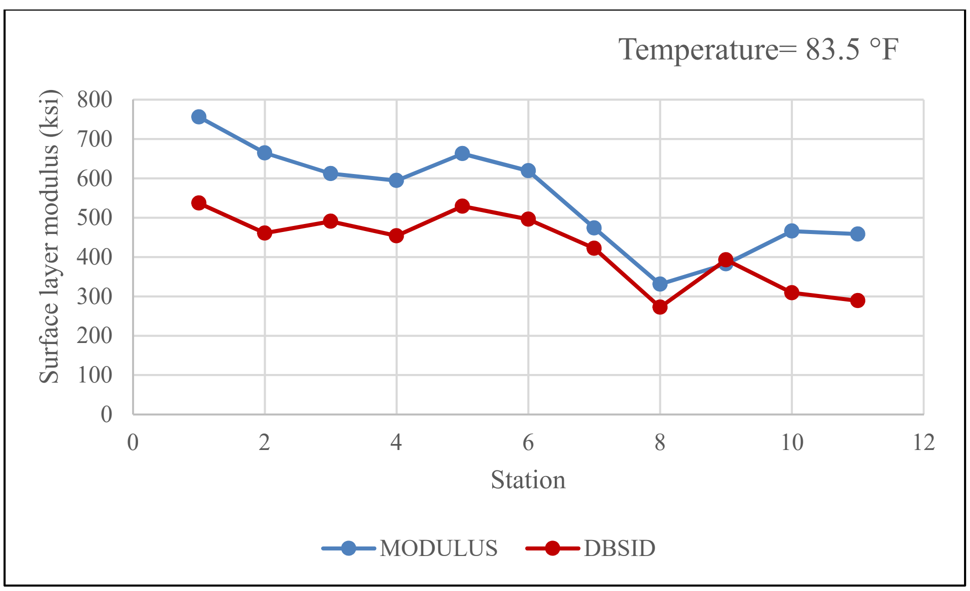

Figure 4.7 Surface layer modulus comparison using MODULUS and DBSID in New York

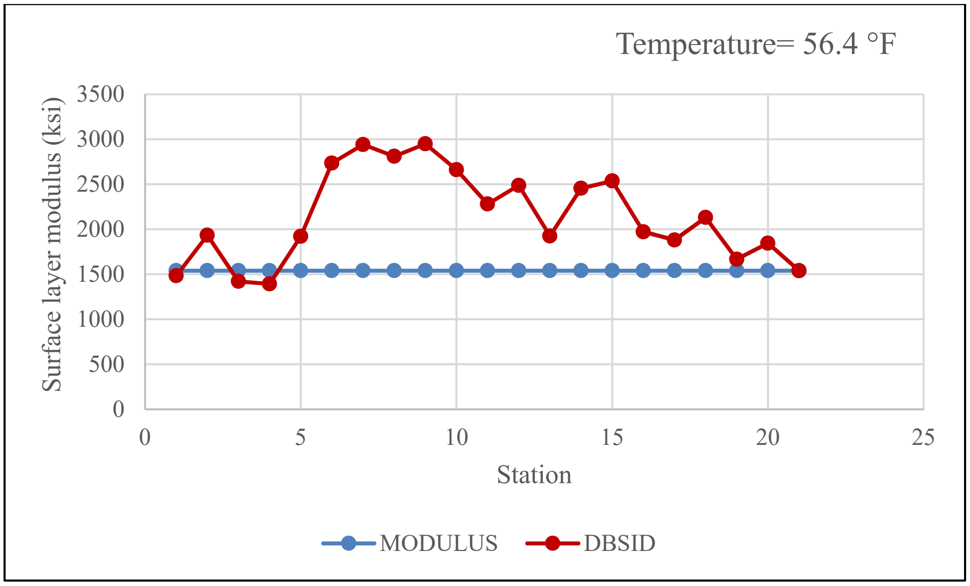

Figure 4.8 Surface layer modulus comparison using MODULUS and DBSID in Pennsylvania

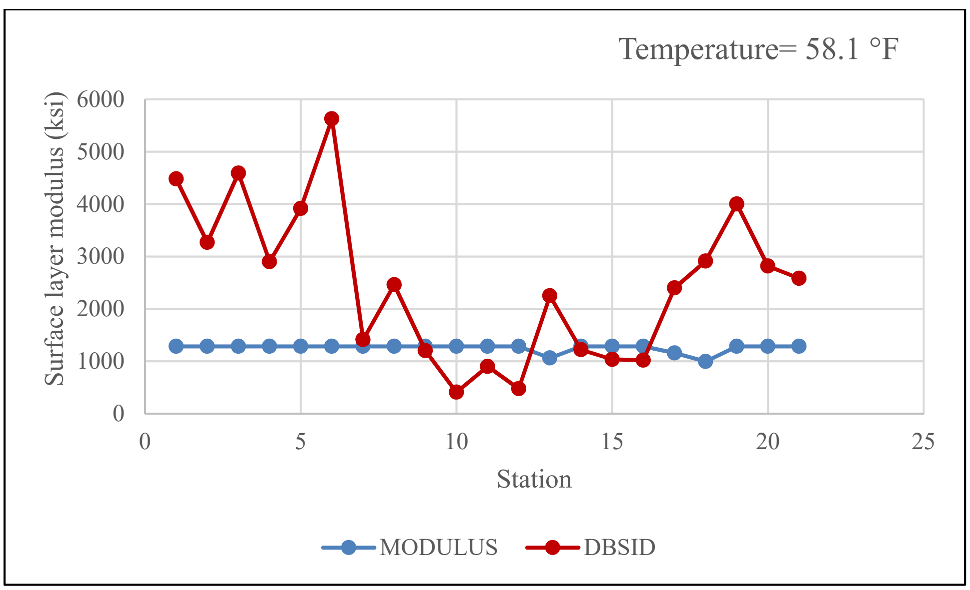

Figure 4.9 Surface layer modulus comparison using MODULUS and DBSID in Texas

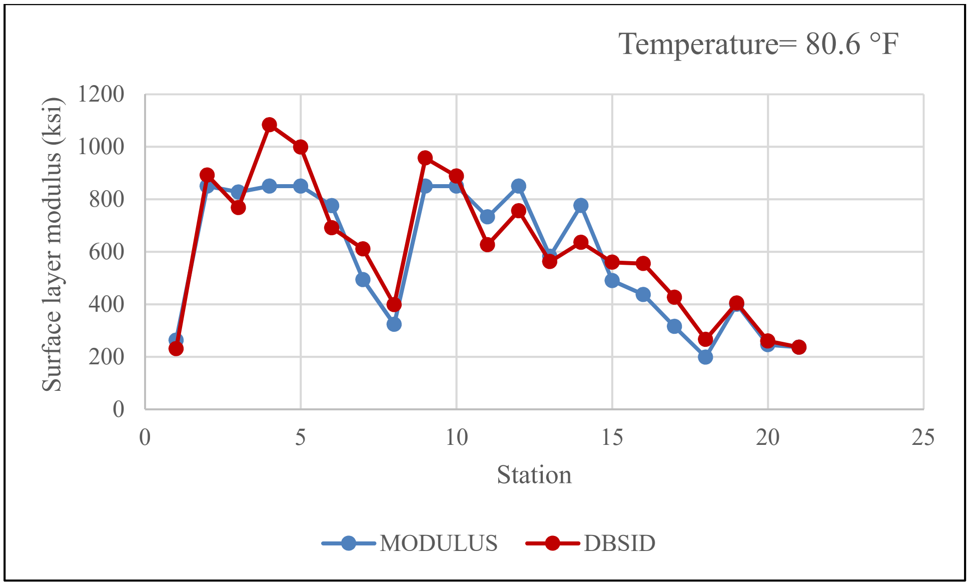

Figure 4.10 Surface layer modulus comparison using MODULUS and DBSID in Washington

As shown in these Figures, in Alabama, Kentucky, Michigan, Missouri, New Jersey, New York, and Washington test sections, the FWD layer modulus values obtained from both programs are close to each other and the trend of the lines are very similar, and a good consistency and similarity is observed; the precise statistical analysis of this assertion will be provided in the following sections. The difference observed in the results of some stations is due to the use of different methods by the programs to obtain the layer modulus. As mentioned earlier, the MODULUS is a static backcalculation software that uses the optimization method for backcalculation and the DBSID is a dynamic backcalculation software utilizes the iterative method to do backcalculation.

In Florida, and Pennsylvania, inputting the initial range of moduli into the MODULUS program does not allow the program to exceed the maximum value and the program shows that maximum value in every station and the line seems constant, while the DBSID program that does not have this limitation, shows different modulus values in every station. In order to be able to have all the backcalculated layer modulus in a single figure, a bar chart is illustrated in the Figure 4.11. This Figure shows the average surface layer modulus obtained from MODULUS and DBSID in different test sections.

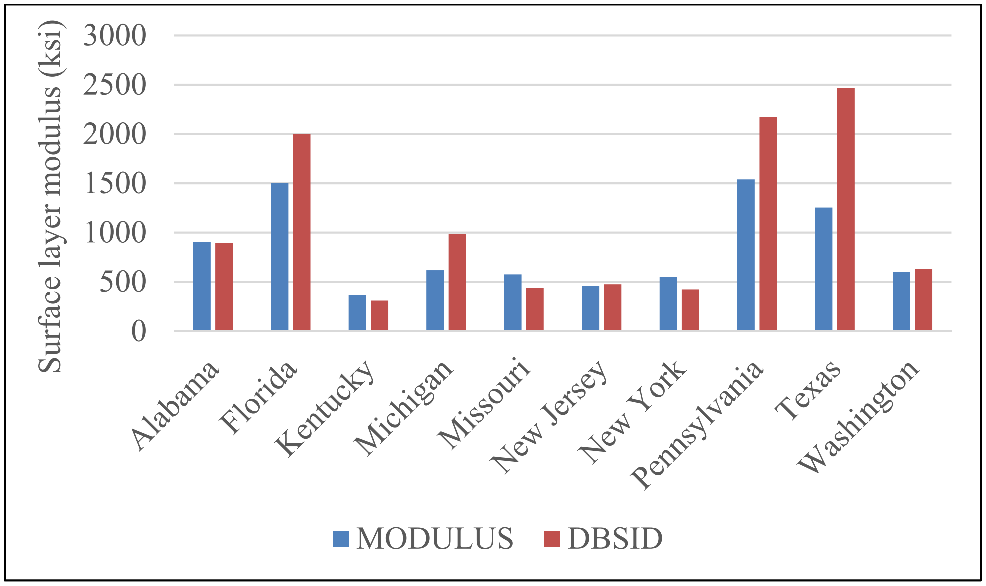

Figure 4.11 Average surface layer modulus obtained from MODULUS and DBSID in different states

As shown in the Figure 4.11, the average modulus values obtained from scattered values of Figure 4.1 to Figure 4.10, backcalculated from both programs have been compared by a bar chart. The blue colour represents the backcalculated layer modulus performed by the MODULUS program and the red colour describes the DBSID program backcalculated layer modulus values. In all the test sections except Florida and Pennsylvania, the modulus changes in consecutive stations. Florida static backcalculated layer modulus values is 1500 ksi in all the stations and the static backcalculated layer modulus in Pennsylvania test section remains at 1540 ksi, it is due to reaching the maximum allowable modulus, which was set in the initial range of moduli when entering the program inputs. As shown in the Figure 4.11, in most test sections, the average modulus value of the surface layer obtained from both programs show good similarity. Due to the fact that each backcalculation software produces different results, we cannot refer to the backcalculation results as unique. You can have mathematically correct backcalculated results that do not make practical sense. However, the answers are practical and make sense in practice, based on our results.

4.5 Correlation Between Static and Dynamic Backcalculated Layer Modulus

Correlation indicates the amount and direction of a linear relationship between two variables that varies between 1 and -1. Two variables may be related, but this relationship is not linear; thus, if the correlation is zero, the two variables may have a nonlinear relationship or no relationship at all. The closer the correlation coefficient is to 1 and -1, the stronger the linear correlation. The positive sign indicates a direct relationship, and the negative sign indicates an inverse relationship (Berman, 2016). In this section, the existence of a relationship between the layer modulus obtained from the two methods of backcalculation (static and dynamic) on the test sections in Alabama, Kentucky, Michigan, Missouri, New Jersey, New York and Washington is investigated. The test sections in Florida, Pennsylvania and Texas were not examined due to uniformity in the MODULUS software data. These results have been obtained from the SPSS 26 software and is presented in the table 4.3.

Table 4.3 Correlation between static and dynamic backcalculated layer modulus

Test Section	Variables	N	Correlation Coefficient	P-value	Result
Alabama	Layer modulus obtained from 2 programs	20	0.937	0.001>	Significant
Kentucky	Layer modulus obtained from 2 programs	21	0.952	0.001>	Significant
Michigan	Layer modulus obtained from 2 programs	21	0.535	0.012	Significant
Missouri	Layer modulus obtained from 2 programs	21	0.842	0.001>	Significant
New Jersey	Layer modulus obtained from 2 programs	21	0.628	0.002	Significant
New York	Layer modulus obtained from 2 programs	11	0.872	0.001>	Significant
Washington	Layer modulus obtained from 2 programs	21	0.932	0.001>	Significant

In the table 4.3, the first column shows the test section names and the second column represent the two variables which are the static and dynamic backcalculated modulus of the surface layer obtained from MODULUS software and DBSID program. The third column shows the number of stations in each test section, on which the FWD test was performed and subsequently the modulus in that station was backcalculated. The next column shows the coefficient of correlation values between the static and dynamic backcalculated modulus of the surface layer in different station in each test section. As can be seen, all values of the correlation coefficient are positive and high, so it can be concluded that these two variables have direct relationship to each other and move in the same direction and with increasing in the values of static backcalculated layer modulus, the dynamic backcalculated layer modulus increases. The next column shows the P-values in different test sections; The P-value is the probability that the null hypothesis is true. Our two hypotheses are presented as follows:

- The null hypothesis (H_0) states that there is no correlation between two variables (correlation coefficient (ρ) is zero).
- The alternative hypothesis (H_1) states that there is a correlation between two variables (correlation coefficient (ρ) is not zero).

According to this table, all P-values obtained are less than the error level of 0.1, so it is concluded that the correlations are significant and there is a linear relationship between the variables. The result column is based on the comparison of P-value with the error level of 0.1, so that if the P-value is less than the error level of 0.1, the hypothesis of no correlation is rejected. Finally, it can be said that there is a 90% probability of significant positive correlations between the static and dynamic backcalculated modulus of surface layer since the error level was set at 0.1.

In order to compare two methods of backcalculation (static and dynamic) using a statistical method, a paired sample T-Test is performed. As mentioned earlier, the T-Test is a test which is utilized in the statistics analysis to find the probable differences and similarities of two groups of data; the results of this test is presented in detail in the following section.

4.6 Paired Sample T-Test

As explained earlier in chapter 3, the paired sample T-test is used to compare the mean of two paired samples. In the paired sample T-test, we have two hypotheses, the null and the alternative.

