A Thesis

entitled

A MODEL FOR THE PREDICTION OF SUBGRADE SOIL RESILIENT MODULUS FOR FLEXIBLE-PAVEMENT DESIGN: INFLUENCE OF MOISTURE CONTENT AND CLIMATE CHANGE

by

Beresford Obafemi Arnold Davies

Submitted as partial fulfillment of the requirements for

the Master of Science Degree in

Civil Engineering

Andrew Heydinger

Adviser: A. G. Heydinger

Graduate School

The University of Toledo

December 2004

An Abstract of

A MODEL FOR THE PREDICTION OF SUBGRADE SOIL RESILIENT MODULUS FOR FLEXIBLE-PAVEMENT DESIGN: INFLUENCE OF MOISTURE CONTENT AND CLIMATE CHANGE

Beresford Obafemi Arnold Davies

As partial fulfillment of the requirements for

The Master of Science Degree in

Civil Engineering

The University of Toledo

December 2004

Subgrade soil plays a very important role in the construction of roadways. Before the use of asphalt in the construction of roadway, roads were being constructed based on experience. The introduction of paving asphalt in road construction has led to the development of engineering procedures and designs for the methods of construction. The resilient modulus of the underlying material supporting the pavement is now considered as a key material property in the AASHTO mechanistic-empirical design procedure. Attempts have been made by researchers to predict the Subgrade resilient modulus from laboratory/field experimental methods based on the soil properties. This research seeks to develop a model for predicting the subgrade resilient modulus due to environmental conditions by considering the seasonal variation of temperature

and moisture content which affects the soil. The limitation of this research model is that it cannot be used universally since environmental conditions vary from place to place, however, it can be modified to suit other local environmental conditions. The detrimental effect of low resilient modulus of subgrade soil is observed in the damaged analysis.

DEDICATION

For all his manifold goodness, this work is dedicated to the one true, omniscience, omnipotent and invisible God who has guided me; and all who have contributed in making it a dream come true.

“In his might and power we find what our souls longed for, our hearts yearned for; the things our hearts conceived our hands have worked towards.” *Obafemi Davies*

“The spirit of man that has laboured diligently will not rest till that which is due is honoured.” *Obafemi Davies*

“Education is not the taming or domestication of the soul's raw passions -- not suppressing them or excising them, which would deprive the soul of its energy -- but forming and informing them as art.” *Allen Bloom*

ACKNOWLEDGEMENTS

The fever of learning is over and my work is done. With a grateful heart my thanks goes to God for his guidance and inspiration.

This work is partially complete if the effort and contribution by the following is not appreciated.

Thanks to my academic mentor and adviser Dr. Andrew Gerald Heydinger for his support and supervision of this work.

Dr. Eddie Y. Chou and Dr. Brian W. Randolph, your role as committee members will always be remembered.

Dr. Douglas K. Nims, I am proud of you, your intervention in my critical situation will not go unrewarded.

Spirituality and family love is just as important as searching for knowledge. Reverends Greg and Peg Sammons and family, you have proved yourselves as emulated examples and mentors. God bless you.

For your patience, love and prayers, I appreciate you mama and papa and my faithful wife, Olorunfumi you are special and loved.

TABLE OF CONTENTS

LIST OF SYMBOLS

A	amplitude
A_0, A_1, A_2, A_3, A_4, A_5	regression constants
B	vertical shift in sinusoidal equation, equal to the mean of the temperature or volumetric water content
C	cohesion
$f(t')$	function of time, used in the sinusoidal equation
k,	model parameter used for various models
k_1, k_2, k_3, k_4, k_6	regression constants, constants depending on soil physical properties
M_C	moisture content
M_R	resilient modulus
$M_{R(mean)}$	mean resilient modulus
n	porosity
n, m	exponential constant
P_a	atmospheric pressure
p_m	mean normal stress
q_m	mean deviator stress
r	coefficient of regression
R^2	coefficient of determination
SN	pavement structural number, function of the thickness and modulus of each layer and the drainage conditions of base and subbase
S_o	combined standard error of the traffic prediction and performance

$S_{u1.0\%}$	strain at 1% during conventional unconfined compression test
S(%)	degree of saturation
t	day of the year, used in calculating the angular frequency ϕ
T	horizontal shift, a guess used in calculating the angular frequency
U_c	unconfined compression strength,
U_f	Relative Damage
W_{t18}	predicted number of 18-kip (80-kN) axle load applications to time t
x	parameter that depends on y in the regression equation
y	parameter, function that depends on x in the regression equation
Y	temperature or volumetric water content parameter, function that depends on other variables in the sinusoidal equation
Z_R	standard normal deviate,
ΔPSI	change in serviceability, difference between initial design serviceability index, p_o, and design terminal serviceability index p_t
ε_r	resilient strain in direction of axial stress
θ	bulk stress
θ_w	volumetric water content
π	mathematical constant
σ_1	major principal stress
σ_2	intermediate principal stress
σ_3	confining stress (minor principal stress)
σ_d	repeated deviator stress, difference between the major and minor principal stress
σ_{di}	deviator stress at which the slope of the graph of the resilient modulus versus the deviator stress changes

σ_{oct}	octahedral normal stress
τ_{oct}	octahedral shear stress
ϕ	function, difference between the day of the year and the horizontal shift
φ	friction angle
ω	angular frequency

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Background Knowledge

The construction of roadways can be dated as far back as 3000 B.C during the Persian Empire (Microsoft Encarta, 2004). Since then, progress has been made in constructing roads on firm foundations (i.e. subgrades). The construction method used by the Romans over 400 years ago resulted in a high quality road system which required very minimal maintenance (Microsoft Encarta, 2004). The reason for this was that great attention was paid to the subgrade. Such methods cannot be adopted today because of the huge volume of excavation and type of construction materials that are required, so the methods used by the Romans are not cost effective.

A high state of development in the western world in road construction is evident in the 15th and 16th centuries under the Aztecs in Mexico, the Maya in Central America and the Incas in South America. These roads were the first American highways (Microsoft Encarta, 2004).

The development of techniques in road construction continued to improve and in 1870, the improvement in materials came with the advent of asphaltic concrete when in Newark, New Jersey, the first asphaltic roadway was constructed (Microsoft Encarta, 2004). The use of asphalt and the popularity of the automobile triggered the dawn of design methods. The aim of these design methods is geared towards better performance and longevity of pavement so that end users could ride comfortably on this major, politically-influenced transportation infrastructure.

With the continuous improvement in the methods and materials used in road construction, several design methods have been developed to account for the importance of the subgrade in design procedures. Until quite recently, the empirical method of designing pavement was the best method known universally. This method relied on index-value-based characterization of material properties such as layer coefficient, California bearing ration (CBR-value) or R-value, correlation with past performance of other pavement as well as judgment from an engineering view point for design strategy selection (Erlingsson, 2004).

With the increase in vehicular traffic, tire pressure, truck weight and introduction of new pavement materials, empirical design procedures require modifications and tend to create uncertainties with changes in site and climatic conditions and performance. Also, the extrapolations the method required are outside the limit which adds to the uncertainty (ORITE, 2004). These limitations together with other factors such as improvement in construction techniques, different subgrade conditions, and the long-term effects that climate and aging has on pavement render the empirical design procedure vague in its application (Erlingsson, 2004).

To mitigate the difficulty associated with the empirical procedures, the mechanistic-empirical (M-E) pavement design method is being developed with the goal of adequately predicting pavement response and performance. In the M-E design method, the basic principles of engineering mechanics are utilized to determine how pavement structures respond to traffic loading and the design methods are improved upon to predict distress or the change in performance with time (ORITE, 2004).

According to Erlingsson (2004), a very important factor when using a mechanistic-empirical design method is the need to use testing equipment and set-ups in the laboratory which adequately simulate the most important aspects of the real behaviour of pavement. Otherwise one cannot expect that predictions will reflect real-world factors and results or predict actual pavement performance.

The most important factors influencing the performance and distress development of pavement structures are (Erlingsson, 2004):-

i. the cross-section of the pavement structure;
ii. the traffic (axle) loading of the structure;

iii. the climatic conditions the pavement will be exposed to during its entire service life; and

iv. the material properties of the different layers in the pavement structure.

1.2 Research Statement

The mechanistic-empirical design method is based largely on material properties that can be determined in the laboratory or in the field. The most important material property input parameters for the flexible pavement structure are resilient/dynamic modulus of asphalt concrete, resilient modulus of base/subbase, and resilient modulus of the subgrade. Among these material properties, those associated with asphalt concrete and subgrades are known to fluctuate seasonally. Therefore seasonal evaluation of pavement material properties is essential for the M-E procedures (ORITE, 2004).

The resilient/dynamic modulus has been regarded as one of the main mechanistic properties of asphalt concrete. This modulus represents the absolute value of the complex modulus, which is used to characterized time-dependent responses of asphalt concrete under a repeated sinusoidal loading (ORITE, 2004).

Determining or estimating accurately this mechanistic property of asphalt concrete has led to the development of analytical models to predict the state of stress in a pavement under simulated wheel and environmental loading conditions. These models developed have been based on multi-layer elastic (MLE) theory and/or finite element (FE) analysis (C-SHRP, 2000). The MLE models are considered satisfactory for predicting flexible pavement response under external wheel loads and are also relatively easy to operate. However, they are not capable of predicting pavement response associated with environmental loading (i.e. that are due to daily temperature changes, temperature gradients, moisture variations, etc.). The FE models are capable of considering both wheel and environmental loading conditions. However, they are relatively complicated to operate and time-consuming (C-SHRP, 2000). Hence, with the shortcomings of using these previously developed models in predicting the state of stress in a pavement structure, this research seeks to develop a statistically based model for the prediction of subgrade soil resilient modulus for flexible-pavement design by considering the influence of moisture and climate change (i.e. daily temperature changes, temperature gradient and other related factors) on the resilient modulus for use with the M-E procedures under development.

1.3 Objectives

The main goal of this research study is to develop a model that can be used to predict subgrade soil resilient modulus under pavement structures. This can be achieved by analyzing statistically, the available data obtained from the

FHWA/LTPP seasonal monitoring program (SMP) in order to demonstrate the effect of variations in temperature and moisture content on pavement subgrade.

1.4 Methodology

This research study is purely a desk-study which is computer based and will consists of two major tasks. Firstly, the collection of necessary data and information was done. Most of the data was obtained from the seasonal monitoring program under the Strategic Highway Research Program (SHRP) through United States and Canadian pavement data base (DataPave online version release-18, 2004;http://www.datapave.com).

Secondly, statistical and probabilistic methods were employed in the analysis in order to incorporate environmental conditions and soil properties in developing a mathematical model to predict subgrade resilient modulus. The model developed will model subgrade soils properties for different pavement designs and enhance the use of the mechanistic-empirical design method by state departments of transportation, since the M-E procedures rely on material properties. It is assumed that this model can be used throughout the cold climatic regions with only slight modifications for areas where there is extremely marked difference in environmental conditions from those considered.

The limitation associated with the model is that it cannot be used universally; therefore, a similar approach has to be used to develop models that can be used in environmental situations completely different from cold, wet climates in the northern United States.

CHAPTER TWO

LITERATURE REVIEW

A literature review was conducted for this study. During the search for related studies, it was discovered that Seed et al (1955) originally introduced the concept of resilient modulus of a material, and defined this material property as " the ratio of applied dynamic stress σ_d to the resilient or elastic strain component ε_r under a transient dynamic pulse load" (Kyatham and Wills, 2003).

Until quite recently, most of the related research on estimating the resilient modulus of subgrade soils, has not dealt with resilient modulus in relation to environmental factors and pavement design. A substantial amount of research has been directed towards the effects of moisture, density, and stress condition on resilient properties, but less effort has been spent on factors important for cold region pavements, such as temperature, unfrozen moisture content, and freeze-thaw cycling (Simonsen et al, 2002).

Johnson et al. (1978), Cole et al. (1986), and Berg et al. (1996) investigated the resilient properties of granular materials from frozen to thawed conditions. Basic findings from these investigations include: (1) significant loss of strength upon thaw for most soils tested; (2) a gradual regain of strength as moisture drained from the soil during the recovery period; and (3) a two-to three-order of magnitude increase in strength of all materials at subfreezing temperatures (Simonsen et al, 2002).

Thompson and Robnett (1979) conducted research with Illinois soils to study their properties which control the resilient behavior of this soil. According to them, resilient behavior of soils is the most significant factor that influences the design thickness of subgrade soil support in flexible pavement. This is well noticeable when the soil support values are low, especially in the case of the Illinois soils.

> "Recognition of the importance of the resilient behavior of flexible pavements is reflected by the fact that many current flexible pavement thickness design philosophies incorporate 'limiting deflection' or 'limiting asphalt concrete radial strain' criteria" (Thompson and Robnett, 1979).

In the study by Thompson and Robnett (1979), 50 individual soil samples were considered of which samples representing approximately 39% of the land area of Illinois were included. These samples were evaluated for selected soil properties (common soil index properties) and properties like organic carbon content and pH. Tests, (repeated load testing) were carried out on the samples. Previous and proposed techniques together with information concerning factors that greatly influence the resilient properties of fine-grained soils were considered. The results from this study indicated that the resilient properties of fine-grained soils in Illinois range over a wide spectrum and that a substantial variability in resilient properties is a result of effect of degree of saturation. Three procedures; soil property based, degree of saturation and soil classification were developed for predicting the resilient response in the analysis and design of flexible pavements. Thompson and Robnett (1976) state that the laboratory resilient testing procedures adopted in this study can be used to evaluate the resilient properties of soil for any desired conditions of moisture and density in situations where the procedures they developed cannot be sufficiently accurate for a specific case. In their conclusion, it was observed that natural soil characteristic and compaction conditions (moisture content) are primarily responsible for controlling resilient behavior.

Li and Selig (1994) investigated the resilient modulus for fine-grained subgrade soils. They determined that the soil physical state (moisture content and dry density) has a significant influence on the resilient modulus of fine-grained subgrade soils. Hence they considered these influences in predicting the resilient modulus. The resilient modulus for most situations they said depends on three primary factors and these are (1) stress state; (2) soil type and its structure and (3) soil physical state. The approach and principles that were developed in this study may be applied generally, but one should note that the correlation and parameters developed and compiled were based primarily on compacted fine-grained subgrade soils.

In an effort to determine the seasonal variation of resilient modulus, Jin et al (1994) presented a description of the results on the seasonal variation of resilient modulus of subgrade soils and also conceptualize a theoretical model which accounts for temperature and moisture effects on the resilient modulus of granular materials. To evaluate the seasonal variation of moduli under field conditions, monitored ranges of temperatures, moisture contents, dry densities, and stress conditions were used. The results indicate that the resilient modulus value decreases as the water content increases up to a certain bulk stress. To predict the resilient modulus under various environmental conditions, multiple regression analysis was done and the equation developed was recommended for the estimation of resilient moduli for the design of flexible pavements in Rhode Island and elsewhere with similar soil conditions.

Lee et al (1997) carried out resilient modulus tests on three (3) clayey subgrade soils with repeated-loading triaxial test equipment. This study was to develop a correlation between resilient modulus and the conventional unconfined compression test, taking into consideration factors (compaction, moisture content and dry unit weight) that affect the resilient modulus of cohesive soil. They determined that soil samples compacted statically have higher M_R when compared to those made by kneading compacting. A relationship between soil moisture suction and M_R exists. The moisture content and dry unit weight have lesser influence on M_R for soil samples compacted using low energy. The conclusions drawn from this study are (1) the stress at 1% strain in the conventional unconfined compression test is a good indicator of the resilient modulus and the relationship between M_R and $S_{u1.0\%}$ for a given soil is unique regardless of moisture content and compactive effort; (2) the proposed correlation equation (2.0), may be applicable for different clayey soils since the relationship between M_R and $S_{u1.0\%}$ is similar for different cohesive soils prepared using laboratory compaction.

$$M_R = 695.4\,(S_{u1.0\%}) - 5.93(S_{u1.0\%})^2 \qquad (2.1)$$

Tian et al (1998) studied the variation of resilient modulus of aggregate base and its influence on pavement performance. They investigated the effects of gradation and moisture content on the resilient modulus values of granular materials from Richard Spur (RS) aggregate. Their observations from the AASHTO T 294-94 testing procedure were: (1) the variability of resilient modulus values due to three different gradations is found to be within 10 – 50%; (2) the pavement designed by using the median gradation required less thickness with good performance, while a coarser limit gradation produced resilient modulus values closer to that of the median gradation and is expected to cause less damage in pavements under saturated conditions and also provide faster drainage; (3) there is an increase in cohesion and a decrease in the friction angle as the fines increase in gradation; (4) increase in moisture leads to a decrease in resilient values. A model was developed that includes the most important factors that have influences on resilient modulus values, thus it can be used to predict the resilient modulus values of similar aggregates under similar compaction states.

The difficulties, complexities and high costs involved in performing cyclic M_R tests led Kim et al (2001) to develop an alternative testing technique for subgrade soils using static triaxial compression (TX) test. The effect of strain amplitude, loading frequency, mean effective stress, and the number of loading cycles on resilient modulus of subgrade soils was investigated. Cyclic M_R, static TX, and resonant column-torsional shear tests were performed to evaluate the deformational characteristics. The conclusions drawn from this study were that (1) within the range of stiffness below about 350 MPa, both the standard and the alternative M_R testing systems provide reliable M_R values with specimen grouting on the end caps; (2) the moduli of subgrade soils increase almost linearly as a function of the logarithm of loading frequency, the effects of loading frequency are in the range of 3.2 to 7.0%, and the frequency was correlated with plasticity index; (3) moduli obtained from standard M_R tests overlapped nicely with M_R values obtained from the proposed alternative with a 95% confidence interval of ±3.59%.

Simonsen and Isacsson (2001) were interested in studying the soil behaviour during freezing and thawing using variable and constant pressure triaxial tests (VCP and CCP). They investigate three types of soil (two subgrade soils and one subbase material) at selected temperatures between +20 and -10 degree centigrade during one full freeze-thaw cycle. After analyzing the soils it was found that at nonfreezing temperatures, the VCP moduli are approximately 45 - 55% lower than the corresponding CCP moduli and decreases to 20% for all soils at subfreezing temperatures. The values of the resilient modulus computed from the CCP and VCP tests are compatible, provided that the product of mean deviator stress (q_m) and mean of mean normal stress (p_m) is similar in both tests for high axial and radial stresses. They were unable to establish any concluding effect of freeze-thaw on the resilient behaviour of the soils.