- The null hypothesis (H_0) states that the true mean difference between the static backcalculated layer modulus values and the dynamic backcalculated layer modulus values is zero.
- The alternative hypothesis (H_1) states that the true mean difference between the static

backcalculated layer modulus values and the dynamic backcalculated layer modulus values is greater than zero.

If the P-value of this test exceeds the error level, the hypothesis of equality of the mean of the two samples is not rejected. If the paired data volume is more than 30, there is no need to check the assumption of normalization (Mordkoff, 2016). The table 4.4 represents the results of the paired sample T-test between the static and dynamic backcalculated layer modulus values. This test was performed by the SPSS 26 software.

Table 4.4 Paired sample T-test results

Paired Sample T-test	**t**	**df**	**P-value**	**Result**
Layer modulus obtained from MODULUS & DBSID software (without Florida, Pennsylvania and Texas test-sections)	-1.269	135	0.207	Equal
Layer modulus obtained from MODULUS & DBSID software	-4.849	188	<0.001	Isn't equal

Based on the table 4.4, the P-value of the T-test is obtained by removing the Florida, Pennsylvania and Texas test-sections equals to 0.207 and is more than the error level of 0.1, which means the hypothesis of equality of the mean of the two samples is not rejected, which can be concluded that the average of two variables of a layer modulus obtained from MODULUS software and DBSID software are not significantly different from each other. This result agrees with the findings by the previous studies (Ameri et al., 2009), where the study concludes that the dynamic backcalculated modulus of the surface layer is often equal to the static backcalculated modulus of the surface layer. The test sections in Florida, Pennsylvania and Texas were not examined due to uniformity in the MODULUS software data, which may be due to reaching to the maximum allowable modulus which was set in the initial range of moduli when entering the program inputs. In the case of including all roads, the P-value of T-test was less than the error level of 0.1, which means the hypothesis of equality of the mean of the two samples is rejected, which can be concluded that the average of the two variables of a layer modulus obtained from MODULUS software and DBSID software are different from each other.

In the table above, t is the test statistic (a function of the difference in observations) obtained from Equation 4.1.

$$t = \frac{m_d}{s_d/\sqrt{n}} \tag{4.1}$$

Where m_d is the average difference in layer modulus of the two software, s_d is the standard deviation and n is the number of differences; df or degree of freedom is the number of the samples minus one. P-value represents the minimum probability that leads to the rejection of the null hypothesis that the mean difference is zero when this hypothesis is true. The result column is also written based on a comparison of the P-value with the error level of 0.1, so that if the P-value is less than the error level of 0.1, the hypothesis that the mean difference is zero or the two means are the same, is rejected. For the asphalt layer, the difference of more than 5% can be called significant. For example, if the static backcalculated modulus is 1000 ksi and the dynamic backcalculated modulus is 950 ksi, this 50 ksi may be considered not significant.

As mentioned earlier, the effect of pavement temperature and layers thickness on the layer modulus obtained from FWD data backcalculation is performed using the Pearson correlation. The results of this effort are presented in the following section.

4.7 Correlation of Temperature, Thickness and Temperature-Thickness Multiplication with Layer Modulus

In order to investigate the linear relationship between pavement temperature, surface layer thickness and the temperature-thickness multiplication with the mean of static and dynamic backcalculated layer modulus obtained from MODULUS software and DBSID program, the correlation analysis is performed. The table 4.5 represents the correlation results. These results have been obtained from the SPSS 26 software.

Table 4.5 Correlation results

Variables	N	Correlation Coefficient	P-value	Result
Mean of static and dynamic backcalculated layer modulus & surface layer thickness	10	-0.349	0.323	Correlation is not significant
Mean of static and dynamic backcalculated layer modulus & pavement temperature	10	-0.525	0.119	Correlation is significant
Mean of static and dynamic backcalculated layer modulus & thick-temp multiplication	10	-0.589	0.073	Correlation is significant

In the table above N represents the number of test sections used in the calculations and the linear correlation coefficient (ρ) has been obtained from Equation 4.1 (Berman, 2016).

$$\rho = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \tag{4.2}$$

Where $\bar{x}$ represents the average of the first variable and $\bar{y}$ represents the average of the second variable. P-value represents the minimum probability that leads to the rejection of the hypothesis of no correlation when this hypothesis is correct. The result column is also written based on the comparison of P-value with the error level of 0.1, so that if the P-value is less than the error level of 0.1, the hypothesis of no correlation is rejected. Correlation coefficient between the mean of static and dynamic backcalculated modulus of the surface layer and the surface layer thickness is -0.349 which means there is an inverse relationship between these two variables; the P-value is 0.323 which is more than the error level of 0.1 and it means that the null hypothesis is not rejected and the correlation between these two variables is not significant.

Correlation coefficient between the mean of static and dynamic backcalculated modulus of the surface layer and the pavement temperature is -0.525 and if we want to investigate the effect of pavement temperature and the surface layer thickness, together, on the layer modulus, a multiplication of these variable can be correlated to the layer modulus. The temperature-thickness multiplier does not have a physical meaning. We defined this variable to investigate the effect of pavement temperature and the surface layer thickness, together, on the layer modulus. Therefore, a multiplication of these variables was correlated to the layer modulus. The coefficient of correlation between the mean of static and dynamic backcalculated layer modulus and the multiplication of surface layer thickness and the pavement temperature is -0.589, which means with the pavement temperature and the surface layer thickness increasing, the layer modulus values decrease. This result agrees with the findings by the previous studies (Cheng et al., 2021; Seo et al., 2013), where the study shows that the pavement temperature and the FWD layer modulus have an inverse relationship. In addition to the inverse effect of temperature on the backcalculated layer modulus, it is observed that if the surface layer thickness of the test section is low, it causes the further increases in the modulus values; on the other hand, if the surface layer is thick, it prevents further increases in the layer modulus values. The P-value is less than the error level of 0.1 and it means that the null hypothesis is rejected and the correlation between the mean of static and dynamic backcalculated layer modulus and the thickness-temperature multiplication is significant. Finally, it can be said that there is a 90% probability of significant negative correlations between the mentioned variables since the error level is set to 0.1.

4.8 Effect of Pavement Temperature and Surface Layer Thickness on Layer Modulus

To be able to investigate the effect of the pavement temperature and the surface layer thickness on the backcalculated modulus of the surface layer, a bubble chat is illustrated in the Figure 4.12, showing the three parameters relation at one single figure.

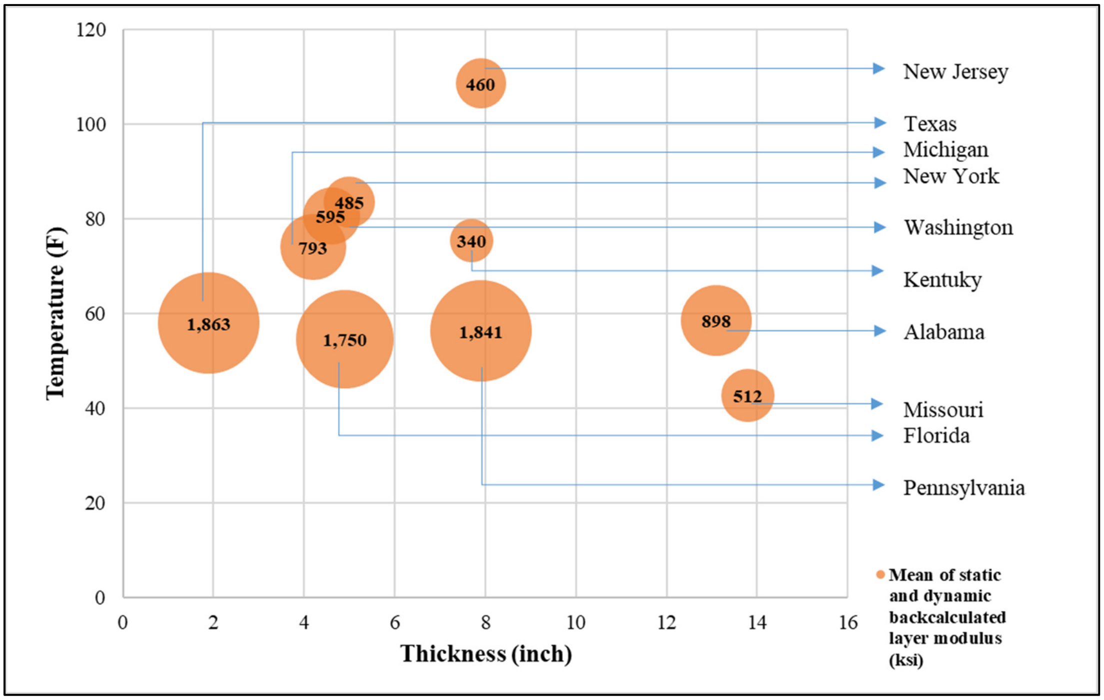

Figure 4.12 Temperature and thickness effect on the backcalculated layer modulus

In the Figure 4.12, the pavement temperature is on the vertical axis and the surface layer thickness is on the horizontal axis. The size of the bubbles indicates the mean of static and dynamic backcalculated modulus of the surface layer obtained from the MODULUS and DBSID software, so that the larger the bubble size, the higher the layer modulus obtained. As can be seen, the maximum values are related to temperatures below 60 °F and thicknesses below 8 inches. By comparing the three parameters represented in the Figure 4.12, it is apparent that the backcalculated layer modulus of the asphalt layer decreases significantly with the temperature increasing and the thicker surface layers show lower values of modulus. As for any asphalt mix, the modulus decreases with an increase of temperature since they are viscoelastic materials; this phenomenon is observed in the modulus obtained from backcalculation and helps to figure out that the modulus obtained from FWD data backcalculation have logical values and results. This result may be due to the presence of bitumen in the asphalt layer that reduces the stiffness of this layer by increasing the temperature. As the stiffness of the asphalt layer decreases, the deflections recorded by the geophones increase, and as a result, the backcalculated modulus decreases. More particularly, with the pavement temperature increasing, the layer modulus values decrease, if the surface layer thickness of the test section is low, it causes the further increases in the modulus values. On the other hand, if the surface layer is thick, it prevents further increasing in the layer modulus values. The reason that less modulus is obtained in thicker pavements is that with the FWD test in thicker pavements, more deflection values are seen in thicker pavements and as a result of more deflection, a lower modulus is obtained. The reason for bigger deflection is to notice that the subgrade and base of the system with higher thickness is low that we needed to use thicker pavement. It is not necessarily related to the quality of the material.

In Alabama and Texas test sections, for example, where the pavement temperature is about 60 degrees, the backcalculated layer modulus varies due to differences in thickness. In fact, in Alabama, with a thickness of 13.1 inches, the backcalculated layer modulus is about 900 ksi, and in Texas, with a thickness of about 2 inches, the backcalculated layer modulus is 1863 ksi. Also, In Pennsylvania and Kentucky test sections, where the surface layer thickness is near 8 inches, the backcalculated layer modulus varies due to differences in the temperature. In fact, in Pennsylvania test section, with the temperature of 56 °F, the backcalculated layer modulus is about 1850 ksi, and in Kentucky test section, with the temperature of 75 °F, the backcalculated layer modulus is about 340 ksi. By comparing the results and according to the Figure 4.12, it can be derived that the surface layer thickness can have a significant impact on the results of backcalculated layer modulus. It is also derived that the pavement temperature affects the backcalculated layer modulus significantly.

As previously stated, estimating the HMA modulus at temperatures other than testing temperature can be performed by employing temperature correction equations. To do this and have the backcalculated layer modulus at a reference temperature, the backcalculated moduli were corrected to the reference temperature of 68 °F based on the Equations 1.4 and 1.5. The results of the calculations are presented in table 4.6, which shows the adjusted moduli to the reference temperature in each test section. We can use the information of this table in the next section where we are trying to find a correlation between the layer modulus and the IRI values of the same test sections. So that we can establish a more confident comparison between the layer modulus, all at the same temperature, and the IRI values of the same test sections.

Table 4.6 Adjusted modulus to the reference temperature

Test Section	Backcalculated Modulus (ksi)	Test Temperature (⁰F)	Reference Temperature (⁰F)	Adjusted Modulus (ksi)		
				Kim et al.	Stubstad et al.	Mean
Alabama	898	59	68	654	704	679
Florida	1750	55	68	1107	1240	1173
Kentucky	340	75	68	435	412	423
Michigan	792	74	68	978	914	946
Missouri	512	43	68	212	238	225
New Jersey	459	109	68	1946	1709	1827
New York	485	83	68	823	715	769
Pennsylvania	1840	56	68	1206	1303	1254
Texas	1863	58	68	1310	1389	1350
Washington	595	81	68	941	834	887

In the table 4.6, the first column shows the names of the test sections on which the FWD test and the IRI test were performed. The second column shows the backcalculated modulus with the temperature of the time of the FWD test. The next two columns represent the test and the reference temperature, respectively. The next three columns show the adjusted modulus to the reference temperature of 68 ºF based on two temperature correction equations, introduced in the Chapter 1, and the mean value of them.

As mentioned earlier, in this study a comparison between the layer modulus obtained from FWD data backcalculation and the International Roughness Index (IRI) values of the same understudy sections is performed to find the probable correlation between functional and structural properties of the flexible pavements.

4.9 IRI Values and Layer Modulus Correlation

To be able to investigate the correlation between the backcalculated modulus of the surface layer and the IRI values of the same test section, a scatter diagram is illustrated in the Figure 4.13.

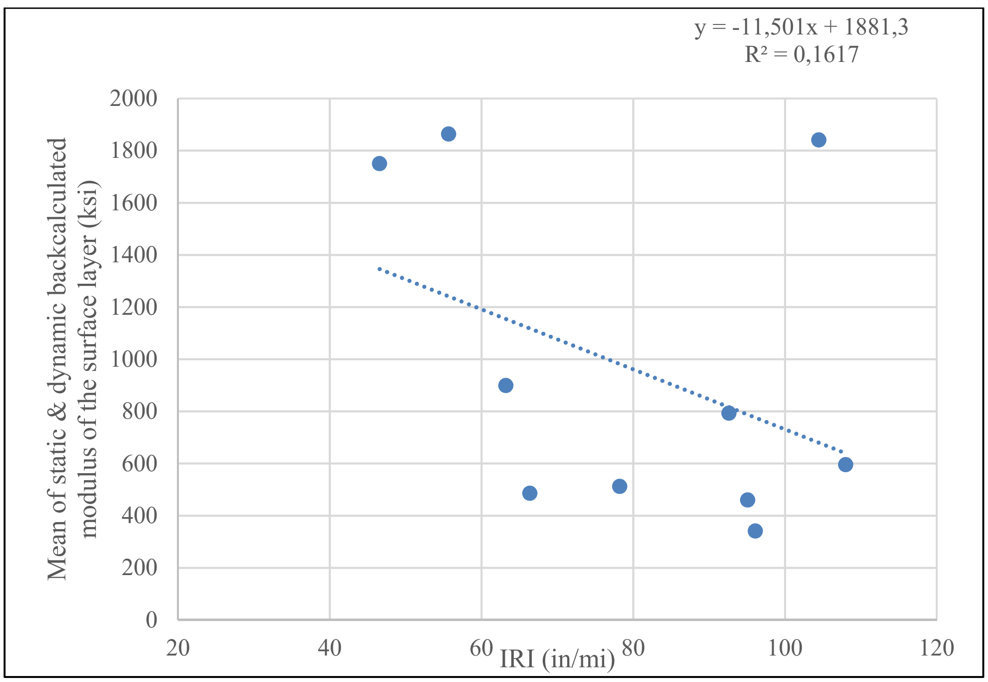

Figure 4.13 Relationship between IRI and the mean of static and dynamic backcalculated modulus

As it can be seen in Figure 4.13, the slope of the trend line is negative, which means there may be an inverse relationship between the backcalculated modulus of the surface layer and the IRI values of the same test section. The coefficient of determination, R^2, is 0.16 which is the square of the correlation coefficient between the backcalculated modulus of the surface layer and the IRI, showing not a significant linear relationship between IRI and the FWD layer modulus. This result agrees with the findings by the previous studies (Barudin et al., 2019; Noor et al., 2019), where the studies conclude that a good riding quality is not totally depending on the structural layers materials properties.

To establish a more confident comparison between the backcalculated modulus of the surface layer, and the IRI values of the same test sections, we can use the information of the tables 4.6 and 4.7, where the backcalculated modulus are adjusted based on the reference temperature of 68 ºF and the pavements with different ages are placed in distinct groups. Therefore, we can compare the backcalculated layer modulus and the IRI values of those test sections more precisely. In fact, we have added the pavement age and temperature factors to the comparison between the backcalculated modulus and the IRI values.

Table 4.7 Year of construction of different test sections

Test Section	Construction Year	Pavement Age at the Time of the Tests (Years)	Backcalculated Modulus (ksi)	Adjusted Modulus (ksi)	IRI in/mi
Alabama	1988	11	898	654	63
Florida	1995	1	1750	1107	46
Michigan	1985	5	793	978	92
Missouri	1980	10	512	212	78
New York	1994	5	485	823	66
Pennsylvania	1989	1	1841	1206	104
Texas	1976	16	1863	1350	55
Washington	1984	15	595	887	108

In the table 4.7, the first column shows the names of the test sections on which the FWD test and the IRI test were performed. The second column shows the year of construction of the different test sections and the third column shows the pavement age at the time of the FWD and IRI tests. The fourth column shows the backcalculated modulus with the temperature of the time of the FWD test. The next two columns represent the adjusted modulus to the reference temperature of 68 ^{0}F and the IRI values of the same test sections, respectively. As represented in the table 4.8, a significant relationship between the backcalculated modulus of the surface layer and the IRI values in the pavements with the same age is not observed. More precisely, in some test sections, with the layer modulus increasing the IRI values decrease and in some test sections with the layer modulus increasing, the IRI values increase as well. For instance, in Alabama and Missouri test sections, with the age of about 10 years, the adjusted layer modulus in Alabama is 654 ksi and the IRI is 63 in/mi; with decreasing of the layer modulus in Missouri test section to 212 ksi, the IRI value increases to 78 in/mi. This inverse relationship between the modulus of the surface layer and the IRI value in the pavements with the same age is observed in the other test sections like Texas and Washington test sections. However, in Florida and Pennsylvania test sections, with the age of about 1 year, the adjusted layer modulus in Florida is 1107 ksi and the IRI is 46 in/mi; with increasing of the layer modulus in Pennsylvania test section to 1206 ksi, the IRI value increases to 104 in/mi.

On this ground, a meaningful connection between the backcalculated modulus of the surface layer and the IRI values on the pavements with the same age was not found which may be due to the effects of other external factors on the pavement roughness including traffic intensity, mechanical characteristics of the granular layers, environmental conditions and so forth that should be taken into account in the further studies.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research was performed to make a comparison between the static and dynamic backcalculation performed by MODULUS program and the DBSID software, respectively, and to find the effect of the pavement temperature and the surface layer thickness on the backcalculated layer modulus. Finding the probable correlation between the functional and structural properties of the flexible pavements by employing the IRI and the layer modulus was also performed. In this regard, 10 test sections were chosen to utilize their data to perform the backcalculation with both approaches with the same inputs. The pavement properties such as the number of layers, the layers thicknesses, Poisson's ratio and the FWD test properties such as the FWD load amplitude and the geophone distances, etc. remained the same in both programs to have a more reliable comparison. Then, the effects of different parameters such as pavement temperature and the surface layer thickness on the FWD layer modulus was performed. A comparison between the FWD layer modulus obtained from both approaches and the IRI values of the same test sections was conducted. An effort to find a correlation between these two parameters (IRI and modulus) was also carried out. By comparing the backcalculated modulus obtained from these two programs results and the other mentioned parameters, the following conclusions have been derived.

- There is a significant correlation between the static and dynamic backcalculation results.
- Results of the T-test indicates that the results of static and dynamic backcalculation are significantly similar.
- In most test sections, the static and dynamic backcalculation results show a good consistency and similarity and the trend of change in different stations is almost the same.
- The MODULUS program backcalculation results become ready in less than a minute, while the DBSID program running procedure takes about 2 hours by regular PCs. Therefore, if

time is not enough, in laboratory conditions, for example, using the MODULUS program is suggested.

- In cases where there is sufficient time for analysis since in dynamic backcalculation, time history data is used for the analysis, meaning that the pavement shape change and all the deflections are recorded and inputted into the analysis (usually each curve of time history data needs 300 data points of deflection to define it), while in static backcalculation, only 1 value is used which is known as the peak value (maximum deflection), using the dynamic backcalculation is suggested.
- One of the problems in using the DBSID and MODULUS programs is that the units are in imperial units and not the SI metric units.
- A combination of the effect of the pavement temperature and the effect of the surface layer thickness on the results of the FWD layer modulus in both programs was observed. With the pavement temperature increasing, the layer modulus values decrease, if the surface layer thickness of the test section is low, it causes further increases in the modulus values. On the other hand, if the surface layer is thick, it prevents further increase in the layer modulus values.
- Although in some test sections, with modulus increasing, the IRI values decrease, no significant correlation between IRI values and the FWD layer modulus was observed. This is probably due to the impact of other factors on the pavement roughness such as traffic intensity, mechanical characteristics of the granular layers, environmental conditions and so forth. Effects of these factors on the pavement roughness prevent to identify a specific correlation between IRI values and the layer modulus.

5.2 Recommendations

Based on this study, the following recommendations and suggestions for future works are listed.

- By the recent improvements in technology, developing a new and up-to-date program to find the layer modulus is proposed. This program can be intelligent by utilizing the ANN methods and having a large amount of data of the previous FWD tests in its memory to suggest the best fit for the layer modulus.

- To find the probable correlation between the functional properties of the pavements like IRI and the structural properties like layer modulus, it is recommended to perform a study on the test sections with having the data of traffic intensity, mechanical characteristics of the granular layers, environmental conditions and so forth beside knowing the modulus of the surface layer and the pavement age and temperature to establish a more precise comparison.

APPENDIX I

A TYPICAL OF FWD FULL-TIME HISTORY DATA FILE

```
R80    13078 990224014126C336F20
700013008002-132144673.403111  6
150 0   203 305 457 610 914 1524 5.9   0     8     12    18    24    36    60
C:\FWD\DATA\                 .FWD
I-65 NB, MP 308.9
S     500F3         18 10 12458     63  50  Heights ...........................
S     261F3         18 10 13079     63  50  Heights ...........................
13394063272937210       .095
13  15  3.5 5   2   15  3.5 8
Ld 190   1.015 87.5
D1 1941  .999  1.029
D2 1942  .999  1.015
D3 1943  .998  1.021
D4 1944  .999  .9930
D5 1945  .997  1.013
D6 1946  1.001 .9960
D7 1947  1     1.027
D0 1948  .997  1.030
D0 1949  .995  1.047
D0 1950  1     1.018
JOHN BENNETT
11010600........................
2.6 2   2   1    ...............
*014126


*
................................
 10968  -10968      0   0Peak...32  0    ......
1234567890123456789.............................................................
CCC1111222233334444111111111111111111111111111111111111111111111111114444444444444444
..................*.............................................................
...*****************************************************************************
................................................................................
......*...*...*...*.............................................................
"FLEX" BASIN TEST
*014126
S       0F3         17 7  I61044    63  44  Heights ...........................
 392  74  60  55  49  42  30  15  6229  2.91  2.34  2.15  1.91  1.63  1.19  0.57
 403  77  62  57  51  44  32  16  6396  3.03  2.44  2.25  2.00  1.72  1.24  0.63
 404  76  61  56  50  43  31  15  6412  2.99  2.42  2.21  1.98  1.69  1.20  0.59
 395  74  60  55  49  42  30  15  6281  2.89  2.36  2.16  1.94  1.65  1.19  0.58
 604 114  95  88  77  67  50  26  9602  4.50  3.74  3.44  3.05  2.63  1.95  1.02
 604 113  95  88  77  67  49  25  9594  4.44  3.74  3.44  3.03  2.62  1.93  0.97
 607 113  96  88  78  67  50  25  9645  4.46  3.76  3.47  3.06  2.64  1.95  1.00
 607 113  96  89  78  67  50  26  9645  4.45  3.77  3.48  3.06  2.65  1.95  1.02
 810 160 135 124 109  95  71  37 12867  6.31  5.31  4.89  4.31  3.74  2.78  1.44
 811 161 135 124 109  95  71  37 12887  6.34  5.31  4.89  4.31  3.75  2.79  1.44
 808 161 134 124 109  95  71  36 12839  6.33  5.28  4.88  4.30  3.74  2.79  1.43
 805 161 135 124 109  95  71  36 12792  6.33  5.30  4.87  4.30  3.73  2.78  1.43
1057 214 180 166 147 128  95  49 16788  8.44  7.07  6.52  5.78  5.04  3.76  1.93
1052 214 179 165 147 128  95  49 16712  8.42  7.06  6.51  5.78  5.04  3.74  1.92
1050 214 179 166 147 128  96  50 16689  8.41  7.06  6.52  5.78  5.04  3.76  1.96
1051 213 179 166 147 128  96  49 16693  8.40  7.06  6.53  5.80  5.05  3.76  1.93
B150  1 rd1 rd2S       0........................................................
0   0   0   0   0   0   0   0   1   0   0   0   0   0   0   0
1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

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14	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0
19	1	0	0	1	0	0	0	23	1	0	0	1	0	0	0
25	1	0	0	1	0	0	0	29	1	0	0	1	0	0	0
34	1	0	0	1	0	0	0	39	1	1	0	1	0	0	0
44	2	1	1	1	1	0	0	53	2	1	1	1	1	0	0
61	2	1	1	1	1	0	0	71	3	2	1	1	1	0	0
83	4	2	2	2	1	0	0	99	5	3	2	2	1	0	0
116	6	4	3	2	2	0	0	135	7	4	3	3	2	0	-1
157	9	5	4	4	2	1	-1	179	10	7	5	4	3	1	-1
202	12	8	6	5	3	1	0	226	14	10	8	6	4	1	0
251	17	11	9	7	5	2	0	272	19	13	11	9	6	2	0
293	22	15	13	10	7	3	-1	312	25	17	14	12	8	3	0
327	28	19	16	13	9	4	0	339	31	22	18	15	11	5	0
347	33	24	20	17	12	6	0	350	36	26	22	18	14	7	0
352	38	28	24	20	15	8	0	349	40	30	26	22	17	8	0
344	42	32	28	24	18	9	1	336	44	34	30	25	20	10	1
329	46	35	31	27	21	12	1	321	47	37	33	28	22	13	2
313	48	38	34	29	24	14	2	305	49	39	35	30	25	15	2
298	50	40	36	32	26	15	3	292	51	41	37	32	27	16	3
288	52	42	38	33	27	17	4	285	52	42	39	34	28	18	4
283	53	43	39	35	29	19	5	284	54	44	40	35	30	19	5
286	54	44	40	36	30	20	6	288	55	45	41	37	31	20	6
293	56	45	41	37	31	21	6	298	56	46	42	37	32	21	7
306	57	46	42	38	32	22	7	314	58	47	43	38	32	22	8
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376	65	52	47	42	35	24	10	383	66	53	48	42	36	24	10
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395	70	56	51	45	38	26	11	393	71	57	52	46	39	27	11
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379	73	59	54	48	40	28	12	372	73	59	54	48	41	28	12
365	73	59	54	48	41	28	12	358	73	60	55	49	41	29	12
352	74	60	55	49	42	29	12	346	73	60	55	49	42	29	13
340	73	60	55	49	42	30	13	334	73	60	55	49	42	30	13
332	73	60	55	49	42	30	13	328	73	60	55	49	42	30	14
324	73	59	55	49	42	30	14	321	73	59	54	49	42	30	14
318	72	59	54	49	42	30	14	315	72	59	54	49	42	30	14
312	72	59	54	49	42	30	14	310	72	58	54	48	41	30	14
308	71	58	53	48	41	30	15	304	71	58	53	48	41	30	15
300	71	57	53	48	41	30	15	296	70	57	53	47	41	30	15
293	70	57	52	47	40	30	15	288	70	56	52	47	40	29	15
284	69	56	52	47	40	29	15	277	69	56	51	46	40	29	15
269	68	55	51	46	39	29	15	264	68	55	50	46	39	29	15
259	67	54	50	45	39	29	15	252	66	54	49	45	38	28	15
244	66	53	49	44	38	28	15	236	65	52	48	44	38	28	15
226	64	52	48	43	37	28	15	219	63	51	47	43	37	27	14
213	62	50	47	42	37	27	14	205	61	50	46	42	36	27	14
196	61	49	45	41	36	26	14	188	60	48	44	41	35	26	14
183	59	47	44	40	35	26	14	176	58	46	43	39	34	26	14
170	57	45	42	39	33	25	14	164	56	45	41	38	33	25	14
157	55	44	40	37	32	24	14	151	53	43	39	36	31	24	14
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125	48	38	35	33	28	22	13	120	47	37	34	32	27	21	12
115	46	36	33	31	27	21	12	111	45	35	32	30	26	20	12

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87	40	30	28	26	23	18	11	84	39	29	27	25	22	17	11
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-10	6	-1	-1	0	-1	-2	-2	-11	6	-1	-1	0	-1	-2	-2
-12	6	-1	-1	0	-1	-2	-2	-12	6	-1	-1	0	-1	-2	-2
-11	6	-1	-1	0	-1	-2	-2	-11	6	-2	-1	0	-1	-2	-2
-11	6	-2	-2	0	-1	-2	-2	-11	6	-2	-2	0	-1	-2	-3
-11	6	-2	-2	0	-1	-3	-3	-11	5	-2	-2	0	-1	-2	-3
-11	5	-2	-2	0	-1	-2	-3	-12	5	-2	-2	0	-1	-2	-3
-12	5	-2	-2	0	-1	-2	-3	-12	5	-2	-2	0	-1	-3	-3
-11	5	-2	-2	0	-1	-3	-3	-11	5	-2	-2	0	-1	-3	-3
-11	5	-2	-2	0	-1	-3	-3	-11	5	-2	-2	0	-1	-3	-3
-10	5	-2	-2	0	-1	-3	-3	-11	5	-2	-2	0	-1	-3	-3
-10	5	-2	-2	0	-1	-3	-3	-10	5	-2	-2	0	-1	-3	-3
-11	5	-2	-2	-1	-1	-3	-3	-10	5	-2	-2	-1	-1	-3	-3
-11	5	-2	-2	-1	-1	-3	-3	-11	5	-2	-2	-1	-1	-3	-3
-10	5	-2	-2	-1	-1	-3	-3	-10	5	-2	-2	-1	-1	-3	-3
-9	5	-2	-2	-1	-1	-3	-3	-9	5	-2	-2	-1	-1	-3	-3
-10	5	-2	-2	-1	-1	-3	-3	-10	5	-2	-3	-1	-1	-3	-4
-11	5	-2	-3	-1	-1	-3	-4	-10	5	-2	-3	-1	-1	-3	-4
-10	5	-2	-3	-1	-1	-3	-4	-10	5	-2	-3	-1	-1	-3	-4
-10	5	-2	-3	-1	-1	-3	-4	-10	5	-2	-3	-1	-1	-3	-4
-10	5	-2	-3	-1	-1	-3	-4	-9	4	-2	-3	-1	-1	-3	-4
-10	4	-2	-3	-1	-1	-3	-4	-10	4	-2	-3	-1	-1	-3	-4
-9	4	-2	-3	-1	-2	-3	-4	-10	4	-3	-3	-1	-2	-3	-4
-9	4	-3	-3	-1	-2	-3	-4	-10	4	-3	-3	-1	-2	-3	-4
-10	4	-3	-3	-1	-2	-3	-4	-9	4	-3	-3	-1	-2	-3	-4
-10	4	-3	-3	-1	-2	-3	-4	-9	4	-3	-3	-1	-2	-3	-4
-9	4	-3	-3	-1	-2	-3	-4	-9	4	-3	-3	-1	-2	-3	-4
-9	4	-3	-3	-1	-2	-3	-4	-9	4	-3	-3	-1	-2	-4	-4
-8	4	-3	-3	-1	-2	-4	-4	-8	4	-3	-3	-1	-2	-4	-4

LOTS OF DATA…………

……………………

……………………

……………………

END OF FILE

APPENDIX II

DBSID BACKCALCULATION RESULT FILE