Simonsen et al (2002) did a similar study to a previous study done in 2001 with Isacsson. This time, five soils from different sources in New Hampshire were investigated in order to characterize their behaviour during seasonal frost conditions. The results indicate that all soils exhibited a substantially reduced resilient modulus after the freeze-thaw cycle. Equations for selecting the resilient modulus for different conditions were presented.

Considering one of the most important factors that affect pavement design and performance, Al-Abdul Wahhab et al (2001) studied the variation effects of temperature across pavement in arid environments. This led them to the development of temperature correction factors and resilient modulus estimation equations using statistical procedures.

Hossain et al (1996) were interested in the seasonal variations in pavement material properties and behaviour due to climatic effects (temperature and moisture variations). An NDT-evaluation of subgrade response in asphalt pavements was performed using the falling weight deflectometer (FWD). The elastic layer theory was used to back-calculate the subgrade moduli. They found that the variation in subgrade moisture content was not very significant over the seasons and the subgrade response pattern, in terms of subgrade moduli versus subgrade moisture content, simulated sine-shaped forms that indicate a possible temperature effect.

CHAPTER THREE

FLEXIBLE PAVEMENT DESIGN METHODS AND RESILIENT MODULUS

3.1 Flexible Pavement Design Methods

Different flexible pavement design methods have been developed in the past. These methods, including the latest mechanistic-empirical method which is currently under review for full scale adoption, seeks to provide for better performance and longevity of pavement structures. Several soil parameters have been considered in their development but are not limited to (i) California Bearing Ratio (CBR) of the soil (ii) shear strength (iii) strain and (iv) deflection.

An empirical method that relies on strength testing was first used by the California highway department in 1929 where pavement thickness was related to the CBR (i.e. the penetration resistance of a subgrade soil relative to a standard crushed rock). This method is disadvantageous because it is limited only to certain set of environmental, material and loading conditions (Huang, 1993), and its application in other situations requires a new method to be developed. The limiting shear failure method considers the angle of internal friction and cohesion of subgrade soils as major properties for pavement thickness determination.

The Boussinesq equation for deflection was modified by the Kansas State Highway commission in 1947 (Huang, 1993). The modification limits the deflection of subgrade to 0.1inch in the limiting deflection method. This method is disadvantageous in that, while it considers deflection as the design criterion, pavement never fails as a result of deflection but excessive strains as it is subjected to stress.

Regression methods based on pavement performance were also developed. The AASHTO regression equation is

$$\log W_{t18} = Z_R \cdot S_0 + 9.36 \cdot \log(SN + 1) - 0.20 + \frac{\log[\Delta PSI / (4.2 - 1.5)]}{0.4 + 1094/(SN + 1)^{5.19}}$$

$$+ 2.32 \cdot \log M_R - 0.87 \qquad (3.1)$$

However, due to variations in climatic conditions from the road test site makes its application questionable.

The mechanistic-empirical method was first developed by Kerkhoven and Dormon in 1953 (Huang, 1993) which considered vertical compressive strain on the surface of subgrade. This method makes use of an input (a wheel load) as relates to an output (stress/strains) for the design. The Asphalt Institute (AI) has adopted this method. It has the advantage of predicting the type of distress a pavement will suffer, and the possibility of extrapolating from limited data (Huang, 1993). This method is gaining firm footing in the worldwide community of highway design of pavement.

A mechanistic-empirical design method for a flexible pavement means application of the principles of engineering mechanics to evaluate the response of pavement structures to traffic loading and much improved design methods to carry out distress prediction or how performance changes with time. Using a method based on the principles of engineering mechanics ensures a fundamental understanding of how the pavement structure responds to a certain action or loading conditions. This more realistic approach should also secure the needed flexibility. In other words, the method should be able to deal with new situations such as new pavement materials and loading situations of individual wheels; their number, different weights and tire pressures, need to be considered, as well as environmental variables, such as changing temperature, frost/thaw conditions and moisture content during the service life of the pavement.

The goal of the 2002 Design Guide is the incorporation of factors that other pavement design methods have failed to consider in their development. It is expected that the 2002 Design Guide will contain unbiased procedures in its design and analysis with the possibility of including design methods for rigid, flexible and semi-rigid pavements. Thus an improvement over currently used design methods for pavement response and performance is expected from the mechanistic-empirical design procedures. The flexibility of this method will allow pavement designers to: (http:www.2002designguide.com/projover.htm)

- Create more efficient and cost- effective designs
- Improve design reliability
- Reduce life cycle costs
- Increase support for cost allocation
- Predict specific failure modes (so they can be minimized)
- Extrapolate from limited field and laboratory data
- Better evaluate the impact of new load levels and conditions
- Make better use of available materials
- Minimize premature failures
- Better characterize seasonal/drainage effects
- Improve rehabilitation design
- Bring daily, seasonal, and yearly changes in materials, climate, and traffic into design process.

In considering moisture content and temperature effect on pavement structure design and on subgrade, the 2002 Design Guide uses the Federal Highway Administration's (FHWA) Integrated Climate Model (ICM) as part of the guide since the ICM is a model that incorporates sub-models of precipitation, infiltration and drainage, climate-materials-structure and frost heave and thaw settlement.

3.2 Resilient Modulus

The resilient modulus can be defined as the elastic modulus based on the recoverable strain under repeated loads (Huang, 1993). Mathematically, the resilient modulus equals the applied deviator stress divided by the recoverable strain that occurs when the applied load is removed from the test specimen in a repeated load triaxial test.

$$M_R = \sigma_d / \varepsilon_r \tag{3.2}$$

In any mechanistically based design/ analysis procedure for flexible pavement, the resilient modulus of pavement materials is a prime input material property necessary for determining deflection in layered systems, resilient stress, and strains and for analyzing the performance of the system.

3.2.1 Determination of Resilient Modulus

The repeated load triaxial test can be used to determine the resilient modulus of both fine-grained and coarse-grained soil. The testing device and setup is shown in Figure 3.1. The procedures are given in AASHTO T294 – 94.

The use of an internal measuring device as required by the AASHTO T274 – 82 and T292 – 91I methods has the “advantage of eliminating equipment deformation, end restraints and piston friction” (Huang, 1993). However, because of many short-comings, changes were made by using external linear variable deflection transducer (LVDT) for deformation measurements of all soil types and a complete modification of loading sequences. Thus low deviator stress that produces high variability and high deviator stress that cause sample failures are eliminated (Huang, 1993).

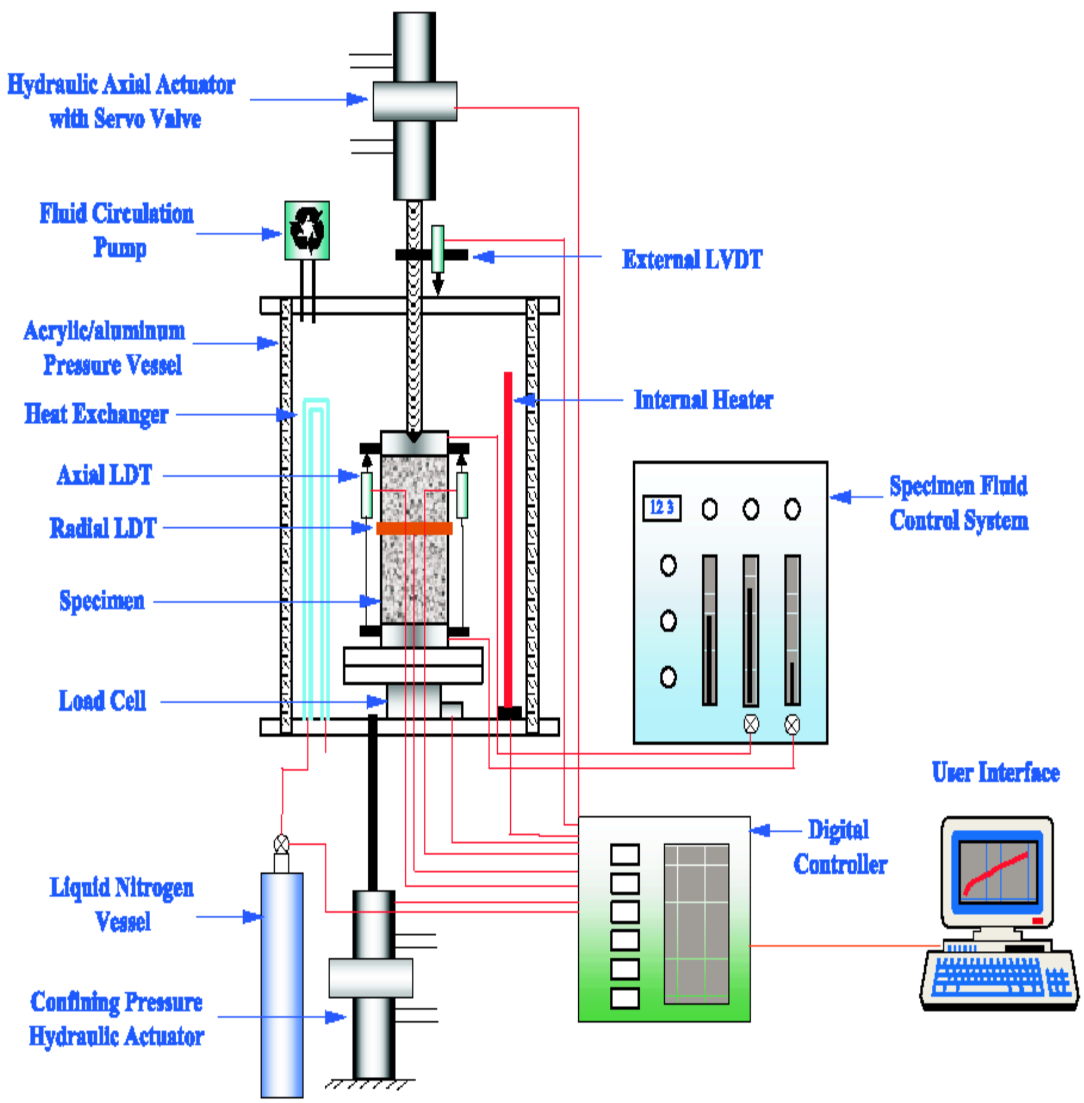


Figure 3.1 — Closed-loop Servo-hydraulic Test Apparatus (from Simonsen and Isacsson, 2001).

As reported by Mohammad et al, M_R values were higher for specimens with the internal LVDT than for specimen with external LVDT. Except for the different LVDT locations, the T294 – 94 requires haversine waveform rather than the triangular or rectangular waveform required by the AASHTO T274 – 82 and T292 – 91I methods (Tian et al, 1998).

3.2.2 Resilient Modulus and Fine-Grained Soil

The resilient modulus of fine-grained soils is not a constant stiffness property, but is dependent upon different factors (Li and Selig, 1994). According to Li and Selig (1994), three categories of factors affect the magnitude of fine-grained soils considerably, and they are (1) loading condition or stress state; (2) soil type and its structure; and (3) soil physical state.

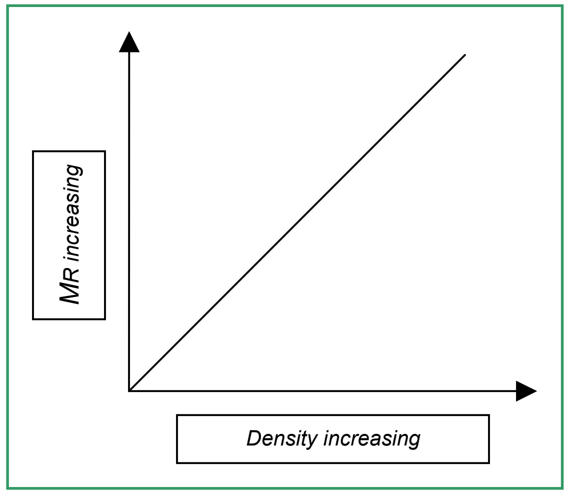
Despite the linear proportionality between resilient modulus and confining pressure, researchers have shown that confining pressure has much less significant effect than deviator stress for fine-grained subgrade soils, especially for clay soils. Lee et al (1997) studied the resilient modulus of cohesive soils and summarized the influential factors affecting resilient modulus value as (i) stress i.e. the maximum axial deviator stress (ii) methods of compaction (iii) compaction parameter that include moisture content and dry unit weight (iv) thixotropy and (v) soil moisture suction.

3.2.3 Resilient Modulus and Coarse-Grained Soils

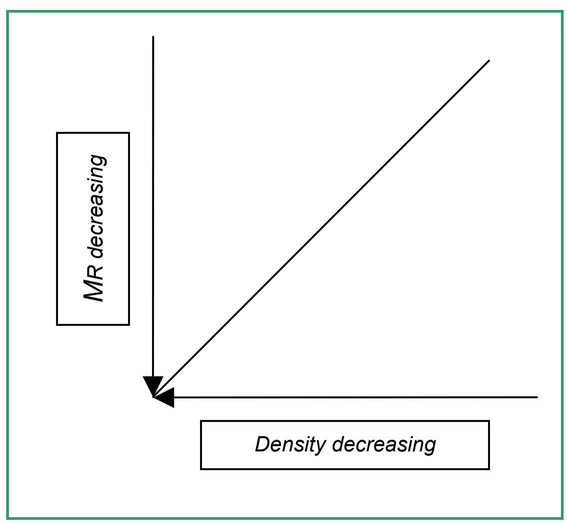
Research on aggregates and granular subgrade soils indicates that resilient modulus is a material property that depends on gradation, density and moisture content of the soil. The resilient modulus of coarse soils decreases significantly as the gradation changes from coarse to fines, as the density decreases and as the moisture content increases (Heydinger, 2002).

From a practical view point, road pavement structures are constructed with open-graded or dense-graded materials for drainage purposes and in studying the dynamic response of these sub-layers, researchers have reported that the dense-graded aggregates exhibits highest M_R values and those values of M_R which are lowest are associated with open-graded aggregates. Figure 3.2 illustrates a relationship between resilient modulus and type of aggregates used in road pavement structures.

Tian et al (1998) reported that Rada and Witczak evaluated a total of 271 test results and concluded that the primary variable that influence the M_R responses of granular materials are (i) stress state; (ii) degree of saturation and, (iii) degree of compaction. They also found that an increase in moisture leads to a decrease in M_R values for crushed angular materials, and that similar compaction effort leads to differences in dry densities depending on the gradation of the aggregate.



(a)



(b)

Figure 3.2 – Variation of Resilient Modulus and Aggregate Type

According to Burczyk et al (1994), water content is an important factor which influences subgrade M_R values determination because of its effect on M_R value below or above the optimum moisture content. Also, they reported that M_R values for subgrade soils decreases as water content increases.

The table below and the following Figures 3.3 and 3.4 are results from drained aggregate test conducted by Tian, et al (1998**)**. The values are mean M_R from six individual tests that are given in terms of bulk stress.

Table 3.0 Mean M_R values at Different Gradations and Moisture Content (from Tian, et al, 1998).

Bulk Stress KPa	Median Gradation MPa	Coarser Limit Gradation MPa	Finer Limit Gradation MPa	Median at 2% Above OMC MPa	Median at 2% Below OMC MPa
82.7	118.2	93.8	83.8	65.5	102.6
103.4	141.3	140.2	82.4	96.6	139.4
124	149.2	144.2	88.8	105.4	188.7
137.8	158.2	156.1	82.4	122	209.4
172.3	172.4	175.1	97	125.8	200.7
206.7	182.5	177.3	103.1	131.5	232.3
275.6	249.3	215.9	108.9	192.2	260.2
344.5	247.5	229.8	121.7	183.2	312.2
413.4	240.9	240.6	129.6	184.2	303.4
379	252.6	236.4	125.1	184.8	271.2
413.4	274	249.8	133	210	321.8
516.8	302.6	293.5	153	234.8	352.3
516.8	311.4	298.3	160.8	235.8	339.8
551.2	334.7	297.9	172.1	266.8	380.8
689	367.6	336.8	198.7	284.7	396

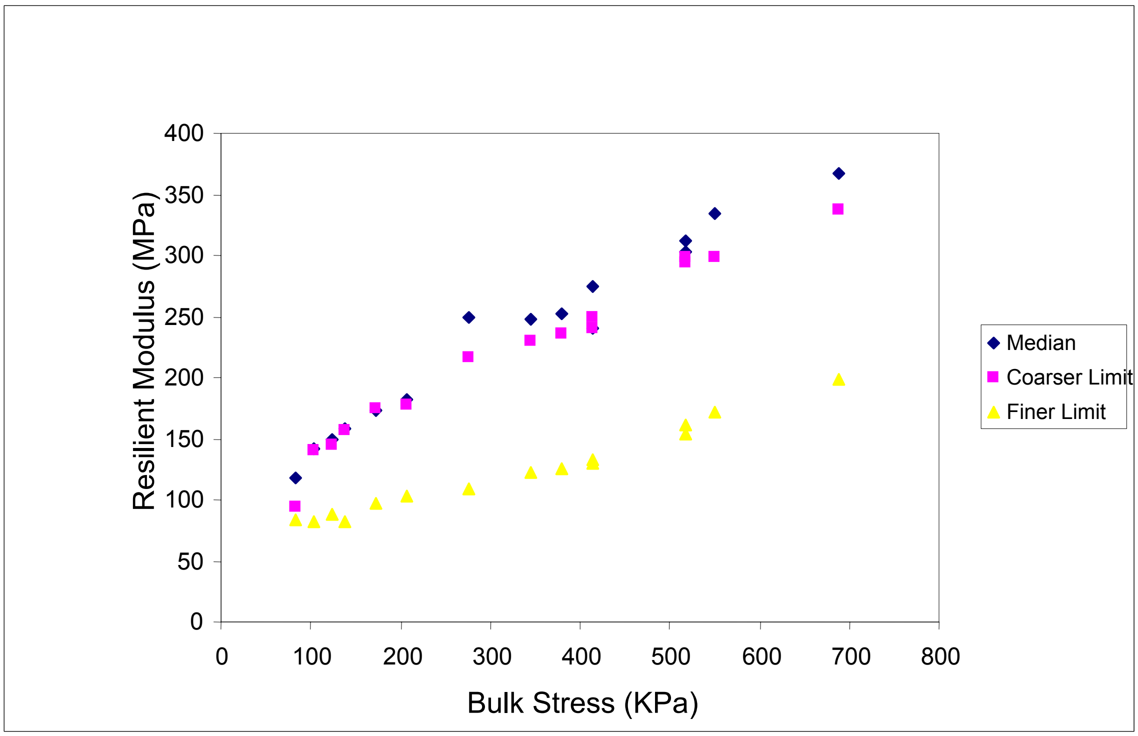


Figure 3.3 – Comparison of Mean M_R values at Different Gradations (from Tian, et al, 1998)

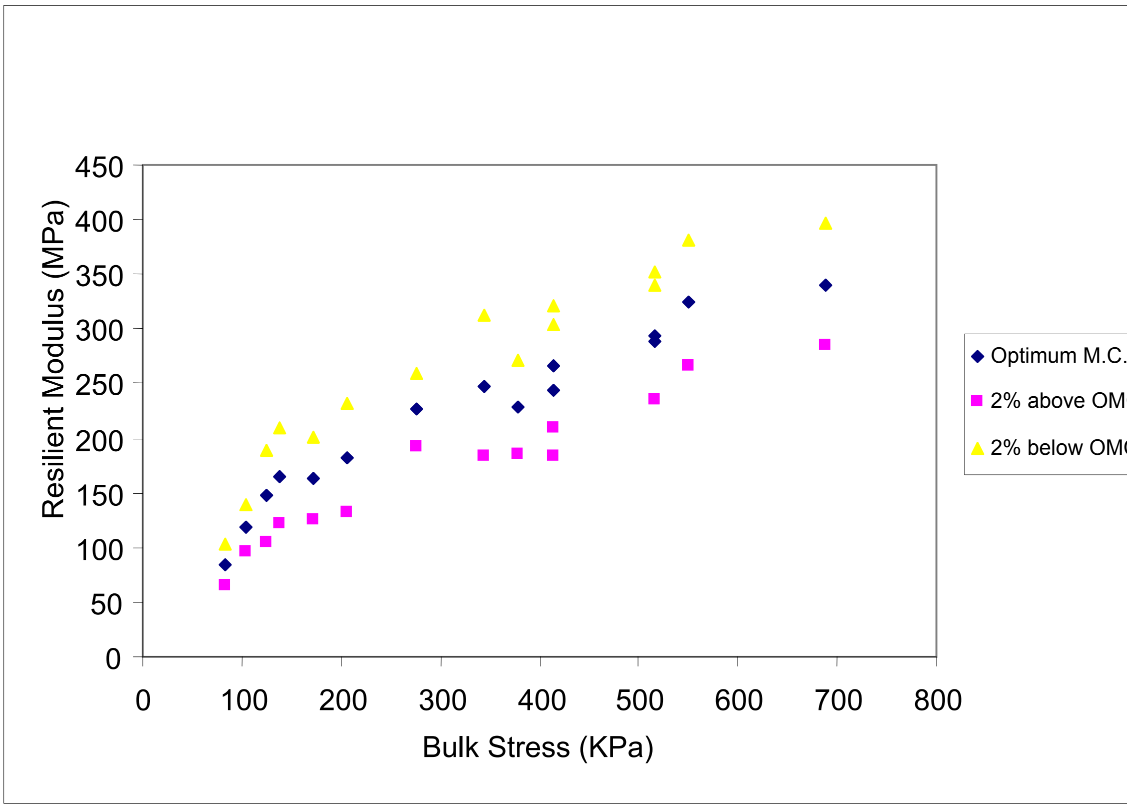


Figure 3.4 – Comparison of Mean M_R values at Different Moisture Contents (from Tian, et al, 1998)

The expression, equation (3.3) is recommended in AASHTO T 294 - 94 for the determination of resilient modulus, where, K_1 and K_2 are both materials dependent parameters and regression constant.

$$M_R = K_1 \, \theta^{K2} \tag{3.3}$$

3.2.4 Seasonal Variation of Resilient Modulus

Generally, the resilient modulus of subgrade soils varies seasonally as a result of climate change. The effect can be severe on pavement structures especially during the wet season when water infiltrates through pavement cracks and surface and become entrapped in the pavement structure. According to Huang (1993), the detrimental effects of entrapped water in pavements not only weakens pavements and subgrades, but also generates high hydrodynamic pressures which pump out the fine materials under the pavement and result in loss of support.

In some frost susceptible areas of the northern climates where the depth of frost penetration is grater than the pavement thickness, high water table causes frost heave and hence load carrying capacity is reduced considerably during thawing. According to Konrad and Roy (2000), the three essential factors for detrimental frost action are; (i) subfreezing temperatures; (ii) high water table and; (iii) frost susceptible soils. Also, the frost action develops in the frost susceptible subgrade leading to ice lens formation, surface heave, and eventually pavement distress.

With respect to freeze-thaw effects on resilient properties, even though previous research is limited, researchers have found that most soil loose significant strength upon thawing and, as moisture drained from the soil, there is a gradual regain of strength. There is a two to three order of magnitude increase in strength of all materials at subfreezing temperature (Simonsen and Isacsson, 2001).

Pavement response in terms of deflection under traffic load varies from season to season depending on the location of the frost front, the position of the thaw fronts, and the moisture contents of each soil layer after thaw is complete. The resilient modulus of the subgrade, subbase, and base layers and the stiffness of the asphalt layer exhibit significant seasonal changes in cold regions. Figure 3.5 shows the seasonal variation of deflection on an asphalt pavement. It can be seen from Figure 3.5 that surface deflection is highest when thaw is complete and lowest in winter when significant rigidity is provided to the pavement structure by frozen soils bonded by pore ice.

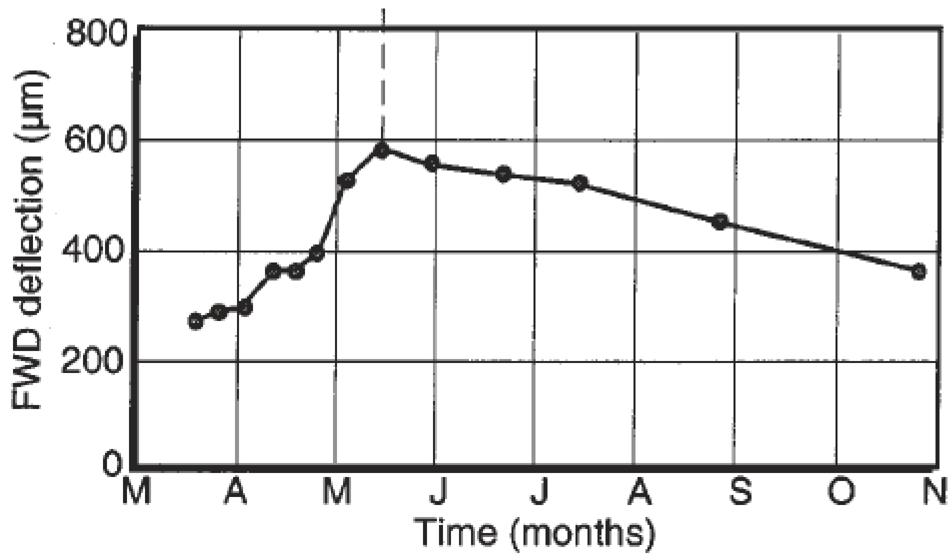


Figure - 3.5 FWD Deflection Data for an AC Pavement (from Konrad and Roy, 2000)

Jin et al (1994) studied the resilient modulus of subgrade soils and found that the resilient modulus value decreases as the water content increases up to a certain bulk stress. Also, they found that the effective resilient modulus, which reflects the overall capacity of subgrade soils to support the pavement during the year, does not vary much with depth.

3.2.5 Environmental Effects on Resilient Modulus

Several environmental factors affect pavement structures and their performance. These factors are mainly: (i) temperature; (ii) solar radiation; (iii) moisture content and; (iv) site geological conditions (Hossain et al, 1996). Of these factors, only moisture content and temperature are of primary concern for subgrade soils in the design of pavements. Therefore our discussion will be limited to these two factors. The effect of moisture content in the form of water or rainfall and frost has been discussed earlier. However, one will note here that there is a strong dependence of soil resilient modulus on the moisture condition of the soil, especially for fine-grained soil. According to Heydinger (2000), soil moisture content should be adopted as the primary variable for predicting seasonal variations of resilient modulus. Temperature is said to cause expansion and contraction of pavement materials. When in its extremes in variations will cause severe damage to pavements and even leads to catastrophic failures, and this is of concern.

Temperature variation affects both the functional performance and the structural performance of asphalt concrete pavements. Cold temperatures accelerate cracking of the asphalt bound layers due to shrinkage, or cause fracture of these layers due to frost heaving of the underlying soils. High temperatures, on the other hand, can cause distortion of the asphalt bound layers (such as rutting) or may produce slippery surfaces due to bleeding of the asphalt. Due to climatological conditions, pavement depth, surface color, the number and properties of each layer, temperature can vary considerably throughout the pavement depth (Al-Abdul Wahhab, 2001).

Figure 3.6 shows the variation in deflection due to temperature over the course of a few hours at the same point within the same day in Nebraska. From the figure, one can notice that temperature affects the deflection close to the load and not away from the load. The reason for this is that the top asphalt layer is very much sensitive to temperature changes whiles the underlying unbound materials succeeding the aggregate base and subgrade soil are not.

According to Al-Abdul Wahhab et al (2001), whose study was based on resilient modulus and temperature correction for Saudi Roads, they found that the single most important factor that affects pavement temperature is the air temperature, which is directly affected by cloud cover and solar radiation. Also, in their study a model was developed to determine the effect of temperature and the asphalt softening point on resilient modulus. It was found that temperature has more effect on M_R values than does asphalt softening point.

$$M_{R\ at\ Temp.} = 5.354 - 0.212\ \text{Temp.} + 0.111\ \text{Sof. Pnt.} - 0.170\ \text{Surface.} \qquad (3.4)$$

Surface – surface area of the aggregate (m^2/kg),

Sof. Pnt. – asphalt softening point (^oC)

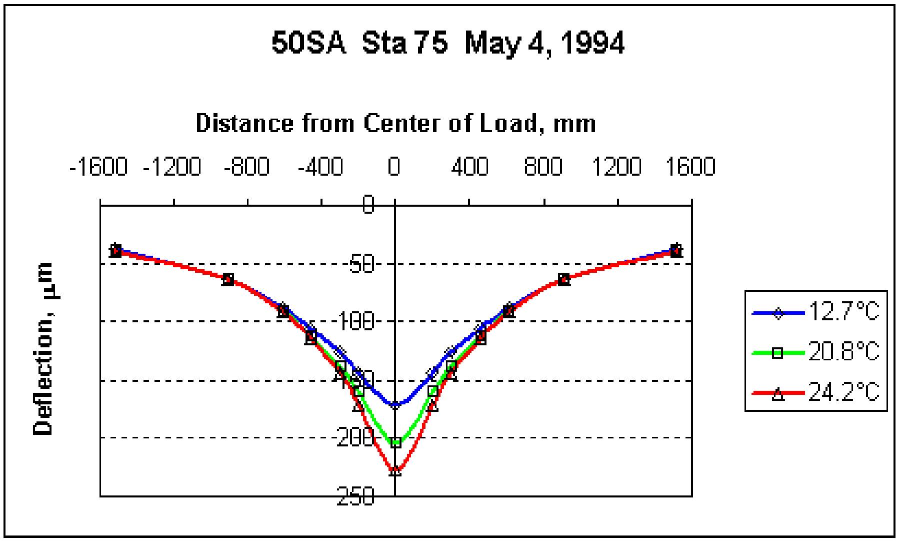


Figure 3.6 - Variations in Deflection due to Temperature in Nebraska (from www.nilsnet.net/fwd/gendis.html)

3.2.6 Models for Predicting Resilient Modulus

Various models have been developed in the past by researchers to predict the resilient modulus of pavement materials and subgrade. These models have taken different forms depending on the soil parameter(s) that are considered to have significant effect on predicting the resilient modulus. Models that have been proposed to simulate resilient modulus for fine-grained soils include the following:

$$M_R = K(\sigma_{oct})^{n} / (\tau_{oct})^{m} \quad \text{, (Shackel, 1973)} \qquad (3.5)$$

$M_R = (k + n\sigma_d) / \sigma_d$, (Drumm et al ,1990) (3.6)

or

$M_R = 10\ (k - n\sigma_d)$

$\log M_R = (k - n\sigma_d)$, (Fredlund et al, 1977) (3.7)

The bilinear model that was proposed in 1976 by Thompson and Robnett is

$M_R = k_1 + k_2\sigma_d$, for $\sigma_d < \sigma_{di}$ and

$M_R = k_3 + k_4\sigma_d$, for $\sigma_d > \sigma_{di}$ (3.8)

Where σ_{di} is the deviator stress at which the slope of M_R versus σ_d changes.

k_1, k_2, k_3 and k_4 are parameter dependent on soil type and its physical state.

The power model adopted by Moossazadeh and Witczak in 1981 is

$M_R = k\ (\sigma_d)^n$ (3.9)

Of the models given above, the bilinear model gives the best fit when fitting test result with model parameters.

In a study of LTPP laboratory resilient modulus test data and response, it was found that the "universal" constitutive equation shown below provided a very good fit to the LTPP M_R Test data (FHWA – RD – 02 – 051, 2002).

$$M_R = k_1 P_a (\theta / P_a)^{k_2} \times (\sigma_d / P_a)^{k_3} \tag{3.10}$$

In an expanded form, can be written as;

$$M_R = k_1 P_a [(\theta - 3k_6) / P_a]^{k_2} \times [(\tau_{oct} / P_a) + 1]^{k_3} \tag{3.11}$$

P_a – atmospheric pressure, θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$

k_1, k_2, k_3, k_6 are regression constant, σ_1 = major principal stress

σ_2 = intermediate principal stress = σ_3 for M_R test on cylindrical specimen

σ_3 = minor principal stress or confining pressure.

τ_{oct} = octahedral shear stress, where

$\tau_{oct} = \frac{1}{3} \sqrt{((\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2)}$

Tian et al (1998) on their study on resilient modulus of aggregate materials found that it is more convenient for designers to predict M_R values of aggregate based on basic material properties such as cohesion and friction angle. They developed a multiple linear regression model which is given below.

$$M_R = A_0 + A_1 C + A_2 \sigma_1 \tan\varphi + A_3 \theta + A_4 M_c + A_5 U_c \tag{3.12}$$

Where A_0, A_1, A_2, A_3, A_4, A_5 are regression constants

C = cohesion, φ = friction angle, θ = bulk stress, σ_1 = major principal stress

U_c = unconfined compression strength, M_c = Moisture Content

CHAPTER FOUR

DATA ACQUISITION AND SEASONAL MONITORING PROGRAM

4.1 Data Acquisition

The first and foremost important task for this research was the collection of the required data that could be used for the data analysis.

The Transportation Research Board (TRB) of the National Research Council, under the sponsorship of the Federal Highway Administration (FHWA) and with the cooperation of the American Association of State Highway and Transportation Officials (AASHTO), undertook a Strategic Transportation Research Study (STRS) of the deterioration of the Nation's highway and bridge infrastructure system. The study recommended that a Strategic Highway Research Program (SHRP) be initiated to focus research and development activities on improving highway transportation. The Long-Term Pavement Performance (LTPP) program was one of the areas recommended.

The LTPP program was envisioned as a comprehensive program to satisfy a wide range of pavement information needs. It draws on technical knowledge of pavements currently available and seeks to develop models that will better explain how pavements perform. It also seeks to gain knowledge of the specific effects on pavement performance of various design features, traffic and environment, materials, construction quality, and maintenance practices. As sufficient data become available, analyses are conducted to provide 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.

The LTPP program was established as a long-term national effort. Under the LTPP paradigm, data collection is conducted in advance of the development of many specific data analysis objectives. Since individuals not involved in data collection operations conduct many of the important data analyses, the LTPP program has invested in the development of a publicly accessible database and database use tools. While the LTPP test section classification methodology is based on experimental concepts, data users are encouraged to develop their own classification methods to meet specific analytical objectives.

The pavement performance database was designed to store the majority of the data collected by the LTPP program for easy and convenient dissemination and use. The pavement performance database is a relational database originally implemented in Oracle 5 format. A *relational* database means that it is composed of separate, but related tables of data. The importance of a relational database from a user's viewpoint is that all data are stored in a simple row/column format in tables (rows are sometimes referred to as records and columns are sometimes referred to as fields). Each row of data is uniquely identified by the values in a *primary key* column or a combination of columns (most of the tables in the LTPP database use multicolumn keys). In addition, relationships exist among the tables of the database that are represented by common data values stored in more than one table. One critical characteristic of relational databases is that they are self-describing. This means that information about the structure of the database is represented in the same row and column format as the data itself. Currently, the LTPP program is using Microsoft Access 2000 as a standard format for data releases.

The overall structure of the database is based on the LTPP data collection and processing flow. Data from the regional databases are uploaded to the national database for consolidation and release to the public on a 6-month cycle. LTPP data can be obtained through a variety of mechanisms, including standard data release, custom data extraction, and via the DataPave computer program and the Internet (http://www.datapave.com).

The LTPP DataPave program provides a static release of data from a majority of tables in a user-interactive format. DataPave was designed as a training tool for users of LTPP data who are not acquainted with the use of modern database technology. The most current LTPP data can be obtained from the LTPP standard data release, which is updated every 6 months.

The standard data release is currently formatted as a series of Microsoft Access 2000 databases based on the North American software version. Use of the standard data release requires knowledge of relational database concepts, the relational design of the LTPP database, and features of the Microsoft Access software. However, the structure of the standard data release format also allows users not familiar with the relational database concept to look at the data in separate tables from a spreadsheet viewpoint. Each table is formatted in columns and rows just like an electronic spreadsheet. This self-discovery feature facilitates progression of use of the expanded data manipulation functions offered by database software that is not available in some spreadsheet types of computational software.

4.2 Quality of the Data

The data used are data which have records status passing “level-D checks” and are categorized as “level-E checks”, which as of this writing, is the highest level of reliable checks. Noting here that these quality control checks are sequentially performed from records with check status beginning as “level-A” and move up the alphabet ladder as the data are being upgraded, checked and reclassified.