```
----------------------------------------------------------------------------------------------
-----------------------------------------
                                       TTI PAVEMENT DYNAMIC ANALYSIS OUTPUT (Summary Report)
( GB & US )
----------------------------------------------------------------------------------------------
-----------------------------------------
  Rem:  Florida  FWD data dynamic analysis with DBSID
  File Name:  C:\w\dyn\dbsid3\SR9SBC1                              Thick   Possion   Unit
Weight  Damping    Material
  Date & Time:  2002. 2. 6     14 :  6                              (in)     Ratio
lb/feet*3    ratio       type
  Pavement Layer :       3                        Surface :    7.00     0.35
140.00             Visco-elastic model
  Station Number :      12                        Base    :   10.50     0.25
120.00    0.040     Damped-elastic
                                                  Subgrade:Back-cal     0.40
100.00    0.040     Damped-elastic
----------------------------------------------------------------------------------------------
-----------------------------------------
  SID ANALYSIS CONTROL PARAMETERS
  Upper re-create sensitive matrix condition    0.40       Negative converge condition
0.0002
  Lower re-create sensitive matrix condition    0.40       Positive converge condition
0.0002
  Perturbation value for form sentive matrix    0.05       Sensors         R1       R2
R3       R4       R5       R6       R7
  Max iterate times for one sensitive matrix       4       Locate(in)     0.00     8.00
12.00    18.00    24.00    36.00    60.00
  Number of parameter to be back-calculated:       6
----------------------------------------------------------------------------------------------
-----------------------------------------
  Back-Calculated Parameters Range Information
                                Min         Max         Ini            Describe
  Surface  DO=x/Es    x=   0.500E-03   0.500E-03   0.500E-03     Three parameter visco-
elastic model
  Surface  D1=x/Es    x=        0.00       80.00        5.00     Three parameter visco-
elastic model
  Surface  dog-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     E =xEs     x=        0.20        3.50        1.00     Damped elastic material
  Subgrade E =xEs     x=        0.20        2.00        1.00     Damped elastic material
  Depth to Bedrock=xH x=        0.20        5.00        1.00
----------------------------------------------------------------------------------------------
-----------------------------------------
  Use Station milepost value to select the station
  Start station milepost  :  18.075
  End   station milepost  :  18.725
  The step  is  ..........:  1
  Station number is.......: 12

  Center Try set is used   All has   9  sets of data and used only  1
----------------------------------------------------------------------------------------------
-----------------------------------------
  Back-Calculated Parameters Range Information
                                Min         Max         Ini            Describe
  Surface  D0    (1/ksi)   0.167E-05   0.167E-05   0.167E-05     Three parameter visco-
elastic model
```

```
  Surface  D1              0.335E-05   0.268E+00   0.167E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       15.90      278.25       79.50     Damped elastic material
  Subgrade modulis (ksi)        9.84       98.40       49.20     Damped elastic material
  Depth to Bedrock  (in)       17.50      317.50      201.70

                           D0        D1        m      MODULUS
  Station   Surface :0.167E-05  0.537E-01  0.5583
 18.725     Surface :     Modulus(ksi)=   413.452    298.60
            B a s e :     Modulus(ksi)=    68.728     79.50     Loop Num   :   40      Min
Adjust:  -0.1297      AveErr(mils):   0.20
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :       11      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    58.910     49.20     Pave Tem   :132.8      Sum
Adjust:   0.2283      AbAvEr(mils):   0.25
            Depth to Bedrock (in)          257.36     85.90     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                  Total   Used  Start  End  Step     (mils)   (ms)      (mils)   (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0  60.0  2.0       6.42   22.0       5.42   24.0
12.31    0.488     1.18    -0.23    15.49
               2    300.0     30   2.0  60.0  2.0       4.13   22.0       3.87   24.0
7.18    0.267     0.77    -0.18     6.34
               3    300.0     30   2.0  60.0  2.0       3.19   24.0       3.09   24.0
7.33    0.256     0.77    -0.08     3.06
               4    300.0     30   2.0  60.0  2.0       2.09   24.0       2.27   24.0
4.81    0.243     0.60    -0.31    -8.62
               5    300.0     30   2.0  60.0  2.0       1.50   24.0       1.72   24.0
3.65    0.211     0.49    -0.36   -14.82
               6    300.0     30   2.0  60.0  2.0       0.94   26.0       1.07   24.0
2.04    0.138     0.35    -0.25   -13.47
               7    300.0     30   2.0  60.0  2.0       0.63   30.0       0.63   28.0
4.10    0.148     0.38    -0.06    -0.56
--------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                                Min         Max         Ini            Describe
  Surface  D0    (1/ksi)   0.144E-05   0.144E-05   0.144E-05     Three parameter visco-
elastic model
  Surface  D1              0.288E-05   0.230E+00   0.144E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       15.92      278.60       79.60     Damped elastic material
  Subgrade modulis (ksi)        8.72       87.20       43.60     Damped elastic material
  Depth to Bedrock  (in)       21.22      317.50      211.80

                           D0        D1        m      MODULUS
  Station   Surface :0.144E-05  0.275E-01  0.3878
 18.675     Surface :     Modulus(ksi)=   325.270    347.50
            B a s e :     Modulus(ksi)=    84.347     79.60     Loop Num   :   40      Min
Adjust:  -0.1046      AveErr(mils):  -0.05
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :       12      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    40.662     43.60     Pave Tem   :132.8      Sum
Adjust:   0.1210      AbAvEr(mils):   0.16
            Depth to Bedrock (in)          300.40    106.10     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
```

```
               No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)    (ms)      (mils)    (ms)
(mils)   (mils)   (mils)   (mils)     (%)
                1    300.0     30   2.0   60.0  2.0       6.38   22.0        6.58   24.0     -
3.61    0.300     0.38    -0.69    -3.14
                2    300.0     30   2.0   60.0  2.0       4.33   24.0        4.57   24.0
0.88    0.194     0.54    -0.27    -5.50
                3    300.0     30   2.0   60.0  2.0       3.46   24.0        3.70   24.0
1.31    0.178     0.50    -0.28    -6.87
                4    300.0     30   2.0   60.0  2.0       2.28   24.0        2.84   24.0     -
2.03    0.154     0.23    -0.57   -24.53
                5    300.0     30   2.0   60.0  2.0       1.65   24.0        2.25   24.0     -
2.58    0.145     0.17    -0.60   -35.84
                6    300.0     30   2.0   60.0  2.0       1.06   26.0        1.53   26.0     -
3.43    0.129     0.04    -0.47   -43.81
                7    300.0     30   2.0   60.0  2.0       0.63   28.0        0.89   28.0     -
0.84    0.055     0.05    -0.26   -41.19
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                             Min         Max         Ini             Describe
  Surface  D0    (1/ksi)   0.144E-05   0.144E-05   0.144E-05     Three parameter visco-
elastic model
  Surface  D1              0.288E-05   0.231E+00   0.144E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       14.48      253.40       72.40     Damped elastic material
  Subgrade modulis (ksi)        9.92       99.20       49.60     Damped elastic material
  Depth to Bedrock  (in)       17.50      317.50      191.50

                        D0       D1       m      MODULUS
  Station   Surface :0.144E-05  0.295E-01  0.4956
 18.575     Surface :     Modulus(ksi)=   539.797    347.00
            B a s e :     Modulus(ksi)=    55.765     72.40     Loop Num   :   40      Min
Adjust:  -0.2182      AveErr(mils):   0.17
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :       26      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    67.271     49.60     Pave Tem   :129.2      Sum
Adjust:   0.3355      AbAvEr(mils):   0.27
            Depth to Bedrock (in)          201.80     65.50     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
               No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)    (ms)      (mils)    (ms)
(mils)   (mils)   (mils)   (mils)     (%)
                1    300.0     30   2.0   60.0  2.0       5.94   22.0        4.98   22.0
8.97    0.534     1.10    -0.62    16.30
                2    300.0     30   2.0   60.0  2.0       3.98   22.0        3.66   22.0
6.24    0.311     0.81    -0.41     7.87
                3    300.0     30   2.0   60.0  2.0       3.07   24.0        2.93   22.0
6.45    0.272     0.83    -0.29     4.54
                4    300.0     30   2.0   60.0  2.0       2.01   24.0        2.09   24.0
4.15    0.242     0.67    -0.29    -3.96
                5    300.0     30   2.0   60.0  2.0       1.42   24.0        1.55   24.0
2.63    0.203     0.57    -0.32    -9.54
                6    300.0     30   2.0   60.0  2.0       0.91   26.0        0.95   24.0
2.50    0.161     0.45    -0.27    -4.40
                7    300.0     30   2.0   60.0  2.0       0.59   28.0        0.54   26.0
4.45    0.153     0.44    -0.06     9.25
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
```

```
                               Min         Max         Ini            Describe
  Surface  D0    (1/ksi)   0.148E-05   0.148E-05   0.148E-05     Three parameter visco-
elastic model
  Surface  D1              0.297E-05   0.237E+00   0.148E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       25.72      450.10      128.60     Damped elastic material
  Subgrade modulis (ksi)        7.62       76.20       38.10     Damped elastic material
  Depth to Bedrock  (in)       60.00      317.50      308.75

                          D0       D1       m      MODULUS
  Station   Surface :0.148E-05  0.373E-01  0.4204
 18.525     Surface :     Modulus(ksi)=   285.887    337.00
            B a s e :     Modulus(ksi)=   143.214    128.60     Loop Num   :   40      Min
Adjust:  -0.0994      AveErr(mils):  -0.03
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :       9      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    35.644     38.10     Pave Tem   :131.0      Sum
Adjust:   0.1320      AbAvEr(mils):   0.16
            Depth to Bedrock (in)          294.05    300.00     Back-calculated

            Sensor   Time History Information(ms)         Tested           Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                     Total   Used  Start  End  Step     (mils)   (ms)      (mils)   (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       5.79   24.0        6.00   24.0     -
1.80    0.228     0.27    -0.58    -3.62
               2    300.0     30   2.0   60.0  2.0       3.94   24.0        4.12   24.0
1.73    0.170     0.44    -0.28    -4.77
               3    300.0     30   2.0   60.0  2.0       3.15   24.0        3.41   24.0
1.98    0.161     0.43    -0.26    -8.17
               4    300.0     30   2.0   60.0  2.0       2.28   30.0        2.71   24.0     -
1.65    0.160     0.22    -0.55   -18.89
               5    300.0     30   2.0   60.0  2.0       1.73   30.0        2.26   26.0     -
3.41    0.170     0.12    -0.62   -30.34
               6    300.0     30   2.0   60.0  2.0       1.18   30.0        1.61   26.0     -
3.63    0.151     0.07    -0.55   -36.36
               7    300.0     30   2.0   60.0  2.0       0.83   32.0        0.94   30.0
0.20    0.059     0.11    -0.20   -13.18
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                               Min         Max         Ini            Describe
  Surface  D0    (1/ksi)   0.135E-05   0.135E-05   0.135E-05     Three parameter visco-
elastic model
  Surface  D1              0.269E-05   0.215E+00   0.135E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       20.72      362.60      103.60     Damped elastic material
  Subgrade modulis (ksi)        8.88       88.80       44.40     Damped elastic material
  Depth to Bedrock  (in)       21.76      317.50      213.15

                          D0       D1       m      MODULUS
  Station   Surface :0.135E-05  0.312E-01  0.4583
 18.475     Surface :     Modulus(ksi)=   419.290    371.30
            B a s e :     Modulus(ksi)=    83.233    103.60     Loop Num   :   40      Min
Adjust:  -0.3214      AveErr(mils):   0.01
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :      16      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    46.193     44.40     Pave Tem   :131.0      Sum
Adjust:   0.2483      AbAvEr(mils):   0.15
            Depth to Bedrock (in)          213.15    108.80     Back-calculated
```