The quality control checks applied to LTPP data are limited. It is not possible to inspect all of the data for all types of potential anomalies. Level-E data should not be considered as more reliable than non-level-E data. Likewise, non-level-E data should not be considered less reliable than level-E data. The record status for non-level-E data can be used as a relative indicator of potential issues that might exist for these data.

4.3 Seasonal Monitoring Program

This program contains SMP-specific data, such as the onsite air temperature and precipitation data, subsurface temperature and moisture content data, and frost-related measurements. The Seasonal Monitoring Program (SMP) study is designed to measure the impact of daily and yearly temperature and moisture changes on pavement structures and the response to loads. Sixty-three sites were selected from the GPS and SPS studies and were monitored for temperature and moisture, and at higher than normal intervals for distress, deflection, and longitudinal profile. Measurements specific to sections in the SMP were made using the following devices:

- Time-Domain Reflectometry: Subsurface moisture changes.
- Thermistor Probes: Subsurface temperature changes.
- Electrical Resistivity: Frost/thaw depth.
- Piezometer: Groundwater table determination.
- Air Temperature Probes: Ambient temperature.
- Tipping-Bucket Rain Gauge: Precipitation.

The data collected from these devices are stored in the tables contained in the SMP module. All other data collected at sites within the SMP, but not specific to sites in the SMP, are stored in the usual tables external to the SMP module.

At the inception of the SMP program, subsurface time-domain reflectometry and electrical resistivity measurements were taken on a nominal monthly cycle. In the latter part of the SMP program, selected sites were instrumented to take these measurements daily and, in some cases, subdaily to capture changes caused by rainfall. The only way to identify the sites with these types of daily measurements is to inspect the contents of the tables containing these data.

In addition to the raw data as collected, several *computed parameters* are included that reduce the raw data into values in engineering units. All of the raw data used to calculate the computed parameters are included in the database.

4.4 Description of Tables

Different tables from the DataPave data base were sought for information regarding this research. The description of these tables and the information they contain are as follows:

a. **SMP_ATEMP_RAIN_DAY:** the information contained in this table contributed significantly to this research, as it is the source for records of the air temperature (i.e. minimum, maximum and average) for a day.

Its computation is from the SMP_ATEMP_RAIN_HOUR when there is an 18- hour minimum of data available for the day. It also contains the cumulative precipitation data from onsite whether stations.

b. **SMP_MRCTEMP_AUTO_DAY_STATS:** similar to the above description, this table has information regarding the temperature that is measured within the subgrade soil. It is used in conjunction with other tables such as the SMP_MRCTEMP_DEPTH that contain information on the various depths at which the temperature probes were installed and their dates; and the SMP_MRCTEMP_MAN, which has subsurface temperature data recorded manually when the probes were malfunctioning.

c. **SMP_TDR_AUTO_MOISTURE:** Information on the gravimetric and volumetric moisture content is found in this table. Time Domain Reflectometry (TDR) was used to determined these parameters. This table is also used together with the SMP_TDR_DEPTHS_LENGTHS, which has information on the installed dates, length of TDR probes and other physical characteristics of the Probes; and the SMP_MOISTURE_SUPPORT, which has the dry density of soils sampled from close proximity to the TDR probes.

Information on the pavement structure and foundation i.e. the thickness of each layer and the material composition are found in the TST_L05B table which is in the module “Test (TST)” that contained field and laboratory material testing data. The files are shown in Table 4.1.

Table 4.1 - Seasonal Monitoring Program and General Pavement Studies Files Used
SPS1_LAYER
SPS2_LAYER
SPS8_LAYER
SPS9_LAYER
SMP_ATEMP_RAIN_DAY
SMP_MRCTEMP_AUTO_DAY_STATS
SMP_MRCTEMP_DEPTHS
SMP_TDR_AUTO_MOISTURE
SMP_TDR_DEPTHS_LENGTH
SMP_TDR_MOISTURE_SUPPORT
SMP_WATERTAB_DEPTH_MAN
TST_LO5B

CHAPTER FIVE

ANALYSIS AND DISCUSSION

A total number of twelve (12) sections from five (5) states were considered for analysis in this research. There were no hard and fast rule in the selection process, but a guiding criterion was to select states that are of the cold region which share similar climatic conditions in terms of rainfall precipitation and temperature variation, and that include continuous data from many months. Most of the sections fall within two main geographic regions i.e. the North Atlantic that had two sections and the North Central having the remaining ten sections. Table 5.1 shows the selected states-sections and other information.

5.1 Data Analysis

The task here is to use the available data obtained from the seasonal monitoring program (SMP) temperature and volumetric water content data and other supportive information to develop a mathematical model, using statistical and probabilistic analysis, that can be used to predict seasonal variation of subgrade temperature and moisture. The variations are used to investigate the seasonal variation of resilient modulus.

Table 5.1 - Pavement Sections and Locations

States	Section ID Number	County	Elevation (ft)	Latitude (deg.)	Longitude (deg.)
North Atlantic Region					
Vermont	50-1002-1 (AC)	Addison	283	44.12	73.18
Pennsylvania	42-1606-1 (PC)	Bedford	1400	40.22	78.47
North Central Region					
Ohio	39-0104-1 (AC)	Delaware	950	40.43	83.07
	39-0108-1 (AC)	Delaware	950	40.43	83.07
	39-0112-1 (AC)	Delaware	950	40.43	83.07
	39-0202-1 (PC)	Delaware	955	40.42	83.07
	39-0204-1 (PC)	Delaware	955	40.42	83.08
	39-0205-1 (PC)	Delaware	955	40.42	83.08
South Dakota	46-0804-1 (AC)	Campbell	1680	45.93	100.42
Minnesota	27-1018-1 (AC)	Morrison	1118	46.03	94.42
	27-1028-1 (AC)	Otter Tail	1384	46.68	95.67
	27-6251-1 (AC)	Beltrami	1364	47.46	94.91

Air and soil temperatures and moisture content were the two (2) main parameters considered for the analysis. In all the sections studied, it was determined from the data that the air temperature and the subgrade soil temperature behave sinusoidally over a period. As seen from Figure 5.1, the mean daily air temperature at the asphalt concrete section is cyclic. This observation is shown in Figure 5.1. Since temperature changes over night and day, it was necessary to use the mean daily air temperature.

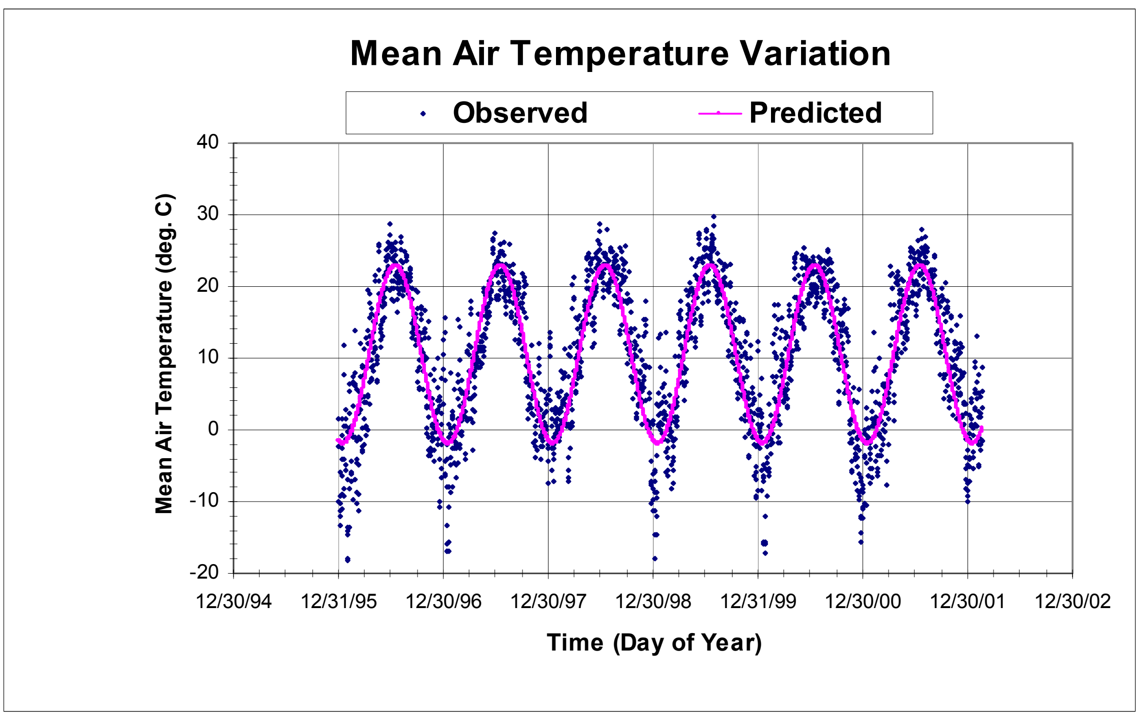


Figure 5.1 – Mean daily Air Temperature Variation for Section 390104 in Ohio

The air temperature used is the mean of the hourly temperatures over a day's period with a minimum of eighteen (18) hours air temperature values recorded. This same cyclic pattern is observed within the subgrade soils where thermistor sensors are installed to record the soil temperature. Figure 5.2 shows the location of the installed sensors for a typical asphalt concrete and Portland cement concrete pavement study section. Eighteen (18) sensors were installed within the asphalt concrete and the subgrade soil. All sensors exhibit the same pattern even at a depth of over 2.0m. This is shown in Figures 5.3 and 5.4

From Figures 5.3 and 5.4 below, there are discontinuities in the observed data, which were caused by the sensors malfunctioning or no event was recorded. The observed data shows a sinusoidal wave pattern, thus, one uses a sine function to match the observed curve and to predict the mean temperature for a given day. The sine function used is,

$$Y = A \sin(\omega t) + B \qquad (5.1)$$

This was modified to

$$Y = A \sin \frac{[2\pi (t - T)]}{365.25} + B \qquad (5.2)$$

Where, Y = temperature, A = amplitude, t = day of the year, T = horizontal shift and B = vertical shift which is equal to the mean temperature

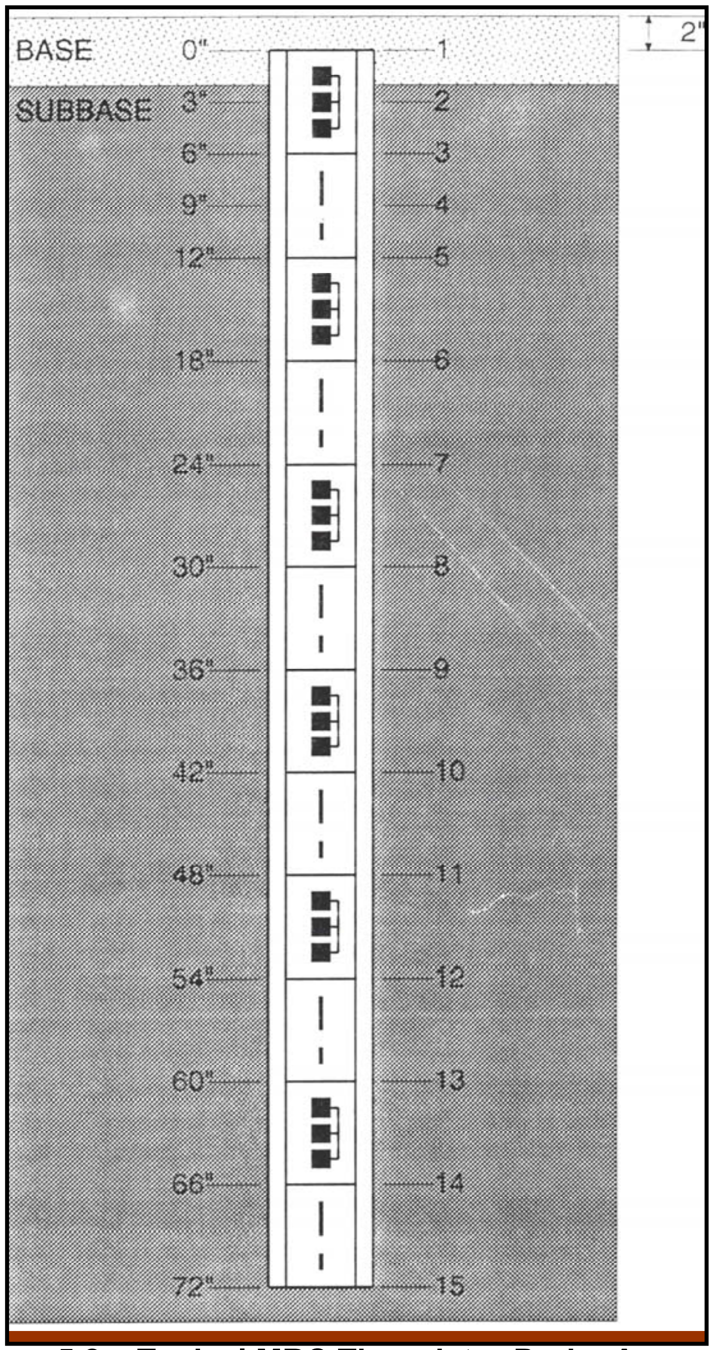


Figure 5.2 – Typical MRC Thermistor Probe Assembly (from ODOT DEL-23-17.48, 1994)

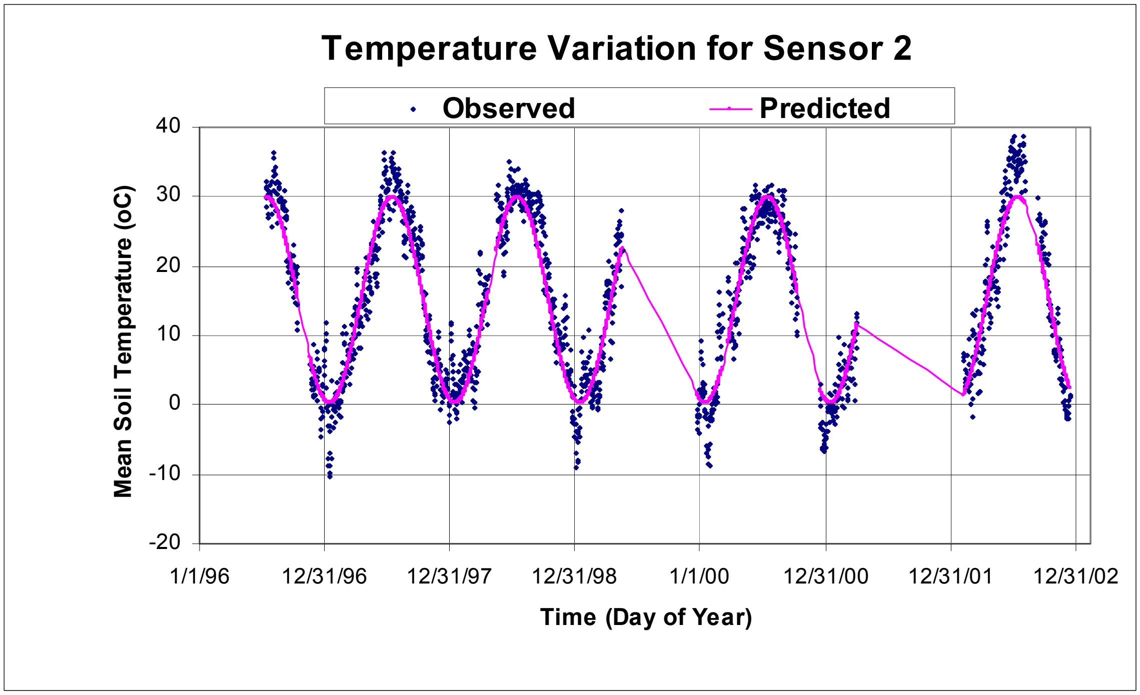


Figure 5.3 – Soil Temperature Variation near Top of Subgrade Soil (0.076m) for Section 390104 in Ohio

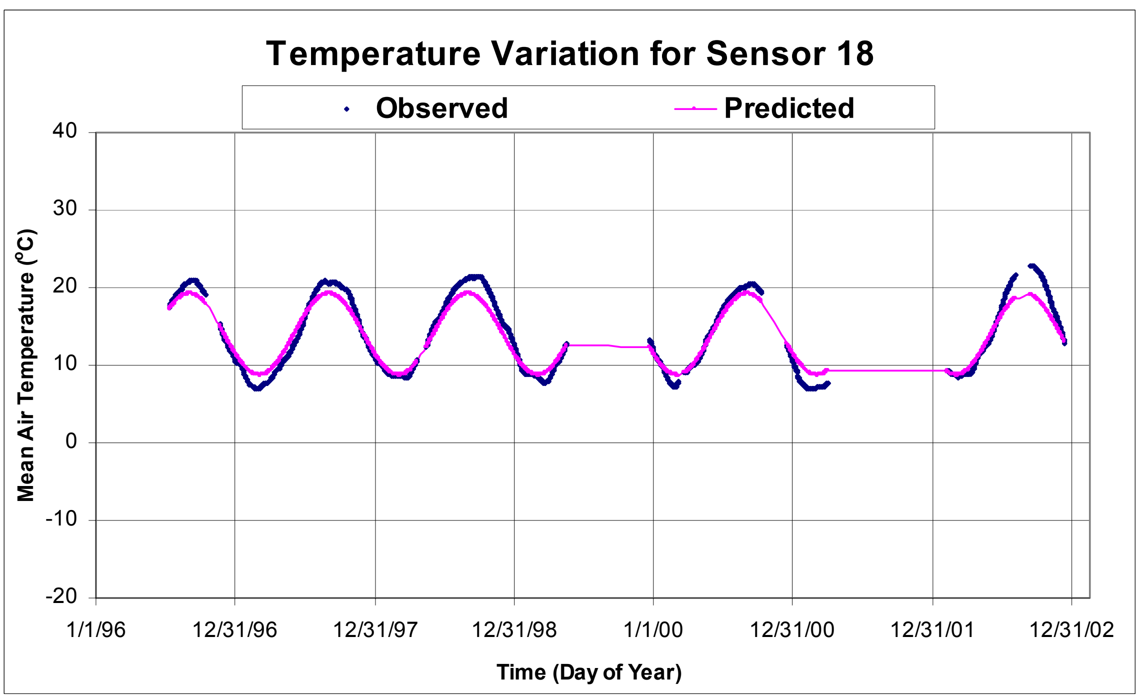


Figure 5.4 – Soil Temperature Variation at a Depth of 2.39m in Subgrade Soil for Section 390104 in Ohio

Equation 5.2 above matches the data well and can be used to predict the mean daily air temperature and the subgrade soil temperature.