```
            Sensor   Time History Information(ms)        Tested           Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)    (ms)      (mils)    (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       5.63   24.0        5.72   24.0     -
0.04    0.230     0.41    -0.56    -1.58
               2    300.0     30   2.0   60.0  2.0       3.82   24.0        4.12   24.0
2.12    0.170     0.46    -0.30    -7.86
               3    300.0     30   2.0   60.0  2.0       3.03   24.0        3.34   24.0
1.69    0.180     0.46    -0.31   -10.23
               4    300.0     30   2.0   60.0  2.0       2.09   32.0        2.51   24.0
0.25    0.166     0.35    -0.46   -20.33
               5    300.0     30   2.0   60.0  2.0       1.54   32.0        1.94   26.0     -
1.35    0.149     0.24    -0.54   -26.32
               6    300.0     30   2.0   60.0  2.0       1.02   32.0        1.32   26.0     -
1.41    0.111     0.15    -0.42   -29.27
               7    300.0     30   2.0   60.0  2.0       0.71   34.0        0.76   28.0
0.68    0.068     0.16    -0.17    -6.75
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                             Min         Max         Ini             Describe
  Surface  D0    (1/ksi)   0.121E-05   0.121E-05   0.121E-05     Three parameter visco-
elastic model
  Surface  D1              0.242E-05   0.193E+00   0.121E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       20.04      350.70      100.20     Damped elastic material
  Subgrade modulis (ksi)        9.90       99.00       49.50     Damped elastic material
  Depth to Bedrock  (in)       17.50      317.50      195.50

                        D0       D1       m      MODULUS
  Station   Surface :0.121E-05  0.201E-01  0.3583
 18.425     Surface :     Modulus(ksi)=   378.411    413.80
            B a s e :     Modulus(ksi)=   106.074    100.20     Loop Num   :   40      Min
Adjust:  -0.0001      AveErr(mils):  -0.04
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :       16      Ntimes     :         0
            Subgrade:     Modulus(ksi)=    48.368     49.50     Pave Tem   :132.8      Sum
Adjust:   0.2000      AbAvEr(mils):   0.14
            Depth to Bedrock (in)         278.88     73.50     Back-calculated

            Sensor   Time History Information(ms)        Tested           Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)    (ms)      (mils)    (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       5.39   24.0        5.57   24.0     -
1.90    0.226     0.36    -0.52    -3.23
               2    300.0     30   2.0   60.0  2.0       3.62   24.0        3.85   24.0     -
0.12    0.173     0.40    -0.31    -6.18
               3    300.0     30   2.0   60.0  2.0       2.95   24.0        3.11   24.0
1.97    0.150     0.44    -0.18    -5.44
               4    300.0     30   2.0   60.0  2.0       2.01   24.0        2.39   24.0     -
0.82    0.120     0.24    -0.38   -19.01
               5    300.0     30   2.0   60.0  2.0       1.42   26.0        1.88   24.0     -
3.10    0.130     0.08    -0.51   -32.90
               6    300.0     30   2.0   60.0  2.0       0.94   26.0        1.30   26.0     -
3.40    0.125     0.03    -0.37   -37.57
               7    300.0     30   2.0   60.0  2.0       0.59   28.0        0.76   28.0     -
0.70    0.040     0.05    -0.17   -28.09
```

```
-----------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                              Min         Max         Ini             Describe
  Surface  D0    (1/ksi)   0.134E-05   0.134E-05   0.134E-05     Three parameter visco-
elastic model
  Surface  D1              0.269E-05   0.215E+00   0.134E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       28.72      502.60      143.60     Damped elastic material
  Subgrade modulis (ksi)        9.26       92.60       46.30     Damped elastic material
  Depth to Bedrock  (in)       28.30      317.50      229.50

                           D0       D1       m      MODULUS
  Station   Surface :0.134E-05  0.279E-01  0.3724
 18.375     Surface :     Modulus(ksi)=   294.689    372.40
            B a s e :     Modulus(ksi)=   179.854    143.60     Loop Num   :   40      Min
Adjust:  -0.0013      AveErr(mils):  -0.01
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   40      Out-
Loop  :        7      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    44.037     46.30     Pave Tem   :131.0      Sum
Adjust:   0.0009      AbAvEr(mils):   0.11
            Depth to Bedrock (in)          314.30    141.50     Back-calculated

            Sensor   Time History Information(ms)         Tested           Calculated
Sum    Error/     Max      Min      Peak
              No.   -----------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)   (ms)      (mils)   (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       5.16   22.0        5.26   22.0     -
1.23    0.183     0.32    -0.34    -2.05
               2    300.0     30   2.0   60.0  2.0       3.39   24.0        3.49   24.0
1.10    0.116     0.35    -0.16    -3.13
               3    300.0     30   2.0   60.0  2.0       2.80   24.0        2.89   24.0
2.32    0.115     0.37    -0.15    -3.26
               4    300.0     30   2.0   60.0  2.0       2.01   24.0        2.34   24.0     -
0.26    0.103     0.16    -0.37   -16.63
               5    300.0     30   2.0   60.0  2.0       1.50   24.0        1.94   24.0     -
1.36    0.116     0.11    -0.46   -29.51
               6    300.0     30   2.0   60.0  2.0       0.98   26.0        1.38   26.0     -
2.30    0.097     0.04    -0.41   -39.84
               7    300.0     30   2.0   60.0  2.0       0.63   28.0        0.80   28.0
0.46    0.065     0.16    -0.17   -27.25
-----------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                              Min         Max         Ini             Describe
  Surface  D0    (1/ksi)   0.154E-05   0.154E-05   0.154E-05     Three parameter visco-
elastic model
  Surface  D1              0.307E-05   0.246E+00   0.154E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       27.00      472.50      135.00     Damped elastic material
  Subgrade modulis (ksi)        8.12       81.20       40.60     Damped elastic material
  Depth to Bedrock  (in)       60.00      317.50      300.00

                           D0       D1       m      MODULUS
  Station   Surface :0.154E-05  0.290E-01  0.3586
 18.325     Surface :     Modulus(ksi)=   263.604    325.60
            B a s e :     Modulus(ksi)=   174.292    135.00     Loop Num   :    8      Min
Adjust:  -0.0001      AveErr(mils):  -0.02
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :    8      Out-
Loop  :        8      Ntimes    :        0
```

```
            Subgrade:     Modulus(ksi)=    36.991     40.60     Pave Tem   :131.0      Sum
Adjust:   0.0000      AbAvEr(mils):   0.14
            Depth to Bedrock (in)         291.69    300.00     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total    Used  Start  End  Step     (mils)    (ms)      (mils)    (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30    2.0   60.0  2.0       5.79    24.0        5.94    24.0     -
2.21    0.240     0.38    -0.46    -2.61
               2    300.0     30    2.0   60.0  2.0       3.86    24.0        3.96    24.0
2.00    0.135     0.46    -0.21    -2.73
               3    300.0     30    2.0   60.0  2.0       3.15    24.0        3.30    24.0
2.35    0.134     0.42    -0.21    -4.63
               4    300.0     30    2.0   60.0  2.0       2.20    24.0        2.68    24.0     -
0.96    0.129     0.18    -0.52   -21.71
               5    300.0     30    2.0   60.0  2.0       1.69    26.0        2.21    24.0     -
2.39    0.133     0.08    -0.60   -30.84
               6    300.0     30    2.0   60.0  2.0       1.14    26.0        1.61    26.0     -
2.66    0.115     0.06    -0.49   -41.44
               7    300.0     30    2.0   60.0  2.0       0.75    30.0        0.93    28.0
0.15    0.073     0.20    -0.22   -24.42
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                              Min          Max          Ini            Describe
  Surface  D0    (1/ksi)   0.175E-05   0.175E-05   0.175E-05     Three parameter visco-
elastic model
  Surface  D1              0.350E-05   0.280E+00   0.175E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05         0.90        0.40     Three parameter visco-
elastic model
  Base     modulus (ksi)       22.26      389.55      111.30     Damped elastic material
  Subgrade modulus (ksi)        8.38       83.80       41.90     Damped elastic material
  Depth to Bedrock  (in)       34.48      317.50      244.95

                           D0       D1       m      MODULUS
  Station   Surface :0.175E-05  0.519E-01  0.4318
 18.225     Surface :     Modulus(ksi)=   218.773    285.70
            B a s e :     Modulus(ksi)=   150.801    111.30     Loop Num   :   23      Min
Adjust:  -0.0001      AveErr(mils):  -0.01
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   23      Out-
Loop  :       23      Ntimes    :         0
            Subgrade:     Modulus(ksi)=    36.821     41.90     Pave Tem   :129.2      Sum
Adjust:   0.0000      AbAvEr(mils):   0.18
            Depth to Bedrock (in)         282.88    172.40     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total    Used  Start  End  Step     (mils)    (ms)      (mils)    (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30    2.0   60.0  2.0       6.18    24.0        6.36    24.0     -
0.84    0.233     0.39    -0.49    -2.89
               2    300.0     30    2.0   60.0  2.0       4.02    24.0        4.14    24.0
2.73    0.185     0.61    -0.25    -3.07
               3    300.0     30    2.0   60.0  2.0       3.15    24.0        3.37    24.0
3.29    0.173     0.55    -0.22    -6.85
               4    300.0     30    2.0   60.0  2.0       2.17    32.0        2.67    26.0     -
1.43    0.180     0.28    -0.66   -23.24
               5    300.0     30    2.0   60.0  2.0       1.61    32.0        2.24    26.0     -
2.85    0.187     0.18    -0.74   -38.62
```

```
               6    300.0     30   2.0   60.0  2.0       1.10   34.0        1.58   26.0     -
3.46    0.168     0.14    -0.68   -43.47
               7    300.0     30   2.0   60.0  2.0       0.79   34.0        0.92   30.0
0.78    0.103     0.22    -0.30   -16.45
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                              Min         Max         Ini             Describe
  Surface  D0    (1/ksi)   0.188E-05   0.188E-05   0.188E-05     Three parameter visco-
elastic model
  Surface  D1              0.376E-05   0.301E+00   0.188E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       33.04      578.20      165.20     Damped elastic material
  Subgrade modulis (ksi)        4.00       40.00       20.00     Damped elastic material
  Depth to Bedrock  (in)       60.00      317.50      180.00

                           D0       D1       m      MODULUS
  Station   Surface :0.188E-05  0.545E-01  0.4109
 18.175     Surface :     Modulus(ksi)=   186.003    266.10
            B a s e :     Modulus(ksi)=   288.524    165.20     Loop Num   :   12      Min
Adjust:  -0.0001      AveErr(mils):  -0.02
            Subbase :     Modulus(ksi)=     0.000               Sensitive  :   12      Out-
Loop  :       12      Ntimes    :        0
            Subgrade:     Modulus(ksi)=    19.481     20.00     Pave Tem   :129.2      Sum
Adjust:   0.0000      AbAvEr(mils):   0.19
            Depth to Bedrock (in)          190.99    300.00     Back-calculated

            Sensor   Time History Information(ms)         Tested           Calculated
Sum    Error/     Max      Min      Peak
              No.   ------------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                  Total   Used  Start  End  Step     (mils)   (ms)      (mils)   (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       7.44   30.0        7.33   30.0     -
1.13    0.230     0.32    -0.59    1.43
               2    300.0     30   2.0   60.0  2.0       5.39   32.0        4.96   30.0
4.13    0.186     0.57    -0.18    7.95
               3    300.0     30   2.0   60.0  2.0       4.57   32.0        4.34   30.0
2.93    0.156     0.47    -0.20    4.90
               4    300.0     30   2.0   60.0  2.0       3.58   32.0        3.82   30.0     -
2.40    0.186     0.20    -0.69   -6.76
               5    300.0     30   2.0   60.0  2.0       2.95   32.0        3.38   32.0     -
3.71    0.229     0.21    -0.86   -14.52
               6    300.0     30   2.0   60.0  2.0       2.17   34.0        2.62   32.0     -
4.28    0.203     0.15    -0.75   -20.89
               7    300.0     30   2.0   60.0  2.0       1.42   36.0        1.59   36.0     -
0.32    0.117     0.29    -0.29   -11.84
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                              Min         Max         Ini             Describe
  Surface  D0    (1/ksi)   0.173E-05   0.173E-05   0.173E-05     Three parameter visco-
elastic model
  Surface  D1              0.345E-05   0.276E+00   0.173E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       29.32      513.10      146.60     Damped elastic material
  Subgrade modulis (ksi)        9.62       96.20       48.10     Damped elastic material
  Depth to Bedrock  (in)       60.00      317.50      308.75

                           D0       D1       m      MODULUS
  Station   Surface :0.173E-05  0.309E-01  0.3607
 18.125     Surface :     Modulus(ksi)=   249.782    289.60
```

```
            B a s e :     Modulus(ksi)=  160.180    146.60     Loop Num   :   40      Min
Adjust:  -0.0003      AveErr(mils):   0.00
            Subbase :     Modulus(ksi)=    0.000               Sensitive  :   40      Out-
Loop  :        6      Ntimes    :         0
            Subgrade:     Modulus(ksi)=   48.817     48.10     Pave Tem   :131.0      Sum
Adjust:   0.0001      AbAvEr(mils):   0.10
            Depth to Bedrock (in)        316.45    300.00     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
              No.  -----------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)   (ms)      (mils)   (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       5.35   22.0        5.45   22.0     -
0.58    0.149     0.28    -0.25    -1.71
               2    300.0     30   2.0   60.0  2.0       3.31   22.0        3.40   22.0
0.17    0.104     0.27    -0.14    -2.66
               3    300.0     30   2.0   60.0  2.0       2.68   24.0        2.73   24.0
1.88    0.094     0.34    -0.11    -2.15
               4    300.0     30   2.0   60.0  2.0       1.85   24.0        2.18   24.0     -
0.48    0.088     0.13    -0.34   -17.64
               5    300.0     30   2.0   60.0  2.0       1.38   24.0        1.78   24.0     -
0.90    0.106     0.10    -0.40   -29.36
               6    300.0     30   2.0   60.0  2.0       0.94   26.0        1.24   26.0     -
1.39    0.076     0.04    -0.30   -30.91
               7    300.0     30   2.0   60.0  2.0       0.63   28.0        0.72   28.0
1.12    0.056     0.15    -0.09   -14.05
---------------------------------------------------------------------------------------------
----------------------------------------
  Back-Calculated Parameters Range Information
                             Min         Max         Ini            Describe
  Surface  D0    (1/ksi)   0.123E-05   0.123E-05   0.123E-05     Three parameter visco-
elastic model
  Surface  D1              0.245E-05   0.196E+00   0.123E-01     Three parameter visco-
elastic model
  Surface  Log-Log slope        0.05        0.90        0.40     Three parameter visco-
elastic model
  Base     modulis (ksi)       20.10      351.75      100.50     Damped elastic material
  Subgrade modulis (ksi)        9.92       99.20       49.60     Damped elastic material
  Depth to Bedrock  (in)       17.50      317.50      198.30

                        D0       D1       m      MODULUS
  Station   Surface :0.123E-05  0.192E-01  0.3503
 18.075     Surface :     Modulus(ksi)=  380.477    407.60
            B a s e :     Modulus(ksi)=  105.317    100.50     Loop Num   :   40      Min
Adjust:  -0.1757      AveErr(mils):  -0.06
            Subbase :     Modulus(ksi)=    0.000               Sensitive  :   40      Out-
Loop  :       37      Ntimes    :         0
            Subgrade:     Modulus(ksi)=   47.430     49.60     Pave Tem   :132.8      Sum
Adjust:   0.3126      AbAvEr(mils):   0.13
            Depth to Bedrock (in)        309.58     79.10     Back-calculated

            Sensor   Time History Information(ms)         Tested            Calculated
Sum    Error/     Max      Min      Peak
              No.  -----------------------------    Peak & Location    Peak & Location
Error   Point     Error    Error    Error
                    Total   Used  Start  End  Step     (mils)   (ms)      (mils)   (ms)
(mils)   (mils)   (mils)   (mils)     (%)
               1    300.0     30   2.0   60.0  2.0       5.31   24.0        5.60   24.0     -
3.38    0.225     0.24    -0.46    -5.38
               2    300.0     30   2.0   60.0  2.0       3.62   24.0        3.88   24.0
0.02    0.146     0.36    -0.26    -7.11
               3    300.0     30   2.0   60.0  2.0       2.87   24.0        3.14   24.0     -
0.08    0.128     0.29    -0.31    -9.24
```

4	300.0	30	2.0	60.0	2.0	1.93	24.0	2.40	24.0	-1.98	0.114	0.15	-0.47	-24.47
5	300.0	30	2.0	60.0	2.0	1.42	26.0	1.88	24.0	-3.66	0.139	0.05	-0.54	-32.76
6	300.0	30	2.0	60.0	2.0	0.94	26.0	1.31	26.0	-3.24	0.121	0.03	-0.38	-39.04
7	300.0	30	2.0	60.0	2.0	0.59	28.0	0.76	28.0	-0.93	0.046	0.05	-0.17	-28.83

APPENDIX III

A TYPICAL OF ASC FILE (MODULUS Program Summary Result)

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  TTI  MODULUS  ANALYSIS  SYSTEM  (SUMMARY REPORT)                            (Version 7.0)
---------------------------------------------------------------------------------------------------------------------------------------
  District:                                                                                MODULI RANGE(psi)
  County  :                                                  Thickness(in)          Minimum        Maximum    Poisson Ratio Values
  Highway/Road:                            Pavement:          13.10                 100,000        1,820,000        H1: v = 0.35
                                           Base:              18.40                  10,000        150,000        H2: v = 0.35
                                           Subbase:            0.00                                               H3: v = 0.00
                                           Subgrade:         132.00(User Input)                    15,000              H4: v = 0.35
---------------------------------------------------------------------------------------------------------------------------------------
             Load    Measured Deflection (mils):                              Calculated Moduli values (ksi):       Absolute Dpth to
  Station    (lbs)    W1      W2      W3      W4      W5      W6      W7    SURF(E1)  BASE(E2)  SUBB(E3)  SUBG(E4) ERR/Sens Bedrock
---------------------------------------------------------------------------------------------------------------------------------------
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Station	Load (lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	ERR/Sens	Bedrock
0.000	9,915	4.92	3.56	3.30	2.90	2.45	1.80	0.94	553.4	87.5	0.0	25.0	1.86	122.1
25.000	9,669	4.39	3.48	3.17	2.76	2.39	1.75	0.94	786.1	49.1	0.0	28.7	0.48	133.3
50.000	9,709	5.30	4.31	3.87	3.36	2.85	2.09	1.11	692.0	26.9	0.0	27.8	0.39	134.8
75.000	9,788	4.14	3.41	3.09	2.75	2.41	1.81	1.02	967.2	48.5	0.0	27.4	0.33	153.5
100.000	9,645	5.50	4.37	3.92	3.40	2.93	2.15	1.15	604.9	39.0	0.0	23.8	0.11	139.4
125.000	9,554	5.09	4.15	3.87	3.47	3.00	2.27	1.22	839.7	31.0	0.0	22.3	0.72	139.5
150.000	9,594	5.34	4.49	4.10	3.63	3.18	2.38	1.32	897.3	13.1	0.0	29.0	0.54	160.7
175.000	9,526	6.29	5.15	4.67	4.04	3.46	2.49	1.27	597.5	18.9	0.0	23.9	0.25	128.9
200.000	9,558	4.74	3.84	3.51	3.08	2.68	2.02	1.13	774.9	45.8	0.0	23.8	0.21	155.0
225.000	9,526	4.52	3.66	3.28	2.89	2.53	1.93	1.09	746.4	64.5	0.0	23.1	0.20	155.7
250.000	9,614	4.61	3.81	3.52	3.17	2.78	2.15	1.21	921.9	48.9	0.0	21.2	0.44	156.1
300.000	9,610	3.92	3.14	2.89	2.62	2.35	1.83	1.03	932.1	105.8	0.0	21.5	0.92	146.8
325.000	9,530	3.59	2.87	2.68	2.37	2.06	1.54	0.91	1066.2	57.6	0.0	31.0	0.92	177.3
350.000	9,387	3.70	2.96	2.72	2.41	2.07	1.59	0.89	924.9	74.9	0.0	27.7	0.64	140.6
375.000	9,427	4.09	3.38	3.16	2.87	2.53	1.97	1.19	1120.7	46.8	0.0	23.1	0.71	300.0
400.000	9,554	3.89	3.38	3.13	2.84	2.54	2.02	1.23	1308.4	53.8	0.0	21.1	0.31	300.0
425.000	9,375	3.66	3.19	3.01	2.74	2.45	1.95	1.18	1466.6	52.8	0.0	21.0	0.57	300.0

450.000	9,411	3.73	3.07	2.86	2.61	2.32	1.84	1.17	1109.2	91.4	0.0	21.2	0.66	300.0	
475.000	9,431	4.00	3.30	3.07	2.75	2.41	1.87	1.11	1042.3	56.1	0.0	23.8	0.51	184.3	
500.000	9,546	4.00	2.93	2.73	2.46	2.19	1.73	1.05	703.7	150.0	0.0	21.8	1.61	300.0	*
Mean:		4.47	3.62	3.33	2.96	2.58	1.96	1.11	902.8	58.1	0.0	24.4	0.62	168.2	
Std. Dev:		0.74	0.61	0.53	0.44	0.36	0.25	0.12	237.4	31.8	0.0	3.1	0.45	46.3	
Var Coeff(%):		16.56	16.73	15.85	14.79	14.05	12.55	11.11	26.3	54.7	0.0	12.7	72.03	27.5	

APPENDIX IV

LIST OF CONTACTED PEOPLE AND ORGANIZATIONS

Table-A IV-1 List of contacted people and organizations

Name	Email Address	Organization Name
Robert Lytton	r-lytton@civil.tamu.edu	Texas A&M University
Matthew Liebo	matthew.liebo@iengineering.com	LTPP
James Phillips	james.phillips@txdot.gov	TxDOT
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Table-A IV-1 (Continued)

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Corey Washington	cwash@msu.edu	Michigan State University
Charles Hasemann	haseman1@msu.edu	Michigan State University
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John Verboncoeur	johnv@msu.edu	Michigan State University
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Table-A IV-1 (Continued)

Name	Email Address	Organization Name
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APPENDIX V

IRI VALUES IN DIFFERENT TEST SECTIONS

Table-A V-1 Florida IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Florida	1	38.33	53.73	46
	2	37.57	55.19	46.38
	3	39.92	54.43	47.20
	4	36.5	57.02	46.76
	5	38.02	54.93	46.51
Mean				46.57

Table-A V-2 Kentucky IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Kentucky	1	93.46	102.20	97.83
	2	95.10	99.67	97.38
	3	90.86	97.45	94.15
	4	90.92	99.73	95.36
	5	91.62	99.92	95.74
Mean				96.12

Table-A V-3 Michigan IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Michigan	1	91.81	92	91.87
	2	92.44	93.58	93.01
	3	95.61	91.81	93.71
	4	93.39	90.48	91.94
	5	95.23	90.1	92.63
Mean				92.63

Table-A V-4 Missouri IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Missouri	1	77.49	85.28	81.35
	2	68.75	84.02	76.41
	3	69.63	86.23	77.93
	4	72.55	84.52	78.50
	5	68.05	85.92	76.98
Mean				78.25

Table-A V-5 New Jersey IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
New Jersey	1	82.43	104.42	93.39
	2	84.65	104.23	94.41
	3	85.03	105.37	95.17
	4	83.70	107.27	95.48
	5	86.17	108.16	97.19
Mean				95.10

Table-A V-6 New York IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
New York	1	66.84	67.16	67.03
	2	67.22	65.32	66.27
	3	66.40	66.84	66.65
	4	67.16	66.53	66.84
	5	63.11	67.22	65.13
Mean				66.40

Table-A V-7 Pennsylvania IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Pennsylvania	1	92.38	114.81	103.59
	2	92.89	114.81	103.85
	3	94.60	116.27	105.43
	4	95.67	114.49	105.05
	5	93.08	116.08	104.61
Mean				104.48

Table-A V-8 Texas IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Texas	1	58.92	53.79	56.39
	2	58.35	51.58	55
	3	59.50	50.43	54.93
	4	60.19	52.21	56.20
	5	58.61	53.29	55.95
Mean				55.69

Table-A V-9 Washington IRI data

State Name	Run Number	IRI Left Wheel Path (in/mi)	IRI Right Wheel Path (in/mi)	MRI (in/mi)
Washington	1	94.85	121.21	108.03
	2	95.74	122.16	108.98
	3	94.72	119.18	106.95
	4	94.85	119.31	107.08
	5	96.18	122.28	109.23
Mean				108.03

APPENDIX VI

MODULUS PROGRAM RESULTS IN DIFFERENT TEST SECTIONS

Table-A VI-1 Florida MODULUS results

	Load	**Measured Deflection (mils)**							**Backcalculated Modulus (ksi)**		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9649	2.07	1.55	1.30	1.07	0.86	0.60	0.32	1500.0	150.0	131.7
50	9713	2.03	1.52	1.39	1.09	0.87	0.57	0.31	1500.0	150.0	132.1
100	9701	1.96	1.48	1.22	1.00	0.80	0.51	0.24	1500.0	150.0	224.2
150	9661	2.17	1.64	1.39	1.15	0.91	0.61	0.32	1500.0	150.0	124.7
200	9665	2.09	1.59	1.37	1.09	0.89	0.59	0.31	1500.0	150.0	128.8
250	9621	1.90	1.47	1.24	1.01	0.80	0.53	0.28	1500.0	150.0	222.8
300	9685	2.07	1.58	1.33	1.08	0.86	0.55	0.28	1500.0	150.0	131.7
350	9594	2.03	1.55	1.33	1.05	0.91	0.58	0.32	1500.0	150.0	130.9
400	9590	2.23	1.76	1.53	1.26	0.98	0.66	0.30	1500.0	150.0	115.7
450	9633	2.12	1.67	1.43	1.15	0.92	0.61	0.29	1500.0	150.0	123.8
500	9641	2.19	1.64	1.40	1.13	0.91	0.57	0.28	1500.0	150.0	124.9
Mean		2.08	1.59	1.36	1.10	0.88	0.58	0.30	1500.0	150.0	144.7
Std.Dev		0.10	0.09	0.09	0.07	0.05	0.04	0.02	0.0	0.0	39.3
Var Coeff (%)		4.72	5.45	6.45	6.66	6.00	7.15	8.34	0.0	0.0	27.2
		Adjusted Mean Modulus (ksi)							1500.00	150.00	127.16

Table-A VI-2 Kentucky MODULUS results

	Load	**Measured Deflection (mils)**							**Backcalculated Modulus (ksi)**		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9384	12.60	9.93	8.07	6.14	4.44	2.12	0.97	410.7	10.3	30.7
25	9608	11.68	9.39	7.61	5.60	4.02	1.99	0.83	441.1	11.5	33.7
50	9664	13.65	10.63	8.65	6.39	4.57	2.21	0.97	359.7	11.0	28.8
75	9392	15.91	12.54	9.98	7.31	5.08	2.34	0.97	268.8	10.0	24.4
100	9248	16.04	12.42	9.94	7.40	5.20	2.47	0.88	270.5	10.0	23.0
125	9232	17.09	13.79	11.10	8.31	5.92	2.64	0.83	246.9	10.0	19.3
150	9208	14.61	11.51	9.15	6.98	4.86	2.04	0.66	295.8	10.0	26.8
175	9248	11.39	9.22	7.53	5.77	4.19	2.04	0.70	480.5	10.0	33.3
200	9368	11.64	9.68	7.74	5.68	4.06	1.82	0.66	419.3	10.5	35.0
225	9032	15.03	11.30	9.36	6.73	4.74	2.21	0.70	282.2	10.0	25.8
250	9136	15.20	11.80	9.61	7.10	5.08	2.38	0.92	292.1	10.0	23.8
275	9104	14.15	11.22	8.82	6.60	4.65	2.12	0.88	310.5	10.0	27.4
300	9200	11.22	9.22	7.57	5.77	4.15	2.16	0.83	495.7	10.3	31.3
325	9208	11.77	9.43	7.78	5.81	4.23	2.12	0.83	444.9	10.7	30.5