5.2 Soil Temperature and Moisture Behaviour

The soil temperature does not react immediately to change as the surrounding air temperature changes during the day and night. There is always a time lag in attaining peak value in the soil and a temperature gradient is expected. Figueroa et al (1994), reported that asphalt concrete temperature does not attain peak temperature value when the surrounding air temperature is maximum, but that the maximum day and night temperatures in the asphaltic concrete occurs at 16:30 and 07:30 a.m. respectively. Probably, one might suggest that this behaviour is as a result of material characteristic; hence, the subgrade soil temperature which depends on the asphalt temperature will lag as well.

The volumetric water content in the subgrade soil was also studied and it was determined that the trend which the air temperature and soil temperature exhibits were the same for the observed volumetric water content. As a result of this behaviour, i.e. sinusoidal, Equation 5.2 was also used to predict the volumetric water content for any given day, where “Y” in the equation will equal to the volumetric water content. Figures 5.5 and 5.6 below which are two of the studied sections in Ohio shows that for an increase in the soil temperature, there is a corresponding increase in the moisture content and a decrease in soil temperature corresponds to a decrease in the moisture content. A typical layout for the TDR probes is shown in Figure 5.7.

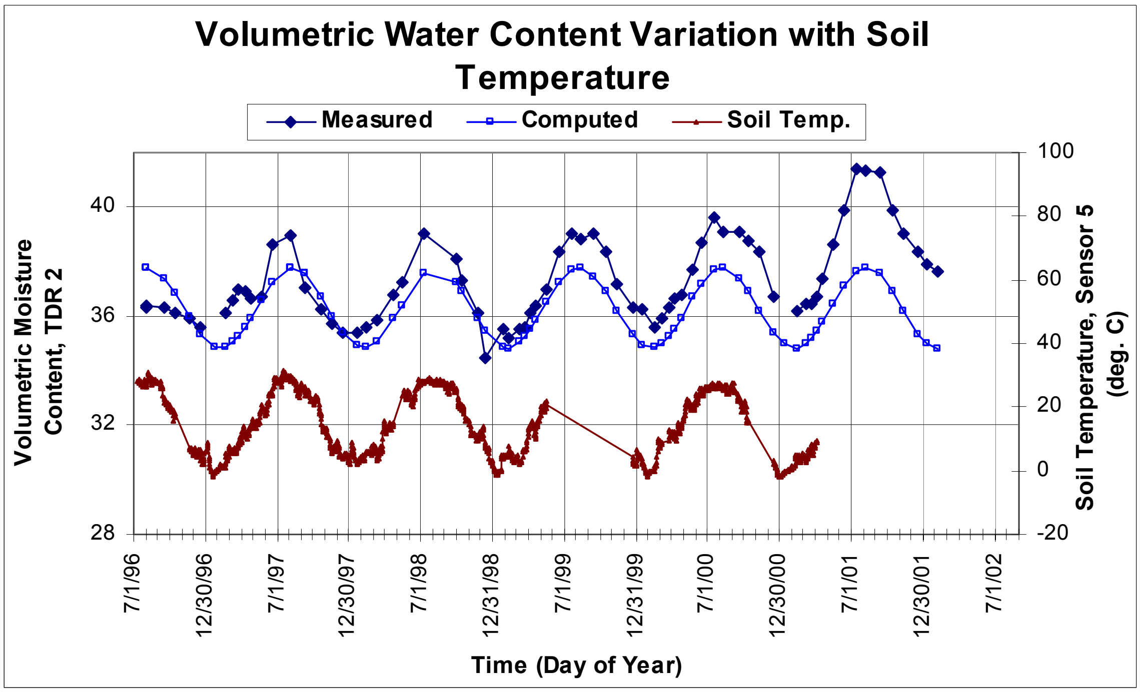


Figure – 5.5 Variation of Moisture Content and Soil Temperature for Section 390104 in Ohio

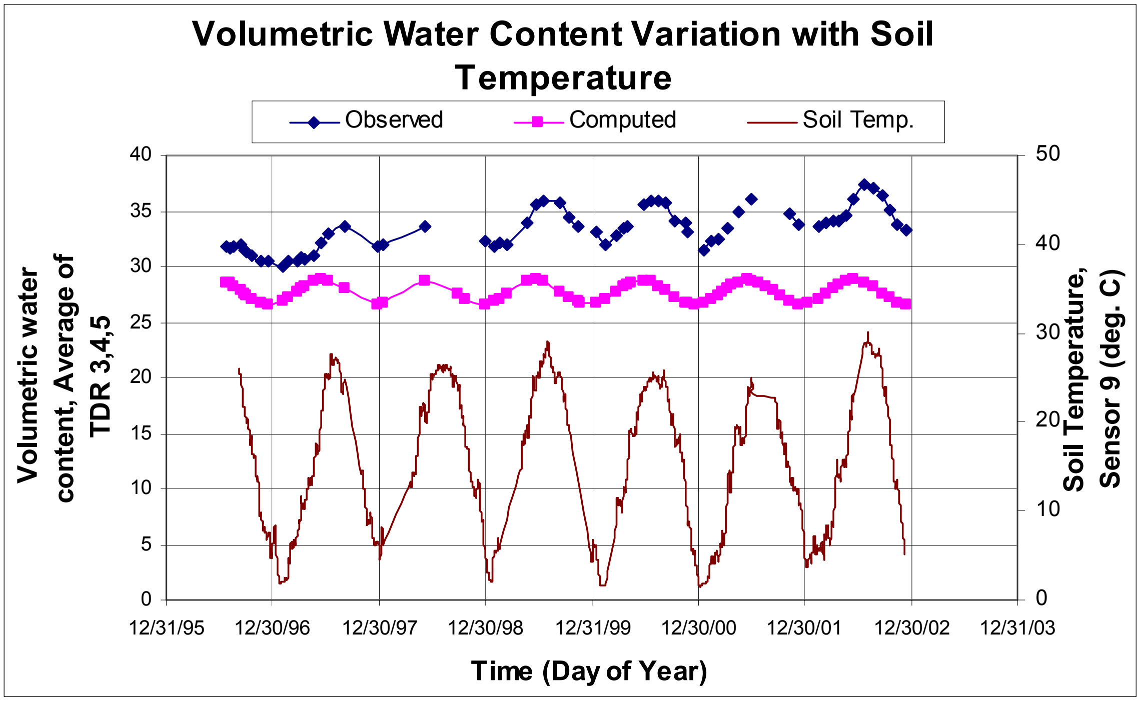


Figure – 5.6 Variation of Moisture Content and Soil Temperature for section 390108 in Ohio

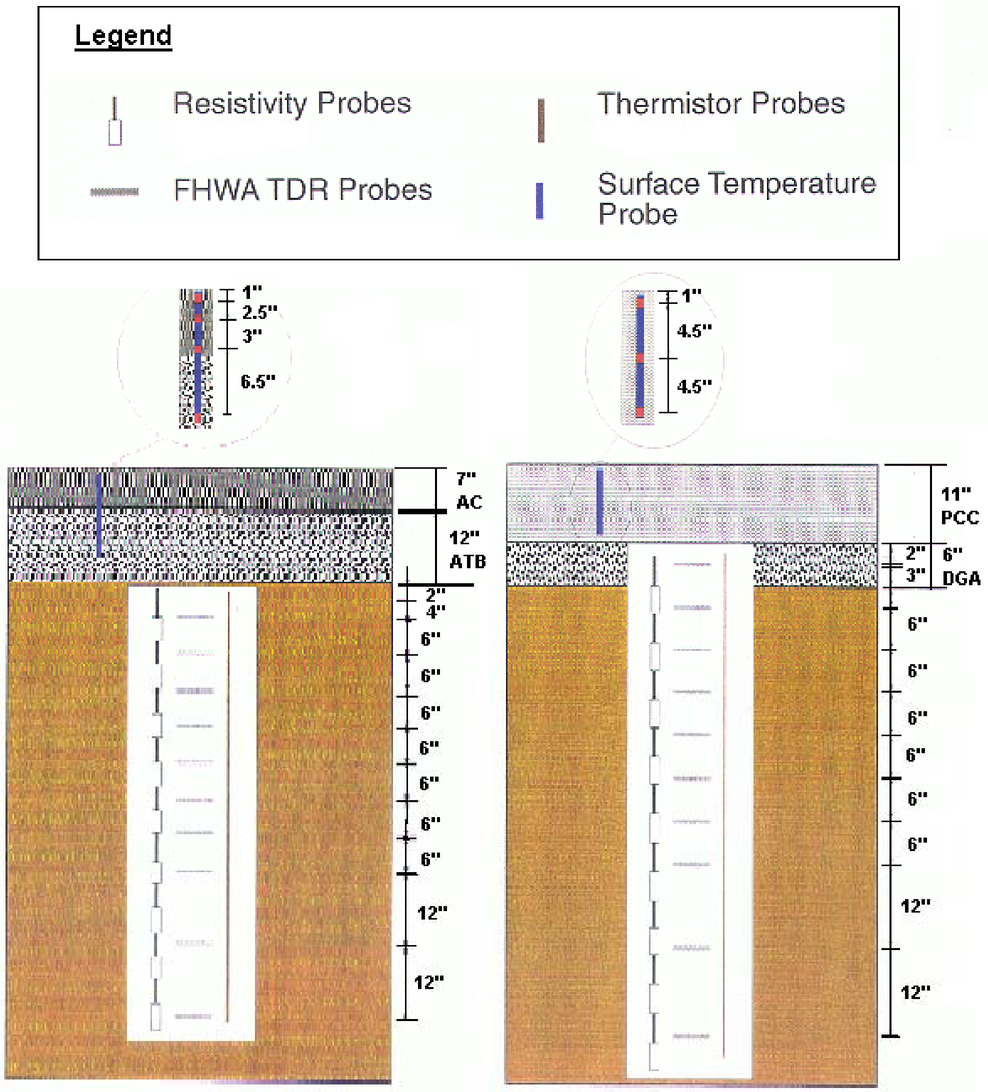


Figure 5.7 – Typical TDR Probes layout for AC and PCC Pavement Sections (from ODOT DEL-23-17.48, 1994)

Most likely, the expectation is the converse i.e. an increase in temperature should lead to a decrease in moisture content of the subgrade soil. However, one observed a completely different behaviour. A plausible explanation for the behaviour is suggested here. Firstly, the soil water content increases with depth as the water table is approached. An increase in the soil temperature increases the soil water vapor evaporation within the soil. Thus there is a net increase in the soil vapor pressure in the subgrade which will condensed before reaching the subbase – subgrade interface or subbase – asphalt interface, which causes the subgrade soil water content to increase.

For some of the studied sections, it was very difficult to even notice the cyclic pattern of the observed data. The reasons one may suggests are:

(i) That there were too few data available

(ii) Malfunctioning time domain reflectometry (TDR) probes

(iii) No event was recorded

(iv) The data is not available in the data-base system

Even for available data, wide gaps existed which really affected the expected result, however, the sinusoidal trend and cyclic behaviour is observed. An example of this behaviour is shown in Figures 5.8, 5.9 and 5.10 which are section 501002 in Addison County in Vermont, section 460804 in Campbell County in South Dakota and section 276251 in Beltrami County in Minnesota, respectively. Tables 5.2 and 5.3 shows the computations for the predicted moisture content for Figures 5.9 and 5.10 respectively.

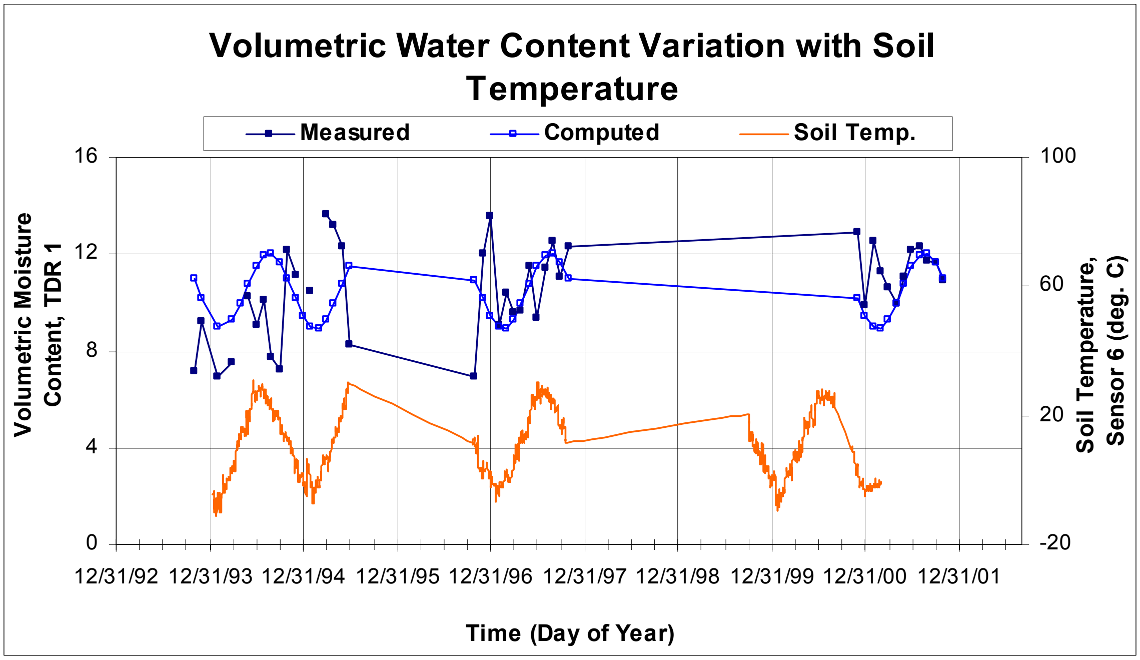


Figure – 5.8 Variation in Water Content with Soil Temperature for Section 501002 in Vermont

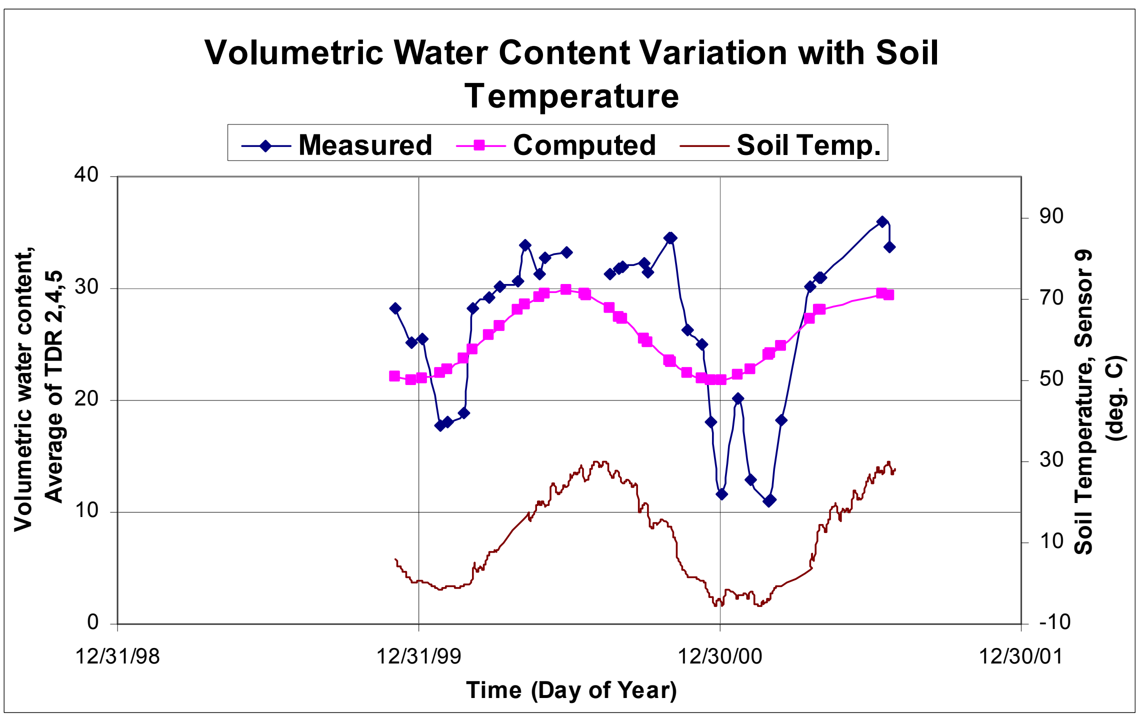


Figure – 5.9 Variation in Water Content with Soil Temperature for section 460804 in South Dakota

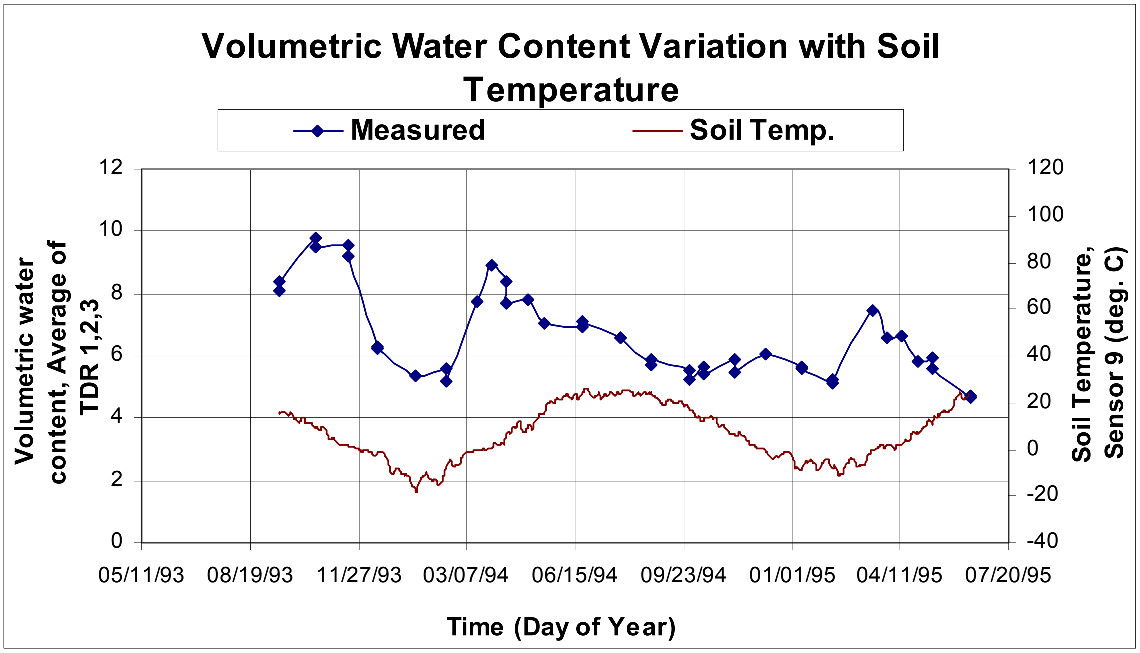


Figure – 5.10 Variation in Water Content with Soil Temperature for section 276251 in Minnesota

The best one can infer from this is that there are portions in the curve when an increase or decrease in temperature corresponds to an increase or decrease in the observed moisture content respectively.