350	9104	12.23	9.76	8.07	6.06	4.48	2.38	1.05	399.6	13.3	23.6
375	9032	13.02	10.55	8.53	6.35	4.61	2.25	0.83	373.1	10.0	27.1
400	9064	11.89	9.47	7.57	5.72	4.31	2.12	0.83	403.7	12.6	27.1
425	9168	11.98	9.47	7.78	5.68	4.19	1.86	0.61	407.2	10.2	33.9
450	9088	10.80	8.27	6.74	5.06	3.47	1.82	0.75	393.6	16.1	30.5
475	9088	11.14	8.68	7.07	5.14	3.72	1.78	0.75	408.9	12.8	33.5
500	8968	11.18	8.39	6.78	4.80	3.26	1.47	0.40	356.6	12.9	39.4
Mean		13.06	10.32	8.35	6.21	4.44	2.11	0.80	369.6	11.1	29.0
Std.Dev		1.91	1.48	1.15	0.87	0.61	0.27	0.15	73.0	1.6	4.9
Var Coeff (%)		14.65	14.36	13.82	13.99	13.69	12.64	18.53	19.8	14.6	16.8
		Adjusted Mean Modulus (ksi)							352.25	10.42	27.81

Table-A VI-3 Michigan MODULUS results

	Load	**Measured Deflection (mils)**							**Backcalculated Modulus (ksi)**		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9496	11.26	8.76	7.07	5.35	3.98	2.38	1.19	887.9	150.0	16.6
25	9400	10.59	7.85	6.16	4.43	3.26	1.86	0.97	633.7	150.0	20.5
50	9368	10.55	8.10	6.53	4.89	3.60	2.12	1.05	888.5	150.0	18.2
75	9400	11.31	8.35	6.65	4.85	3.55	2.12	1.01	626.8	150.0	18.5
100	9440	10.47	7.85	6.16	4.51	3.30	1.99	1.10	753.0	150.0	20.0
125	9480	11.18	8.35	6.61	4.80	3.51	2.08	1.10	638.5	150.0	18.9
150	9440	10.05	7.89	6.11	4.39	3.17	1.82	0.92	761.1	150.0	20.7
175	9344	10.22	7.64	6.03	4.30	3.13	1.78	0.92	665.7	150.0	21.1
200	9328	9.55	6.94	5.45	3.80	2.75	1.56	0.92	655.0	150.0	24.0
225	9288	9.88	7.23	5.53	3.84	2.71	1.52	0.79	525.7	150.0	23.9
250	9248	9.38	6.69	5.07	3.47	2.41	1.34	0.75	490.7	150.0	26.7
275	9280	9.38	6.90	5.28	3.68	2.58	1.43	0.83	589.7	150.0	25.1
300	9280	9.59	7.02	5.41	3.80	2.66	1.52	0.83	590.8	150.0	24.3
325	9224	10.01	7.27	5.66	3.97	2.83	1.60	0.92	552.0	150.0	22.9
350	9232	10.68	7.98	6.28	4.55	3.30	1.95	1.01	630.1	150.0	19.6
375	9192	12.31	9.14	7.15	5.18	3.81	2.16	1.10	439.0	150.0	17.1
400	9168	11.06	8.22	6.45	4.64	3.30	1.86	1.01	511.3	150.0	19.4
425	9152	10.01	7.39	5.74	4.09	2.96	1.65	0.92	595.3	150.0	22.0
450	9176	9.80	7.06	5.41	3.80	2.66	1.56	0.97	532.8	150.0	23.9
475	9168	10.55	7.52	5.70	3.93	2.75	1.60	0.97	393.2	150.0	23.1
500	9152	10.26	7.31	5.74	4.05	2.92	1.69	0.97	528.0	150.0	22.3
Mean		10.39	7.69	6.01	4.30	3.10	1.79	0.96	613.8	150.0	21.4
Std.Dev		0.74	0.65	0.58	0.52	0.43	0.28	0.11	128.3	0.0	2.8
Var Coeff (%)		7.14	8.44	9.72	12.09	13.88	15.55	11.41	20.9	0.0	13.0
		Adjusted Mean Modulus (ksi)							564.60	150.00	20.71

Table-A VI-4 Missouri MODULUS results

	Load	**Measured Deflection (mils)**							**Backcalculated Modulus (ksi)**		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9360	5.36	4.32	3.58	2.84	2.28	1.34	0.57	421.7	11.1	37.1
25	9400	4.73	3.82	3.33	2.63	2.03	1.30	0.57	511.9	11.9	39.6
50	9408	3.64	2.99	2.66	2.26	1.95	1.39	0.75	910.2	31.3	31.9
75	9336	5.53	4.82	4.37	3.84	3.43	2.55	1.41	737.6	48.0	14.6
100	9352	5.07	4.32	3.87	3.34	2.88	2.04	1.01	703.2	16.4	20.9
125	9344	5.11	4.36	3.95	3.38	2.92	2.12	1.19	683.8	48.5	18.7
150	9544	9.05	7.89	7.11	6.27	5.50	4.07	2.06	442.8	29.1	9.5
175	9536	5.82	4.94	4.45	3.84	3.30	2.47	1.45	622.0	47.9	16.5
200	9432	5.86	5.15	4.70	4.05	3.64	2.68	1.54	697.6	39.3	14.1
225	9344	9.76	8.35	7.36	6.06	5.03	3.38	1.49	300.1	10.0	13.1
250	9352	5.70	4.78	4.12	3.38	2.75	1.86	1.10	492.9	10.0	26.9
275	9680	7.04	5.69	4.82	3.97	3.26	2.21	1.23	395.0	10.8	23.5
300	9656	5.82	4.86	4.20	3.47	2.92	2.12	1.23	531.4	20.9	22.5
325	9568	5.28	4.15	3.53	2.88	2.41	1.73	1.19	517.2	25.2	28.9
350	9592	4.90	4.20	3.70	3.13	2.71	1.91	1.05	699.6	23.7	22.9
375	9536	6.03	5.07	4.45	3.68	3.09	2.21	1.27	517.8	18.0	20.9
400	9528	4.19	3.49	2.91	2.42	2.07	1.52	0.92	714.6	31.7	31.6
425	9488	3.81	3.07	2.62	2.13	1.78	1.26	0.83	718.2	34.2	38.4
450	9400	4.31	3.53	3.04	2.51	2.03	1.34	0.75	639.2	11.6	38.8
475	9304	6.53	5.03	3.95	2.80	1.86	1.08	0.66	249.9	13.6	45.3
500	9392	3.69	3.03	2.58	2.09	1.73	1.13	0.61	731.2	13.9	46.2
Mean		5.58	4.66	4.06	3.38	2.84	1.99	1.09	582.8	24.2	26.8
Std.Dev		1.56	1.38	1.25	1.11	1.00	0.76	0.38	164.5	13.4	11.0
Var Coeff (%)		27.98	29.55	30.86	32.76	35.13	38.19	35.06	28.2	55.4	41.0
		Adjusted Mean Modulus (ksi)							566.39	19.02	22.09

Table-A VI-5 New Jersey MODULUS results

	Load	Measured Deflection (mils)							Backcalculated Modulus (ksi)		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9224	5.85	4.36	3.44	2.45	1.78	0.99	0.42	517.4	58.7	41.4
25	9128	5.80	4.32	3.35	2.41	1.74	0.95	0.38	505.6	58.3	42.2
50	9000	5.85	4.23	3.35	2.37	1.74	0.95	0.34	462.6	65.4	41.1
75	8816	5.85	4.27	3.39	2.41	1.78	0.95	0.34	472.6	60.5	40.0
100	8808	5.68	4.23	3.35	2.41	1.78	0.95	0.34	523.0	56.6	40.4
126	8840	5.34	3.92	3.14	2.25	1.65	0.90	0.29	543.9	64.3	43.1
150	8744	5.85	4.23	3.39	2.41	1.74	0.95	0.29	466.0	59.6	40.0
175	8672	5.51	4.05	3.27	2.45	1.82	0.95	0.34	550.7	62.4	38.9
200	8640	5.55	3.79	2.97	2.12	1.52	0.77	0.25	417.4	68.4	46.2
225	8640	5.72	3.97	3.10	2.16	1.52	0.77	0.29	430.1	54.0	46.9
250	8568	5.80	4.10	3.22	2.29	1.61	0.82	0.25	451.4	49.7	44.0
275	8624	6.02	4.27	3.39	2.45	1.78	0.99	0.42	402.8	72.3	37.5
300	8616	5.89	4.27	3.35	2.41	1.74	0.95	0.42	437.3	62.6	39.1
326	8600	5.00	3.75	3.10	2.29	1.65	0.95	0.38	630.3	69.0	40.4
350	8504	5.34	3.88	3.05	2.16	1.61	0.82	0.29	501.2	58.6	44.0
375	8496	6.74	4.27	3.05	2.00	1.43	0.73	0.25	247.3	63.3	48.5
400	8536	5.42	3.84	3.01	2.08	1.48	0.73	0.29	483.9	48.2	48.8
425	8576	5.55	3.97	3.10	2.20	1.65	0.90	0.42	430.3	76.2	41.0
450	8560	5.93	4.14	3.31	2.41	1.78	0.99	0.42	385.3	84.4	36.8
475	8560	6.57	4.36	3.44	2.41	1.74	0.99	0.42	294.9	83.6	37.4
500	8512	6.82	4.62	3.52	2.50	1.78	0.95	0.42	304.2	62.7	37.9
Mean		5.81	4.14	3.25	2.32	1.68	0.90	0.35	450.4	63.8	41.7
Std.Dev		0.45	0.22	0.16	0.14	0.11	0.09	0.06	90.5	9.5	3.6
Var Coeff (%)		7.73	5.40	5.07	6.21	6.83	9.89	18.76	20.1	14.9	8.6
		Adjusted Mean Modulus (ksi)							429.63	60.80	40.30

Table-A VI-6 New York MODULUS results

	Load	Measured Deflection (mils)							Backcalculated Modulus (ksi)		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9681	13.10	10.23	8.25	5.98	4.36	2.39	1.04	756.1	23.2	24.0
50	9578	13.94	10.79	8.72	6.35	4.64	2.57	1.11	664.6	24.2	22.0
100	9566	12.76	9.73	7.87	5.76	4.29	2.44	1.02	612.2	35.7	22.9
150	9494	12.91	9.67	7.82	5.66	4.16	2.29	0.95	594.5	31.7	23.9
200	9514	12.05	9.18	7.34	5.37	3.98	2.19	0.88	662.7	33.6	25.1
250	9490	12.83	9.77	7.99	5.87	4.35	2.51	0.98	619.3	35.5	22.2
300	9471	11.77	8.39	6.51	4.58	3.28	1.78	0.74	473.8	38.3	29.8
350	9431	12.83	8.71	6.64	4.67	3.33	1.83	0.78	330.8	41.6	28.6
400	9399	12.27	8.64	6.51	4.60	3.32	1.82	0.63	382.6	41.0	28.9
450	9367	12.74	9.36	7.44	5.37	3.96	2.26	0.95	465.8	40.4	23.9
500	9455	11.61	8.62	6.94	5.22	3.97	2.40	1.10	458.3	63.2	23.2
Mean		12.62	9.37	7.46	5.40	3.97	2.23	0.93	547.3	37.1	25.0
Std.Dev		0.66	0.75	0.75	0.59	0.47	0.29	0.15	132.8	10.7	2.8
Var Coeff (%)		5.24	8.03	9.99	11.01	11.80	12.94	16.59	24.3	28.7	11.3
		Adjusted Mean Modulus (ksi)							526.46	34.53	23.39

Table-A VI-7 Pennsylvania MODULUS results

	Load	Measured Deflection (mils)							Backcalculated Modulus (ksi)		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9032	3.42	2.84	2.52	1.99	1.58	0.92	0.41	1540.0	58.6	63.7
25	9264	3.70	3.14	2.77	2.23	1.75	1.09	0.37	1540.0	33.8	68.8
50	9288	3.42	2.76	2.44	1.99	1.53	0.96	0.37	1540.0	74.7	63.3
75	9304	3.74	3.09	2.73	2.19	1.71	1.05	0.41	1540.0	34.4	69.9
100	9288	3.25	2.76	2.48	1.99	1.62	0.96	0.37	1540.0	38.1	80.2
125	8976	3.09	2.63	2.35	1.95	1.62	1.05	0.41	1540.0	52.6	70.4
150	9320	2.92	2.50	2.27	1.91	1.62	1.09	0.49	1540.0	83.4	68.1
175	9248	3.46	2.97	2.68	2.27	1.88	1.30	0.57	1540.0	137.3	45.6
200	9432	3.25	2.80	2.52	2.15	1.84	1.26	0.61	1540.0	61.4	64.1
225	9288	3.33	2.80	2.44	2.23	1.84	1.26	0.53	1540.0	61.4	60.6
250	9256	3.62	3.09	2.77	2.31	1.97	1.34	0.66	1540.0	121.6	44.4
275	9288	3.46	2.97	2.68	2.23	1.88	1.30	0.61	1540.0	138.3	46.1
300	9344	3.70	3.18	2.77	2.27	1.93	1.21	0.53	1540.0	93.7	48.2
325	9304	3.13	2.67	2.40	2.03	1.66	1.17	0.57	1540.0	61.4	68.6
350	9520	3.50	3.01	2.77	2.27	1.88	1.30	0.61	1540.0	139.7	46.6
375	9232	4.07	3.52	3.18	2.64	2.19	1.46	0.70	1540.0	92.1	39.6
400	9280	4.16	3.56	3.22	2.68	2.19	1.42	0.66	1540.0	74.1	41.4
425	9272	3.99	3.48	3.10	2.64	2.19	1.51	0.78	1540.0	88.7	40.2
450	9328	4.65	4.07	3.63	3.00	2.45	1.63	0.74	1540.0	48.8	38.2
475	8904	4.44	3.90	3.51	2.96	2.45	1.67	0.82	1540.0	63.1	34.7
500	9160	5.68	5.04	4.58	3.86	3.19	2.13	1.02	1540.0	26.7	29.7
Mean		3.71	3.18	2.85	2.37	1.95	1.29	0.58	1540.0	75.4	53.9
Std.Dev		0.63	0.59	0.54	0.46	0.39	0.29	0.17	0.0	34.9	14.6
Var Coeff (%)		17.00	18.65	19.11	19.60	20.09	22.17	29.19	0.0	46.2	27.0
		Adjusted Mean Modulus (ksi)							1540.00	61.59	48.39

Table-A VI-8 Texas MODULUS results

	Load	**Measured Deflection (mils)**							**Backcalculated Modulus (ksi)**		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	9864	9.31	6.82	5.23	3.85	3.03	1.98	0.94	1285.4	150.0	21.4
25	9808	7.31	4.69	3.43	2.44	1.89	1.19	0.56	1285.4	150.0	38.4
50	9744	8.80	5.75	4.14	2.86	2.11	1.27	0.56	1285.4	150.0	30.0
75	9608	10.46	7.12	5.27	3.76	2.81	1.71	0.68	1285.4	150.0	21.0
100	9552	10.16	7.03	5.27	3.76	2.85	1.80	0.77	1285.4	150.0	20.9
125	9496	10.12	6.99	5.35	4.10	3.11	2.11	1.11	1285.4	150.0	19.8
150	9496	8.63	6.14	4.85	3.72	2.98	2.06	1.07	1285.4	150.0	21.4
177	9424	9.69	6.91	5.23	3.80	3.03	1.89	0.90	1285.4	150.0	20.8
200	9472	7.35	5.29	4.22	3.29	2.63	1.76	0.81	1285.4	150.0	30.2
225	9472	6.93	5.07	4.06	3.16	2.50	1.76	0.85	1285.4	150.0	33.8
250	9464	5.99	4.26	3.34	2.56	2.06	1.41	0.77	1285.4	150.0	43.1
275	9376	8.16	5.63	4.47	3.42	2.68	1.84	0.90	1285.4	150.0	27.1
300	9152	17.86	12.15	8.70	5.64	3.86	2.06	1.02	1063.5	61.2	14.0
325	9400	6.67	4.73	3.68	2.69	2.15	1.49	0.85	1285.4	150.0	37.7
350	9424	5.82	3.96	3.18	2.52	2.06	1.41	0.77	1285.4	150.0	43.2
375	9376	7.86	5.07	3.76	2.82	2.24	1.58	0.85	1285.4	150.0	31.8
400	9256	10.25	6.61	4.85	3.38	2.50	1.49	0.73	1158.9	144.0	22.6
425	9248	11.31	7.16	4.93	3.21	2.28	1.32	0.56	996.8	104.1	24.8
450	9296	9.35	6.05	4.26	2.82	1.97	1.10	0.47	1285.4	131.1	28.5
475	9312	6.63	4.05	2.84	1.80	1.18	0.53	0.17	1285.4	150.0	48.8
500	9400	6.42	3.96	2.63	1.62	1.10	0.57	0.21	1285.4	150.0	51.5
Mean		8.81	5.97	4.46	3.20	2.43	1.54	0.74	1255.1	142.4	30.0
Std.Dev		2.64	1.81	1.29	0.87	0.64	0.44	0.25	80.4	21.4	10.4
Var Coeff (%)		29.91	30.24	28.87	27.15	26.53	28.70	33.61	6.4	15.0	34.6
		Adjusted Mean Modulus (ksi)							1255.06	142.40	26.13

Table-A VI-9 Washington MODULUS results

	Load	Measured Deflection (mils)							Backcalculated Modulus (ksi)		
Station	(lbs)	W1	W2	W3	W4	W5	W6	W7	SURF(E1)	BASE(E2)	SUBG(E3)
0	8589	19.90	12.89	9.28	5.56	3.13	0.38	0.08	263.0	10.0	29.5
25	8990	13.33	10.44	8.18	5.63	3.55	1.04	0.16	850.0	10.2	27.8
50	8918	13.52	10.12	7.86	5.19	3.23	1.06	0.30	827.3	10.0	29.7
75	8827	10.74	8.51	6.69	4.49	2.76	0.96	0.39	850.0	15.4	32.0
100	8906	11.41	9.09	7.05	4.64	2.84	1.03	0.41	850.0	14.5	30.4
125	8910	11.83	9.15	6.94	4.63	3.11	1.40	0.50	775.0	24.0	23.3
150	8767	14.44	10.81	7.93	5.26	3.40	1.55	0.63	493.2	23.0	20.1
175	8811	17.73	12.57	8.95	5.72	3.54	1.58	0.56	323.5	19.3	18.9
200	8863	13.43	10.87	8.83	6.39	4.43	2.01	0.65	850.0	23.7	16.0
225	8791	13.38	10.65	8.57	6.02	3.96	1.68	0.54	850.0	14.6	19.8
250	8767	15.70	12.45	9.74	6.62	4.36	1.93	0.66	732.5	12.6	17.5
275	8875	14.96	12.30	9.95	7.00	4.65	1.97	0.51	850.0	12.4	16.8
300	8751	18.65	14.39	11.18	7.65	4.89	1.96	0.62	582.8	10.0	16.2
325	8744	15.96	12.51	9.88	6.80	4.47	1.82	0.53	776.2	10.0	18.6
350	8795	19.47	15.11	11.75	7.74	4.80	1.70	0.37	490.0	10.0	16.5
375	8799	20.91	16.65	13.08	8.72	5.42	1.72	0.28	437.0	10.0	14.6
400	8684	23.31	18.20	14.20	8.76	5.11	1.67	0.36	315.3	10.0	14.0
425	8648	26.53	19.74	14.02	8.24	4.43	1.24	0.35	198.5	10.0	15.0
450	8684	15.20	10.53	7.32	4.31	2.46	0.88	0.45	399.8	14.7	29.8
475	8501	21.81	15.11	10.44	5.98	3.54	1.39	0.72	245.6	11.5	19.3
500	8513	20.21	14.55	9.64	5.44	3.21	1.52	0.94	236.2	14.1	19.7
Mean		16.78	12.70	9.59	6.23	3.87	1.45	0.48	580.8	13.8	21.2
Std.Dev		4.25	3.04	2.21	1.37	0.85	0.43	0.20	252.9	4.8	6.0
Var Coeff (%)		25.33	23.91	23.08	22.03	21.98	29.77	41.38	43.5	34.7	28.4
		Adjusted Mean Modulus (ksi)							473.06	11.76	17.75

APPENDIX VII

DBSID PROGRAM RESULTS IN DIFFERENT TEST SECTIONS

Table-A VII-1 Alabama DBSID results

State Name	Station Number	Surface Modulus(ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thickness (Inches)
Alabama	1(0.000)	656.67	50.0	42.8	Surface=13.10 Base=18.4 Subgrade=132.0
	2(25.000)	801.50	51.8	42.8	
	3(50.000)	667.90	53.6	42.8	
	4(75.000)	952.25	55.4	42.8	
	5(100.000)	615.16	57.2	44.6	
	6(125.000)	803.02	57.2	44.6	
	7(150.000)	795.00	59.0	42.8	
	8(175.000)	603.37	59.0	44.6	
	9(200.000)	800.26	59.0	44.6	
	10(225.000)	919.45	59.0	44.6	
	11(250.000)	886.24	59.0	44.6	
	12(300.000)	1036.32	59.0	44.6	
	13(325.000)	1010.42	62.6	46.4	
	14(350.000)	949.21	60.8	44.6	
	15(375.000)	1048.51	60.8	44.6	
	16(400.000)	1108.01	62.6	44.6	
	17(425.000)	1311.04	62.6	46.4	
	18(450.000)	1188.45	62.4	44.6	
	19(475.000)	1022.31	64.4	46.4	
	20(500.000)	707.42	57.2	46.4	
Mean		894.13	58.6	44.5	
Std Dev		195.7	3.8	1.2	
Var Coeff (%)		21.89	6.48	2.70	

Table-A VII-2 Florida DBSID results

State Name	**Station Number**	**Surface Modulus (ksi)**	**Pavement Temp (F)**	**Air Temp(F)**	**Layer Thicknesses (Inches)**
Florida	1(0.000)	2765.78	55.4	48.2	Surface=4.9 Base=7.9 Subgrade=87.6
	2(50.000)	2059.84	55.4	48.2	
	3(100.000)	1648.79	55.4	48.2	
	4(150.000)	1122.23	55.4	48.2	
	5(200.000)	1210.86	53.6	48.2	
	6(250.000)	1793.33	55.4	48.2	
	7(300.000)	1773.69	55.4	48.2	
	8(350.000)	1625.39	53.6	48.2	
	9(400.000)	4219.48	53.6	46.4	
	10(450.000)	2376.95	53.6	48.2	
	11(500.000)	1403.59	53.6	46.4	
Mean		2000	54.58	47.87	
Std Dev		881.18	0.94	0.73	
Var Coeff (%)		44.06	1.72	1.53	

Table-A VII-3 Michigan DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
Michigan	1(0.000)	1016.53	66.2	64.4	Surface=4.20 Base=5.00 Subgrade=60.00
	2(25.000)	1101.64	68.0	64.4	
	3(50.000)	1213.98	68.0	64.4	
	4(75.000)	829.24	69.8	66.2	
	5(100.000)	825.01	69.8	64.4	
	6(125.000)	780.06	71.6	64.4	
	7(150.000)	1284.76	71.6	66.2	
	8(175.000)	1270.90	73.4	66.2	
	9(200.000)	1265.45	73.4	66.2	
	10(225.000)	1155.64	73.4	66.2	
	11(250.000)	984.94	75.2	66.2	
	12(275.000)	1156.22	75.2	68.0	
	13(300.000)	1073.19	75.2	66.2	
	14(325.000)	923.06	75.2	66.2	
	15(350.000)	949.19	77.0	68.0	
	16(375.000)	744.33	77.0	66.2	
	17(400.000)	828.75	78.8	68.0	
	18(425.000)	949.28	78.8	66.2	
	19(450.000)	748.36	78.8	69.8	
	20(475.000)	618.47	80.6	68.0	
	21(500.000)	682.35	77.0	68.0	
Mean		971.49	74.0	66.4	
Std Dev		205.21	4.04	1.50	
Var Coeff (%)		21.12	5.46	2.26	

Table-A VII-4 Missouri DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
Missouri	1(0.000)	336.06	42.8	50.0	Surface=13.80 Base=4.20 Subgrade=90.00
	2(25.000)	485.10	44.6	50.0	
	3(50.000)	648.37	44.6	50.0	
	4(75.000)	614.76	44.6	51.8	
	5(100.000)	579.77	44.6	50.0	
	6(125.000)	601.64	44.6	50.0	
	7(150.000)	381.58	42.8	51.8	
	8(175.000)	466.52	44.6	51.8	
	9(200.000)	565.45	44.6	53.6	
	10(225.000)	293.94	44.6	53.6	
	11(250.000)	328.25	46.4	53.6	
	12(275.000)	338.90	41.0	50.0	
	13(300.000)	432.64	39.2	50.0	
	14(325.000)	273.89	41.0	48.2	
	15(350.000)	497.58	41.0	48.2	
	16(375.000)	316.48	42.8	48.2	
	17(400.000)	391.01	41.0	48.2	
	18(425.000)	454.96	41.0	48.2	
	19(450.000)	509.23	39.2	48.2	
	20(475.000)	248.70	41.0	48.2	
	21(500.000)	495.92	41.0	48.2	
Mean		440.99	42.7	50.1	
Std Dev		120.35	2.1	1.9	
Var Coeff (%)		27.29	4.9	3.8	

Table-A VII-5 New Jersey DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
New Jersey	1(0.000)	516.76	102.2	77.0	Surface=7.90 Base=7.50 Subgrade=74.40
	2(25.000)	539.60	102.2	78.8	
	3(50.000)	531.83	102.2	80.6	
	4(75.000)	538.14	102.2	80.6	
	5(100.000)	620.40	102.2	78.8	
	6(126.000)	622.48	102.2	80.6	
	7(150.000)	601.02	104.0	82.4	
	8(175.000)	644.86	104.0	82.4	
	9(200.000)	510.63	107.6	82.4	
	10(225.000)	452.04	111.2	82.4	
	11(250.000)	159.39	111.2	82.4	
	12(275.000)	470.04	111.2	84.2	
	13(300.000)	432.69	111.2	84.2	
	14(326.000)	623.59	111.2	84.2	
	15(350.000)	432.84	113.0	82.4	
	16(375.000)	341.20	113.0	84.2	
	17(400.000)	518.42	113.0	82.4	
	18(425.000)	180.60	113.0	84.2	
	19(450.000)	452.63	114.8	84.2	
	20(475.000)	314.26	114.8	86.0	
	21(500.000)	345.19	114.8	86.0	
Mean		468.98	108.6	82.4	
Std Dev		137.24	5.1	2.3	
Var Coeff (%)		29.26	4.7	2.8	

Table-A VII-6 New York DBSID results

State Name	**Station Number**	**Surface Modulus (ksi)**	**Pavement Temp (F)**	**Air Temp(F)**	**Layer Thicknesses (Inches)**
New York	1(0.000)	537.09	80.6	78.8	Surface=5.0 Base=8.4 Subgrade=168.0
	2(50.000)	460.88	82.4	78.8	
	3(100.000)	490.60	82.4	78.8	
	4(150.000)	453.86	82.4	78.8	
	5(200.000)	529.10	82.4	78.8	
	6(250.000)	496.05	84.2	78.8	
	7(300.000)	422.13	84.2	80.6	
	8(350.000)	272.38	84.2	80.6	
	9(400.000)	392.92	84.2	80.6	
	10(450.000)	309.05	86.0	80.6	
	11(500.000)	289.04	86.0	80.6	
Mean		423.01	83.5	79.6	
Std Dev		95.44	1.7	0.9	
Var Coeff (%)		22.56	2.0	1.1	

Table-A VII-7 Pennsylvania DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
Pennsylvania	1(0.000)	1482.94	53.6	41.0	Surface=7.90 Base=9.60 Subgrade=204.00
	2(25.000)	1933.68	55.4	41.0	
	3(50.000)	1421.11	53.6	41.0	
	4(75.000)	1392.98	53.6	41.0	
	5(100.000)	1921.24	55.4	41.0	
	6(125.000)	2735.22	53.6	41.0	
	7(150.000)	2941.25	55.4	41.0	
	8(175.000)	2811.02	55.4	41.0	
	9(200.000)	2949.21	53.6	41.0	
	10(225.000)	2662.39	53.6	41.0	
	11(250.000)	2280.70	53.6	41.0	
	12(275.000)	2487.31	55.4	41.0	
	13(300.000)	1925.53	55.4	41.0	
	14(325.000)	2454.58	59.0	41.0	
	15(350.000)	2536.52	59.0	41.0	
	16(375.000)	1971.59	59.0	41.0	
	17(400.000)	1880.94	59.0	42.8	
	18(425.000)	2131.29	59.0	44.6	
	19(450.000)	1667.06	62.6	44.6	
	20(475.000)	1845.24	60.8	42.8	
	21(500.000)	1539.35	59.0	42.8	
Mean		2141.48	56.4	41.6	
Std Dev		508.96	2.8	1.2	
Var Coeff (%)		23.77	5.0	2.9	

Table-A VII-8 Texas DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
Texas	1(0.000)	4479.10	55.4	44.6	Surface=1.90 Base=8.40 Subgrade=48.00
	2(25.000)	3268.93	53.6	46.4	
	3(50.000)	4591.49	55.4	44.6	
	4(75.000)	2901.68	55.4	46.4	
	5(100.000)	3915.42	55.4	46.4	
	6(125.000)	5627.82	57.2	46.4	
	7(150.000)	1414.04	57.2	46.4	
	8(177.000)	2462.28	57.2	46.4	
	9(200.000)	1205.07	57.2	46.4	
	10(225.000)	410.64	57.2	46.4	
	11(250.000)	902.69	57.2	46.4	
	12(275.000)	477.36	59.0	48.2	
	13(300.000)	2249.91	60.8	48.2	
	14(325.000)	1221.23	60.8	48.2	
	15(350.000)	1037.48	62.6	48.2	
	16(375.000)	1021.33	62.6	48.2	
	17(400.000)	2398.87	59.0	46.4	
	18(425.000)	2912.64	59.0	46.4	
	19(450.000)	4002.07	59.0	46.4	
	20(475.000)	2817.02	59.0	44.6	
	21(500.000)	2583.10	60.8	48.2	
Mean		2471.44	58.1	46.7	
Std Dev		1470.48	2.5	1.2	
Var Coeff (%)		59.50	4.3	2.6	

Table-A VII-9 Washington DBSID results

State Name	Station Number	Surface Modulus (ksi)	Pavement Temp (F)	Air Temp(F)	Layer Thicknesses (Inches)
Washington	1(0.000)	230.56	82.4	66.2	Surface=4.60 Base=8.00 Subgrade=66.00
	2(25.000)	891.53	80.6	66.2	
	3(50.000)	767.72	82.4	66.2	
	4(75.000)	1083.21	82.4	66.2	
	5(100.000)	998.61	82.4	66.2	
	6(125.000)	691.13	82.4	64.4	
	7(150.000)	610.48	80.6	62.6	
	8(175.000)	398.21	78.8	62.6	
	9(200.000)	956.95	80.6	64.4	
	10(225.000)	887.92	80.6	64.4	
	11(250.000)	626.68	80.6	66.2	
	12(275.000)	755.85	80.6	64.4	
	13(300.000)	562.15	80.6	64.4	
	14(325.000)	635.67	80.6	64.4	
	15(350.000)	559.78	80.6	64.4	
	16(375.000)	554.89	80.6	64.4	
	17(400.000)	426.16	80.6	66.2	
	18(425.000)	266.09	78.8	62.6	
	19(450.000)	404.67	78.8	62.6	
	20(475.000)	260.09	78.8	64.4	
	21(500.000)	236.30	78.8	64.4	
Mean		609.74	80.6	64.7	
Std Dev		260.62	1.3	1.3	
Var Coeff (%)		42.74	1.6	2.0	

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