Table 5.2 - Computations for Predicted Volumetric Water Content - Section 460804

					A =		3.999
					B =		25.80
					T =		86
					Sum Sq. Diffs. =		1328.05
sin(Φ)	Day of Year t	Days Since 03-Dec-99	Period	Date	Measured VMC AVE 2,4,5	f(t')*sin(Φ)	Calc. Moisture Content
-0.923	337	0	10.0	3-Dec-99	28.23	-26.06	22.11
-0.999	357	20	16.5	23-Dec-99	25.10	-25.07	21.81
-0.984	5	33	17.5	5-Jan-00	25.47	-25.07	21.87
-0.849	27	55	15.0	27-Jan-00	17.67	-15.01	22.40
-0.769	35	63	14.0	4-Feb-00	18.13	-13.95	22.73
-0.508	55	83	15.5	24-Feb-00	18.83	-9.57	23.77
-0.337	66	94	15.5	6-Mar-00	28.27	-9.53	24.45
0.000	86	114	16.0	26-Mar-00	29.27	0.00	25.80
0.205	98	126	17.0	7-Apr-00	30.17	6.18	26.62
0.552	120	148	16.0	29-Apr-00	30.63	16.91	28.01
0.687	130	158	13.0	9-May-00	33.83	23.23	28.55
0.858	146	174	12.0	25-May-00	31.30	26.87	29.23
0.921	154	182	16.5	2-Jun-00	32.67	30.07	29.48
1.000	179	207	23.5	27-Jun-00	33.23	33.22	29.80
0.918	201	229	12.0	19-Jul-00	N/A	N/A	29.47
0.904	203	231	15.0	21-Jul-00	N/A	N/A	29.42
0.603	231	259	20.5	18-Aug-00	31.37	18.91	28.21
0.411	244	272	8.5	31-Aug-00	31.80	13.07	27.45
0.347	248	276	14.5	4-Sep-00	31.97	11.11	27.19
-0.075	273	301	14.5	29-Sep-00	32.23	-2.42	25.50
-0.144	277	305	15.5	3-Oct-00	31.47	-4.52	25.23
-0.572	304	332	15.0	30-Oct-00	34.57	-19.76	23.52
-0.613	307	335	11.5	2-Nov-00	34.50	-21.16	23.35
-0.844	327	355	18.0	22-Nov-00	26.37	-22.25	22.43
-0.958	343	371	14.0	8-Dec-00	24.97	-23.91	21.97
-0.996	355	383	12.5	20-Dec-00	18.00	-17.94	21.82
-0.992	2	396	16.5	2-Jan-01	11.63	-11.54	21.83
-0.892	22	416	17.5	22-Jan-01	20.23	-18.04	22.24
-0.747	37	431	18.5	6-Feb-01	12.93	-9.66	22.82
-0.448	59	453	12.0	28-Feb-01	10.93	-4.90	24.01
-0.417	61	455	7.0	2-Mar-01	11.10	-4.63	24.13
-0.222	73	467	23.5	14-Mar-01	18.20	-4.04	24.91
0.369	108	502	23.5	18-Apr-01	30.10	11.12	27.28
0.552	120	514	6.5	30-Apr-01	31.00	17.12	28.01
0.566	121	515	38.5	1-May-01	30.93	17.52	28.07
0.943	197	591	41.5	16-Jul-01	36.03	33.99	29.57
0.896	204	598	3.5	23-Jul-01	33.70	30.21	29.39

Table 5.3 - Computations for Predicted Volumetric Water Content - Section 276251

					A =		**-1.587**
					.C =		**6.61**
					T =		**100**
					Sum Sq. Diffs. =		**127.55**
sin(Φ)	**Day of Year t**	**Days Since 05-Aug-96**	**Period**	**Date**	**Measured VMC AVE 1,2,3**	**f(t')*sin(Φ)**	**Calc. Moisture Content**
0.411	258	0	0.0	15-Sep-93	8.10	3.33	5.96
0.411	258	0	17.0	15-Sep-93	8.37	3.44	5.96
-0.161	292	34	17.0	19-Oct-93	9.80	-1.57	6.86
-0.161	292	34	14.5	19-Oct-93	9.47	-1.52	6.86
-0.613	321	63	14.5	17-Nov-93	9.53	-5.85	7.58
-0.909	321	63	14.0	17-Nov-93	9.20	-8.37	8.05
-0.909	349	91	14.0	15-Dec-93	6.30	-5.73	8.05
-0.984	349	91	17.5	15-Dec-93	6.23	-6.14	8.17
-0.791	19	126	31.5	19-Jan-94	5.37	-4.24	7.86
-0.791	47	154	14.0	16-Feb-94	5.57	-4.40	7.86
-0.417	47	154	14.0	16-Feb-94	5.20	-2.17	7.27
-0.188	75	182	21.0	16-Mar-94	7.77	-1.46	6.91
0.052	89	196	14.0	30-Mar-94	8.90	0.46	6.91
0.052	103	210	7.0	13-Apr-94	8.40	0.43	6.53
0.385	103	210	10.0	13-Apr-94	7.70	2.97	6.53
0.594	123	230	17.0	3-May-94	7.80	4.64	6.00
0.594	137	244	25.0	17-May-94	7.07	4.20	5.67
0.951	173	280	18.0	22-Jun-94	6.93	6.59	5.10
0.951	173	280	17.5	22-Jun-94	7.10	6.75	5.10
0.959	208	315	17.5	27-Jul-94	6.57	6.30	5.09
0.959	208	315	14.0	27-Jul-94	6.57	6.30	5.09
0.719	236	343	14.0	24-Aug-94	5.73	4.12	5.47
0.719	236	343	18.0	24-Aug-94	5.90	4.24	5.47
0.182	272	379	18.0	29-Sep-94	5.53	1.01	6.32
0.182	272	379	6.5	29-Sep-94	5.23	0.95	6.32
-0.041	285	392	6.5	12-Oct-94	5.67	-0.23	6.67
-0.041	285	392	14.0	12-Oct-94	5.40	-0.22	6.67
-0.499	313	420	14.0	9-Nov-94	5.90	-2.94	7.40
-0.499	313	420	14.0	9-Nov-94	5.47	-2.73	7.40
-0.844	341	448	31.5	7-Dec-94	6.03	-5.09	7.95
-0.999	11	483	17.5	11-Jan-95	5.67	-5.66	8.20
-0.999	11	483	14.0	11-Jan-95	5.60	-5.60	8.20
-0.999	39	511	14.0	8-Feb-95	5.13	-5.13	8.20
-0.867	39	511	18.0	8-Feb-95	5.23	-4.54	7.99
-0.867	75	547	25.0	16-Mar-95	7.43	-6.45	7.99
-0.417	89	561	14.0	30-Mar-95	6.60	-2.75	7.27
-0.188	103	575	14.0	13-Apr-95	6.67	-1.25	6.91
0.052	117	589	13.5	27-Apr-95	5.83	0.30	6.53
0.288	130	602	6.5	10-May-95	5.93	1.71	6.15
0.493	130	602	18.0	10-May-95	5.57	2.75	5.83
0.493	166	638	18.0	15-Jun-95	4.63	2.29	5.83
0.907	166	638	0.0	15-Jun-95	4.73	4.29	5.17

5.3 Regression Analysis of Subgrade Temperature Variations

A simple regression analysis was done on the amplitude, mean and time shift, to observe the behaviour of these parameters with increase in depth. For section 460804 in Campbell County in South Dakota, Table 5.4 and Figure 5.10 gives the typical information on the analysis.

Table 5.4 – Temperature – Depth Regression Coefficients for Section in Campbell County

Section ID	Variable	Slope	Intercept	Coefficient of Determination (R^2)
460804-1	Mean	-0.219	11.666	0.7807
	Amplitude	-5.197	20.961	0.9897
	Time Shift	27.027	96.815	0.9988

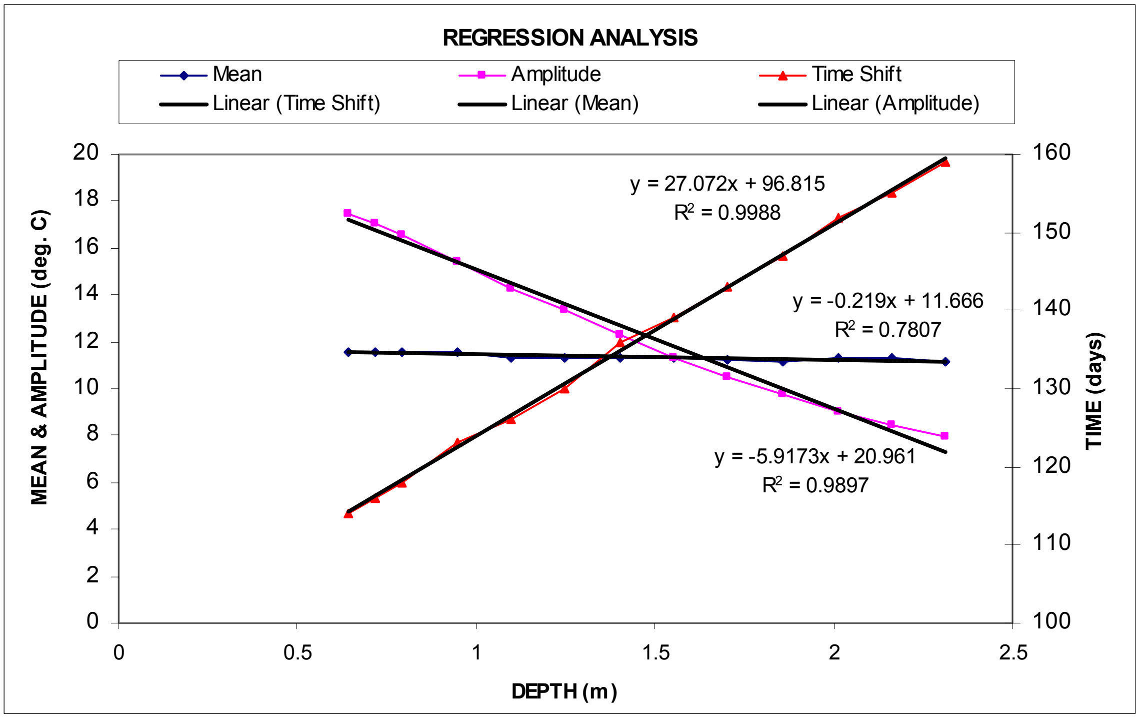


Figure 5.11 – Graph of Mean, Amplitude & Time Shift vs. Depth Section - 460804

As depth increases, the following are noticed

(i) the amplitude decreases

(ii) the time shift increases

The mean value shows a fairly constant trend with depth for nearly all the sections. The coefficient of determination is shown in Table 5.4. Results from analysis of all pavements sections are given in Table 5.5. An expression for the mean daily air temperature variation in Figure 5.1 for section 390104 can be expressed by rewriting Equation 5.2 as Equation 5.3

$$Y = 15.215 \sin \frac{[2\pi (t - 102.27)]}{365.25} + 14.859 \tag{5.3}$$

This research was primarily concerned with flexible pavement sections, but it was possible to study a few sections that are rigid pavement in the Delaware County in Ohio and Bedford County in Pennsylvania. The following Figures 5.13 and 5.14 shows the mean air temperature and volumetric water content variation with time respectively. It is observed that a similar trend as in the flexible pavement sections existed for the rigid pavement sections.

From Figure 5.12 and Table 5.5, it is observed that for section 390205 in Delaware County in Ohio, the coefficient of determination (R^2) value is lower than the expected value when comparing it with those from other sections in the same county. A 62.5% difference is observed between the average value of the R^2 values for other sections in that county. Despite this noticeable difference, the mean, amplitude and time-shift intercept values are close. In finding an explanation for this anomaly that occurred in the regression analysis, one studied the pavement structure layers and their material composition of section 390205 and other similar sections in the same county.

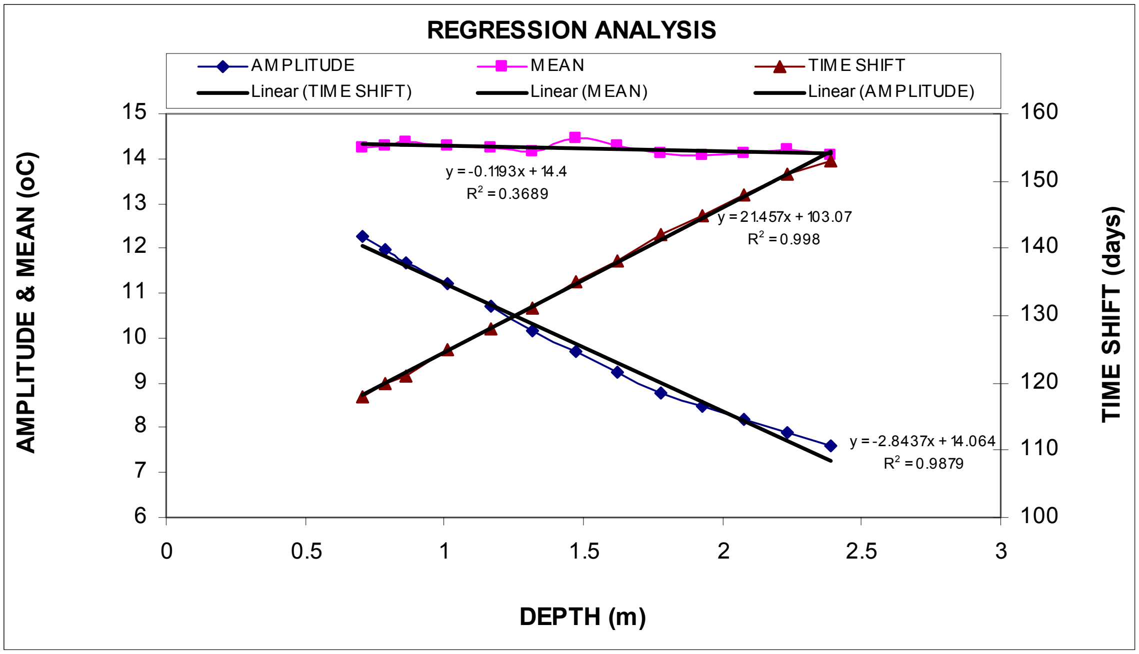


Figure 5.12 – Graph of Mean, Amplitude & Time Shift vs. Depth Section - 390205

An observation is that in section 390205, there is no granular base. A treated base layer of lean concrete which is 6.2 inches thick underlies the original surface layer of Portland cement concrete (JPCP), whereas the other sections of rigid pavement have a granular base layer. Hence, this suggests that the granular base layer of crushed stone in the other sections allows for temperature exchange between the pavement surface and the subgrade. The treated base layer of lean concrete creates a barrier between the pavement surface and the subgrade as it adds to the total thickness of "impervious" concrete layer to overcome for a noticeable gradient to be observed.

Table 5.5 - Regression Coefficients for Temperatures

Section ID	Variable	Slope	Intercept	Coefficient of Determination (R^2)
VERMONT_1002	Mean Amplitude Time Shift	-0.3079 -4.9594 21.291	12.093 16.776 107.58	0.9222 0.9994 0.9901
OHIO_0104	Mean Amplitude Time Shift	-0.3884 -4.283 22.356	14.859 15.215 102.27	0.9876 0.9967 0.9965
OHIO_0108	Mean Amplitude Time Shift	-0.4339 -3.357 22.232	15.843 15.178 102.84	0.982 0.9788 0.998
OHIO_0205	Mean Amplitude Time Shift	-0.1193 -2.8437 21.457	14.4 14.064 103.07	0.3689 0.9879 0.998
OHIO_0204	Mean Amplitude Time Shift	-0.6635 -4.2821 21.769	15.178 15.085 99.004	0.9825 0.9879 0.9949
MINNESOTA_1018	Mean Amplitude Time Shift	-0.4598 -3.8583 19.367	11.755 19.845 103.92	0.985 0.9774 0.9913
MINNESOTA_1028	Mean Amplitude Time Shift	0.4894 -4.3965 19.38	7.1452 20.024 99.456	0.9141 0.9984 0.9964
MINNESOTA_6251	Mean Amplitude Time Shift	-0.293 -4.9008 22.159	9.0871 21.568 102.55	0.8343 0.9991 0.9961
SOUTH DAKOTA_0804	Mean Amplitude Time Shift	-0.219 -5.9173 27.072	11.666 20.961 96.815	0.7807 0.9897 0.9988

Equation 5.2 is recommended to predict the seasonal variation of soil temperatures of subgrade soils overlaid with either asphalt concrete or Portland cement concrete.

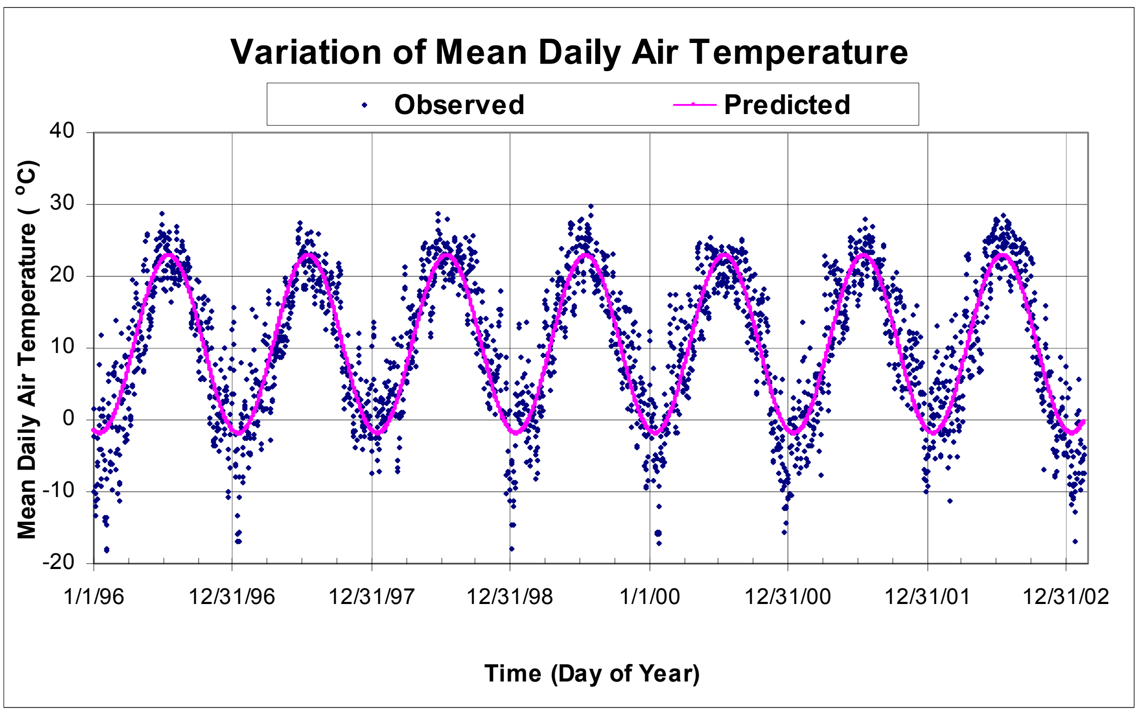


Figure 5.13 – Mean Daily Air Temperature Variation for Rigid Pavement – Section 390204 in Ohio

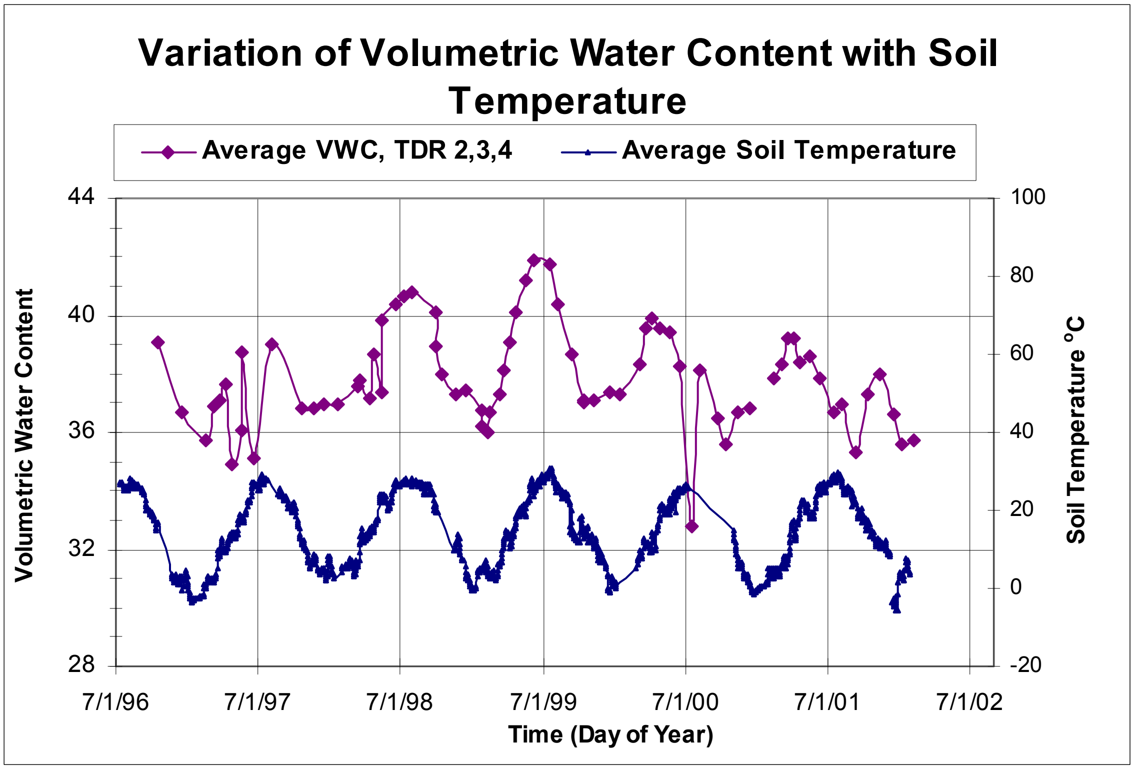


Figure – 5.14 Subgrade Soil Variation of Moisture Content and Soil Temperature– Section 390204 (Rigid Pavement) in Ohio

5.4 Analysis of Resilient Modulus

Researchers have shown that temperature affects the resilient modulus of subgrade soil. Simonsen et al (2002) have shown that, depending on the condition to which the subgrade soil is subjected, that is freezing or thawing, the resilient modulus may vary significantly.

Temperature affects both surface tension and matric suction and hence resilient modulus. The difficulty in determining seasonal variation of matric suction due to hysteresis and insufficient data require one to depend on moisture content variation since previous research have shown that resilient modulus depends on moisture content and dry density during compaction and on moisture content or matric suction thereafter (Heydinger, 2003). Hence, it is recommended that state parameters such as volumetric water content or degree of saturation be used in determining the resilient modulus.

Figueroa et al (1994) and Debuty (1997) performed tests on fine-grained soils in Ohio and have shown that the deviator stress at the break point is at least 41.4 kPa (6 psi). Tests done by Alvarez (2000) also showed that the deviator stress is between 14 and 20 kPa (2 and 3 psi) and developed an expression (Equation 5.4) for variation of resilient modulus obtained from laboratory tests on soil from the Ohio SHRP test section.

$$M_R \text{ (psi)} = 77235.54 - 639.121\, S(\%) - 5418.33\sigma_d \qquad (5.4)$$

where M_R is the resilient modulus corrected for saturation, S%, and σ_d is the deviator stress estimated at 1.2 psi (8.3 kPa).

The degrees of saturation were computed using Equation 5.5

$$S(\%) = \theta_w / n \qquad (5.5)$$

where θ_w is the average volumetric water content, and n is the porosity, assumed to be 40%.

Since one of the test sections of this research is located Delaware County in Ohio, Equation 5.4 and 5.5 were used to predict the resilient modulus of Section 390108 in Delaware County. The mean monthly degree of saturation was computed using values from the average of three TDR probes installed in the subgrade. Figures 5.15 show the seasonal variation of the observed and predicted resilient modulus calculated respectively from the observed and predicted volumetric water content for the subgrade soil in section 390108 in Delaware County in Ohio. The calculations are shown in Tables 5.6(a) and (b).

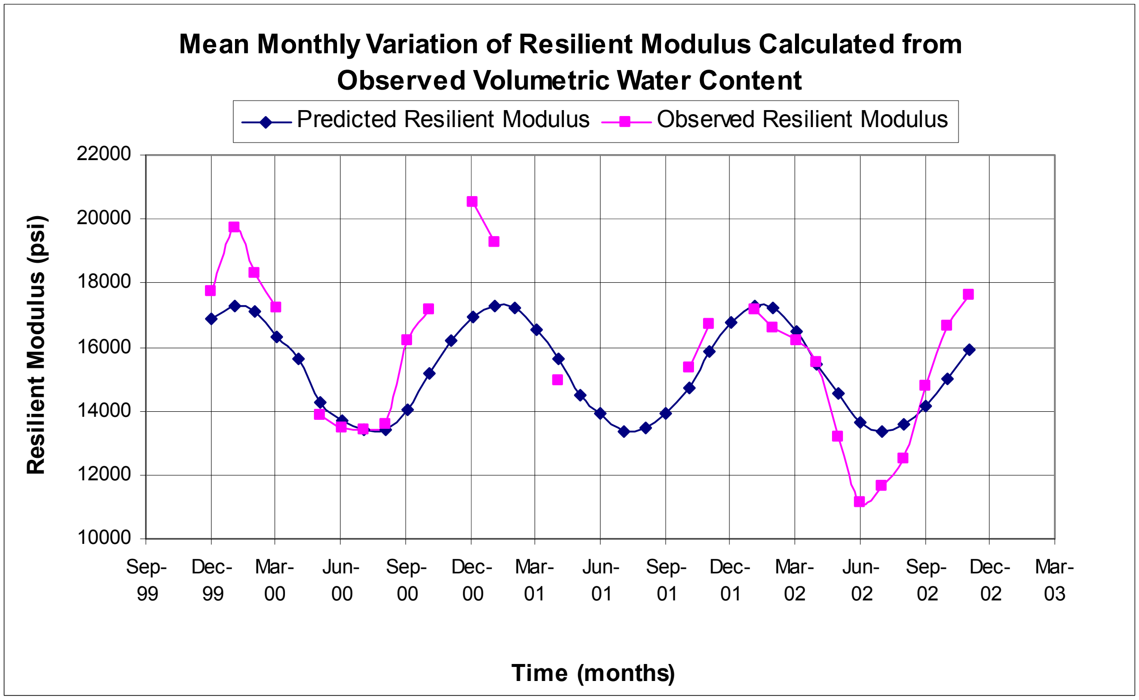


Figure 5.15 – Observed and Predicted Resilient Modulus Variation Calculated from Observed Volumetric Water Content for Section – 390108 in Ohio (Depth ≈ 0.45m)

Table 5.6(a) Computation of Resilient Modulus from Observed Volumetric Water Content - Section 390108

Months	Ave. Monthly VWC Observed	S (%)	$-5418.33\sigma_d$	(-639.121 S (%))	Constant	M_R (psi)
Jan-00	33.17	82.93	-6502	-53004.77	77235.54	17728.77
Feb-00	31.92	79.81	-6502	-51008.41	77235.54	19725.14
Mar-00	32.83	82.07	-6502	-52453.32	77235.54	18280.22
Apr-00	33.49	83.73	-6502	-53510.41	77235.54	17223.14
May-00	12.68	31.69	-6502	-20255.52	77235.54	50478.02
Jun-00	35.60	88.99	-6502	-56877.51	77235.54	13856.04
Jul-00	35.84	89.61	-6502	-57270.59	77235.54	13462.96
Aug-00	35.89	89.73	-6502	-57348.64	77235.54	13384.91
Sep-00	35.78	89.46	-6502	-57173.37	77235.54	13560.17
Oct-00	34.13	85.33	-6502	-54538.83	77235.54	16194.71
Nov-00	33.52	83.80	-6502	-53558.34	77235.54	17175.20
Dec-00	11.73	29.32	-6502	-18737.09	77235.54	51996.46
Jan-01	31.43	78.56	-6502	-50212.17	77235.54	20521.38
Feb-01	32.22	80.54	-6502	-51477.04	77235.54	19256.51
Mar-01	21.98	54.95	-6502	-35119.70	77235.54	35613.85
Apr-01	22.84	57.10	-6502	-36493.81	77235.54	34239.73
May-01	34.90	87.25	-6502	-55766.31	77235.54	14967.23
Jun-01	13.82	34.54	-6502	-22075.25	77235.54	48658.29
Jul-01	25.07	62.68	-6502	-40056.91	77235.54	30676.64
Aug-01	13.63	34.07	-6502	-21776.13	77235.54	48957.42
Sep-01	13.75	34.37	-6502	-21967.74	77235.54	48765.80
Oct-01	13.05	32.63	-6502	-20852.41	77235.54	49881.14
Nov-01	34.67	86.68	-6502	-55400.10	77235.54	15333.45
Dec-01	33.81	84.53	-6502	-54022.65	77235.54	16710.90
Jan-02	11.82	29.55	-6502	-18889.01	77235.54	51844.53
Feb-02	33.54	83.86	-6502	-53593.95	77235.54	17139.60
Mar-02	33.89	84.73	-6502	-54153.61	77235.54	16579.93
Apr-02	34.13	85.33	-6502	-54533.00	77235.54	16200.54
May-02	34.55	86.37	-6502	-55200.96	77235.54	15532.58
Jun-02	36.01	90.02	-6502	-57533.66	77235.54	13199.89
Jul-02	37.31	93.27	-6502	-59609.78	77235.54	11123.77
Aug-02	36.99	92.47	-6502	-59099.21	77235.54	11634.33
Sep-02	36.46	91.15	-6502	-58258.68	77235.54	12474.86
Oct-02	35.03	87.57	-6502	-55970.96	77235.54	14762.58
Nov-02	33.85	84.62	-6502	-54084.58	77235.54	16648.96
Dec-02	33.24	83.10	-6502	-53112.35	77235.54	17621.20

Table 5.6(b) Computation of Resilient Modulus from Predicted Volumetric Water Content - Section 390108						
Months	**Ave. Monthly VWC Observed**	**S (%)**	**$-5418.33\sigma_d$**	**(-639.121 S (%))**	**Constant**	**M_R (psi)**
Jan-00	28.40	71.00	-6502	-45376.55	77235.54	25356.99
Feb-00	27.98	69.95	-6502	-44704.05	77235.54	26029.5
Mar-00	28.18	70.45	-6502	-45023.66	77235.54	25709.89
Apr-00	28.91	72.28	-6502	-46192.47	77235.54	24541.07
May-00	29.54	73.84	-6502	-47191.18	77235.54	23542.36
Jun-00	30.82	77.05	-6502	-49246.86	77235.54	21486.69
Jul-00	31.37	78.42	-6502	-50117.77	77235.54	20615.77
Aug-00	31.66	79.16	-6502	-50590.22	77235.54	20143.33
Sep-00	31.62	79.06	-6502	-50526.27	77235.54	20207.28
Oct-00	31.04	77.61	-6502	-49599.84	77235.54	21133.7
Nov-00	29.99	74.98	-6502	-47918.10	77235.54	22815.45
Dec-00	29.01	72.52	-6502	-46347.32	77235.54	24386.22
Jan-01	28.32	70.80	-6502	-45250.35	77235.54	25483.19
Feb-01	27.98	69.96	-6502	-44711.22	77235.54	26022.33
Mar-01	28.08	70.20	-6502	-44866.29	77235.54	25867.25
Apr-01	28.67	71.68	-6502	-45809.00	77235.54	24924.55
May-01	29.54	73.84	-6502	-47191.18	77235.54	23542.36
Jun-01	30.60	76.49	-6502	-48888.09	77235.54	21845.46
Jul-01	31.17	77.93	-6502	-49803.50	77235.54	20930.04
Aug-01	31.68	79.19	-6502	-50612.38	77235.54	20121.16
Sep-01	31.61	79.01	-6502	-50499.02	77235.54	20234.52
Oct-01	31.16	77.90	-6502	-49785.17	77235.54	20948.37
Nov-01	30.41	76.02	-6502	-48585.34	77235.54	22148.21
Dec-01	29.34	73.34	-6502	-46872.91	77235.54	23860.63
Jan-02	28.49	71.21	-6502	-45513.51	77235.54	25220.03
Feb-02	27.99	69.97	-6502	-44719.26	77235.54	26014.28
Mar-02	28.05	70.13	-6502	-44824.37	77235.54	25909.18
Apr-02	28.75	71.88	-6502	-45936.82	77235.54	24796.72
May-02	29.69	74.23	-6502	-47445.06	77235.54	23288.48
Jun-02	30.57	76.42	-6502	-48841.45	77235.54	21892.1
Jul-02	31.43	78.59	-6502	-50225.64	77235.54	20507.91
Aug-02	31.68	79.19	-6502	-50612.38	77235.54	20121.16
Sep-02	31.46	78.65	-6502	-50266.13	77235.54	20467.41
Oct-02	30.94	77.36	-6502	-49441.13	77235.54	21292.42
Nov-02	30.13	75.32	-6502	-48139.31	77235.54	22594.23
Dec-02	29.27	73.19	-6502	-46774.72	77235.54	23958.82

Table 5.6(a) shows very high values for some of the calculated mean observed resilient modulus. This is as a result of very low volumetric water content values recorded by the TDR probes, which is thought to be malfunctioning at certain times, thereby giving error observed values. The affected data are shaded in the table.

Figure 5.16 shows the regression correlation between the observed and predicted resilient modulus calculated from the volumetric water content. The coefficient of regression r is 0.871 indicates a strong correlation between the two values. The mean observed resilient modulus calculated from the observed volumetric water content that gave very high values as a result of error in the readings of the TDR sensors, were made up for in the regression analysis by taking the average of the other corresponding months reading which is assumed to be correct values and use it in the regression analysis. Table 5.6(c) shows the values used. The regression equation obtained is shown in Figure 5.16.

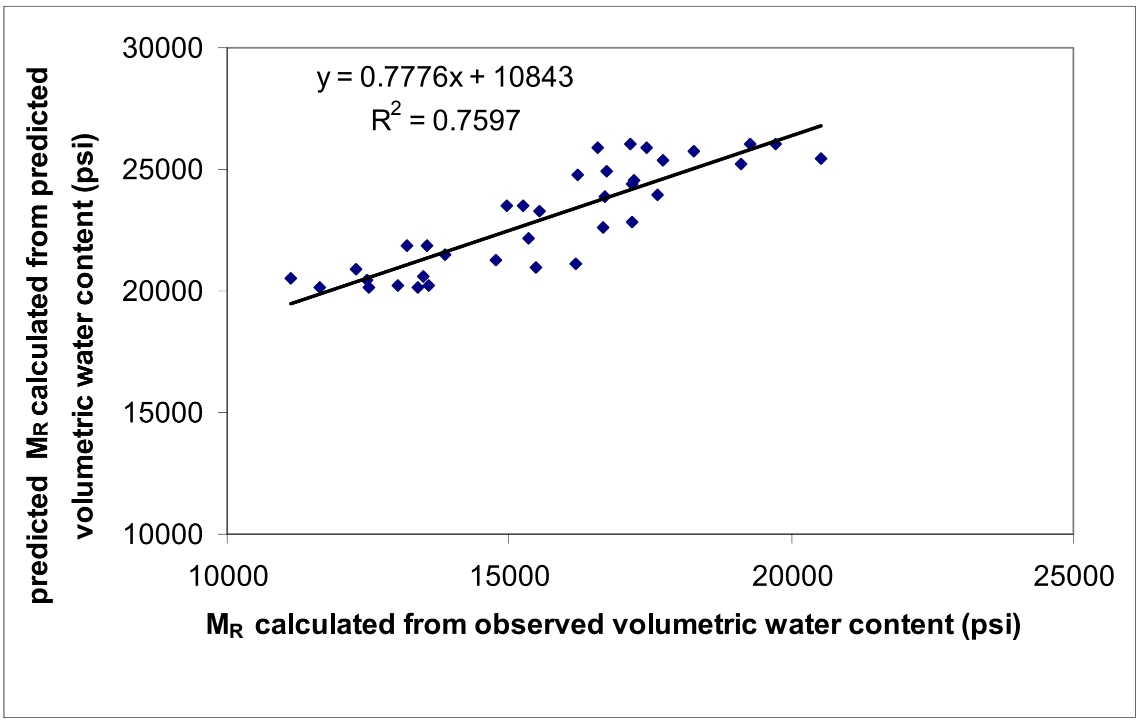


Figure 5.16 – Regression Analysis on calculated Observed and Predicted M_R

Table 5.6c – M_R Values for Regression Analysis

Months	Observed M_R	Predicted M_R
Jan-00	17729	25357
Feb-00	19725	26029
Mar-00	18280	25710
Apr-00	17223	24541
May-00	**15250**	23542
Jun-00	13856	21487
Jul-00	13463	20616
Aug-00	13385	20143
Sep-00	13560	20207
Oct-00	16195	21134
Nov-00	17175	22815
Dec-00	**17166**	24386
Jan-01	20521	25483
Feb-01	19257	26022
Mar-01	**17430**	25867
Apr-01	**16712**	24925
May-01	14967	23542
Jun-01	**13528**	21845
Jul-01	**12293**	20930
Aug-01	**12510**	20121
Sep-01	**13018**	20235
Oct-01	**15479**	20948
Nov-01	15333	22148
Dec-01	16711	23861
Jan-02	**19125**	25220
Feb-02	17140	26014
Mar-02	16580	25909
Apr-02	16201	24797
May-02	15533	23288
Jun-02	13200	21892
Jul-02	11124	20508
Aug-02	11634	20121
Sep-02	12475	20467
Oct-02	14763	21292
Nov-02	16649	22594
Dec-02	17621	23959

5.5 Damage Analysis

The goal of this research is to predict the resilient modulus of subgrade soils and be able to use it in the mechanistic empirical design for pavements. To accomplish this task, damage analysis was done in order to observed the impact of the resilient modulus on the pavement foundation and also, to obtain a minimum resilient modulus value for design purpose. The results of the analysis are presented in Table 5.7 where it is observed that relative damage on the subgrade is high during the months intervening between June and September inclusive, and lowest in the winter months when the resilient modulus is high. Figure 17 is a graphical illustrating the information in Table 5.7.

Table 5.7 - Determination of Effective Subgrade Resilient Modulus from Damage Ratio

Month	Average of Mean Monthly Observed M_R (psi)	Damage Ratio $U_f = 1.18E8\ M_R$^(-2.32)
Jan	19125	0.01375824
Feb	18707	0.01448198
Mar	17430	0.01706348
Apr	16712	0.01881333
May	15250	0.02326495
Jun	13528	0.03072011
Jul	12293	0.03835712
Aug	12510	0.03683626
Sep	13018	0.03358742
Oct	15479	0.02247510
Nov	16386	0.01969304
Dec	17166	0.01767856
	Average =	***0.02389413***
Effective Resilient Modulus		***15076***

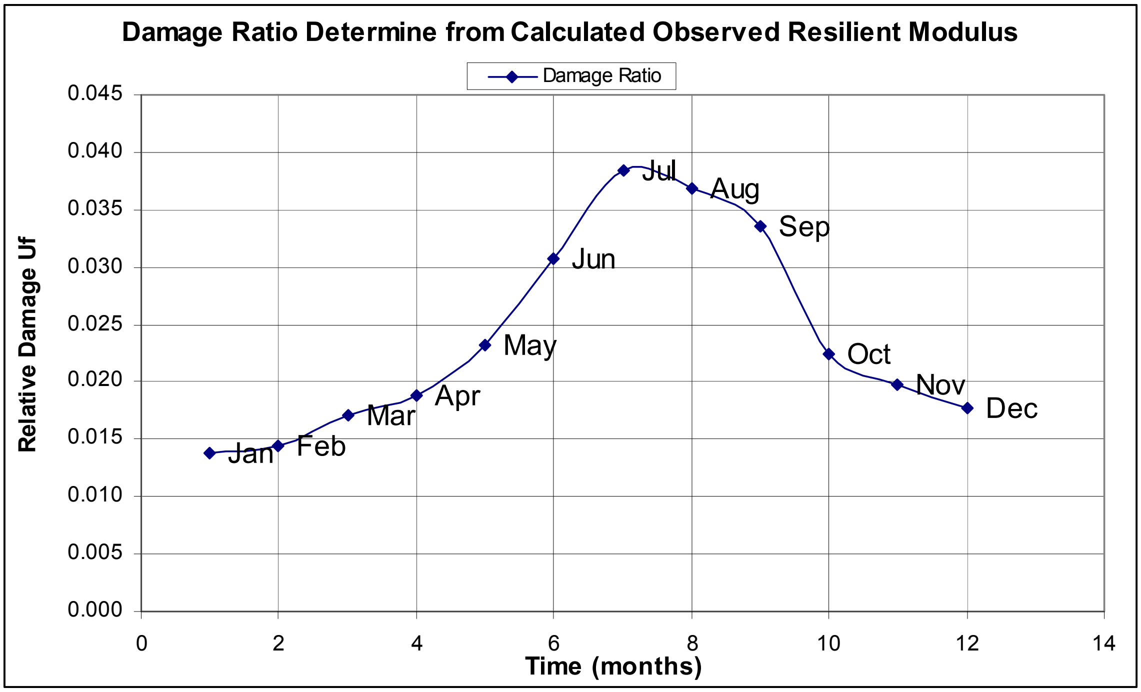


Figure 5.17 – Three years Average of Relative Damage for Every Month - Section 390108 in Ohio

The relative damage analysis showed that the minimum effective resilient modulus for the subgrade soil is 15076psi, which is approximately 23% higher than the minimum resilient modulus that will cause the greatest damage in the subgrade.

This research has shown that temperature and moisture content vary sinusoidally as a function of the day of the year "t". The resilient modulus is expected to follow a sinusoidal variation as shown in Figure 5.15 and can be predicted in a similar fashion using Equation 5.6.

$$M_R = M_{R\,(mean)} + A \sin \frac{[2\pi\,(t - T)]}{365.25} \tag{5.6}$$

Where M_R is the predicted resilient modulus, $M_{R\ (mean)}$ is the mean resilient modulus, A is the amplitude and T is the time shift.

CHAPTER SIX

CONCLUSION

The M – E design method under review can be enhanced by the inclusion of climatic / environmental factors that affects both design and performance of pavement structures. A model for predicting the climatic effect (temperature and moisture content) on the pavement foundation (subgrade soil) has been developed. Also, a framework for developing a model for predicting the seasonal variation of resilient modulus is presented.

Though this research has been limited to cold regions, the methodology used in developing the model can be adopted for any climatic conditions that pavement structures are subjected to. An increase or decrease in the soil temperature has a corresponding increase or decrease, respectively, in the soil moisture content throughout a year's cycle and the trend is a continuous repetition. The subgrade resilient modulus can be predicted for any seasonal climate change; hence, the model can be adopted for use in the M - E design method for pavement design. The longevity of pavement structures as related to their performance is expected.

The lack of good data in the DataPave database presented difficulties in the analysis and development of the model. It is therefore recommended that thorough scrutiny be carried out on all data, and that sufficient data from all regions be made available in the database system thereby enhancing and complementing the effort made by researchers using them. It is also recommended that further analysis be done for other sites to confirm that the greatest damage is done to the subgrade during the summer period.

The model developed to predict temperature and moisture content fits well with the observed data for most of the studied sections. The computations done for resilient modulus indicates that it is affected by climatic conditions and also varies seasonally. Damage on the subgrade is observed to be high in summer months. Similar research is recommended for hot climate regions to determine to what extent moisture content and temperature can influence the resilient modulus of subgrade soil and which of these parameters has a dominant effect.

REFERENCES

1. Al-Abdul Wahhab, H. I., Asi, I. M., and Ramadhan, R. H. (2001). "Modeling resilient modulus and temperature correction from Saudi Roads." J. Mat. In Civil Engrg., ASCE, 14(4), pp. 298 – 305. http://www.pubs.asce.org/WWWdisplay.cgi?0103466

2. Alvarez, C. A., (2000). "Study of Environmental Factors and Load Response in Flexible and Rigid Pavements at the Ohio Test Road" Masters Thesis, CWRU, OH.

3. Berg, L., Bigl, S. R., Stark, J. A., and Durell, G. D. (1996). "Resilient modulus testing of materials from Mn/ROAD, phase 1." USA Cold Regions Research and Engineering Laboratory Report 96-19, Hanover, N.H.

4. Cole, D., Bently, D., Durell, G., and Johnson, T. (1986). "Resilient modulus of freeze-thaw affected granular soils for pavement design and evaluation: Part 1, laboratory tests on soils from Winchedon, Massachusetts, test sections." USA Cold Regions Research and Engineering Laboratory Report 86-4, Hanover, N.H.

5. C-SHRP. 2000. "Pavement design and performance: Current issues and research needs", Millennium Research Brief #2, Canadian Strategic Highway Research Program (C-SHRP). http://www.cshrp.org/products/milbr-2.pdf

6. Design Parameters – Environment http://hotmix.ce.washington.edu/wsdot_web/Modules

7. Diefenderfer, B. K., and Al-Qadi, I. (2002) "Moisture content determination and temperature profile modeling of flexible pavement structures." http://scholar.lib.vt.edu/theses/available/etd-05022002-145649/unrestricted/abstract.PDF

8. Drumm, E. C., Yoder, R. E., and Wilson, G. V. "Incorporation of Environmental Factors in Flexible Pavement Design" http://www.engr.utk.edu/~drumm/research

9. Elkins, G. E., Schmalzer, P., Thompson, T., and Simpson, A., (2003). "Long-term Pavement Performance, Information Management System -

Pavement Performance Database User Reference Guide." Final Report FHWA-RD-03-088. http://www.tfhrc.gov/pavement/ltpp/reports/03088/

10. Erlingsson, S. (2004). "Mechanistic pavement design methods – A road to better understanding of pavement performance." University of Iceland, Iceland.

11. FHWA. 1998. " LTPP Temperature Prediction and Correction Guide – Discussion", FHWA-RD-97, http://www.nilsnet.net/fwd/gendis.html

12. FHWA. 2002. "Study of LTPP laboratory resilient modulus test data and response", FHWA-RD-02-051. Federal Highway Administration (FHWA), (http://www.tfhrc.gov/pavement/ltpp/reports/02051/02051.htm)

13. Figueroa, J. L., Angyal, E., Su, X., (1994). "Characterization of Ohio Subgrade Types", Final Report No. FHWA/OH-94/006.

14. Heydinger, A. G., (2002) "Evaluation of Seasonal Effects on Subgrade Soils", TRB Paper 03-03801

15. Heydinger, A. G., (2003). "Monitoring Seasonal Instrumentation and Modeling Climatic Effects on Pavements at the Ohio/SHRP Test Road." ODOT Project No. 14704(0) http://www.dot.state.oh.us/research/2003/Pavement/14704-FR.pdf

16. Hossain, M., Long, B., and Gisi, A. J. (1996). "NDT- Evaluation of seasonal variation of Subgrade response in asphalt pavements." Semisesquicentinnial Transportation Conference, Centre for Transportation Research and Education (CTRE), Iowa State University. http://www.ctre.iastate.edu/index.html

17. Huang, Y. A., (1993). "Pavement Analysis and Design." Prentice Hall, Englewood Cliffs, NJ.

18. Janoo, V. C., Bayer Jr., J. J., Durell, G. D., and Smith Jr. C. E. (1999) "Resilient Modulus for New Hampshire Subgrade soils for use in Mechanistic AASHTO Design." CRREL. Cold Regions Research and Engineering Laboratory. Special Report 99-14. US Army Corps of Engineers. http://www.stormingmedia.us/44/4468/A446863.html

19. Jin, M. S., Lee, W., and Kovacs, W. D., (1994). "Seasonal Variation of Resilient Modulus of Subgrade soils." J. Trans. Engrg., ASCE, 120(4), pp. 603 – 615.

20. Johnson, T.C., Cole, D. M., and Chamberlain, E. J. (1978). "Influence of freezing and thawing on resilient properties of a silt beneath an asphalt

concrete pavement." USA Cold Regions Research and Engineering Laboratory Report 78-23, Hanover, N. H.

21. Kim, D., Kweon, G., and Lee, K. (2001). "Alternative method of determining resilient modulus of Subgrade soils using a static triaxial test." Can. Geotech. J. 38: pp. 107 – 116.

22. Konrad, J., and Roy, M., (2000). "Flexible pavements in cold regions: a geotechnical perspective." Can. Geotech. J. 37: pp. 689 – 699.

23. Kyatham, V., and Wills, M. (2003). "Predictive Equations for Determination of Resilient Modulus.", Thesis, Rowan University, Glassboro, NJ. (http://users.rowan.edu/~willis84//FinalReport.pdf).

24. Lee, W., Bohra, N. C., Altschaeffi, A. G., and White, T. D. (1997). "Resilient Modulus of Cohesive Soils." J. Geotech. And Geoenviro. Engrg., ASCE, 123(2), pp. 131 – 136.

25. Li, D., and Selig, E. T. (1994). "Resilient Modulus for Fine-Grained Subgrade Soils." Journal of Geotechnical Engineering, ASCE, 120(6), pp. 939 – 957.

26. Microsoft Encarta Online Encyclopedia 2004. "Road," (http://encarta.msn.com)

27. Masada, T., Sargand, S. M., Abdalla, B., and Figueroa, J. L. (2004). "Material properties for implementation of mechanistic-empirical (M - E) pavement design procedures." ORITE final report. Ohio Research Institute for Transportation and Environment, Ohio University, Athens, OH. http://www.dot.state.oh.us/research/2004/Materials/14767-FR.pdf

28. NCHRP, National Corporative Highway Research Program, "Design Process – 2002 Guide, Using Mechanistic Principles to Improve Pavement Design", Project 1-37A. (http://www.2002designguide.com/design.htm)

29. Scheaffer, R. L., and McClave, J. T. (1986). "Probability and Statistics for Engineers." Duxbury Press, Boston MA.

30. Simonsen, E., and Isacsson, U. (2001). "Soil behaviour during freezing and thawing using variable and constant confining pressure triaxial tests." Can. Geotech. J. 38: pp. 863 – 875. (http://cgj.nrc.ca)

31. Simonsen, E., Janoo, V. C., and Isacsson, U. (2002). "Resilient properties of unbound road materials during seasonal frost conditions." J. Cold Regions Engrg. ASCE, 16(1), pp. 28 – 50.

32. Southgate, H. F., and Mahboub, K. C. (1994). “Proposed uniform scale for stiffness of unbound pavement materials for pavement design.” J. Trans. Engrg., ASCE, 120(6), pp. 940 – 952.

33. Thompson, M. R., and Robnett, Q. L., (1979). “Resilient Properties of Subgrade Soils.” Trans. Engrg. Journal, ASCE, 105(TE1), pp. 71 – 89.

34. Tian, P., Zaman, M. M., and Laguros, J. G. (1998). “ Variation of Resilient Modulus of Aggregate Base and its Influence on Pavement Performance.” J. Testing and Evaluation, JTEVA 26(4), pp. 329 – 335.

35. Yavuzturk, C., and Ksaibati, K. (2002). “Assessment of temperature fluctuations in asphalt pavements due to thermal environmental conditions using a two-dimensional transient finite difference approach.” University of Wyoming, Laramie, Wyoming. http://www.ndsu.nodak.edu/ndsu/ugpti/MPC_Pubs/html/MPC02-136/index.html

APPENDIX A

Table A - 1 Pavement Layers Information

States	Section ID Number	County	Layer Type	Material Type	Thick-ness (in)
Vermont	50-1002-1 (AC)	Addison	AC Overlay	Hot Mixed, Hot Laid AC, Dense Graded	3
			AC Binder Course	Hot Mixed, Hot Laid AC, Dense Graded	5.5
			Granular Base	Crushed Gravel	25.8
			Subgrade Soil	Coarse-grained soil: poorly graded gravel with silt and sand	
Pennsyl-vania	42-1606-1 (PC)	Bedford	Original Surface Layer	Portland Cement Concrete (JRCP)	9.9
			Granular Base	Crushed Gravel	7.8
			Subgrade Soil	Fine-Grained Soils: Gravelly Lean Clay with Sand	204
Ohio	39-0104-1 (AC)	Delaware	AC Overlay	Hot Mixed, Hot Laid AC, Dense Graded	1.7
			AC Binder Course	Hot Mixed, Hot Laid AC, Dense Graded	5.5
			Treated Base	HMAC	11.8
			Subgrade Soil	Fine-Grained Soils: Silty Clay	

Table A – 1 Contd.

States	Section ID Number	County	Layer Type	Material Type	Thick-ness (in)
Ohio	39-0108-1 (AC)	Delaware	AC Overlay	Hot Mixed, Hot Laid AC, Dense Graded	1.7
			AC Binder Course	Hot Mixed, Hot Laid AC, Dense Graded	4.9
			Treated Base	Open Graded, Hot Laid, Central Plant Mix	4
			Granular Base	Crushed Stone	8
			Subgrade Soil	Fine-Grained Soils: Silty Clay	
Ohio	39-0112-1 (AC)	Delaware	AC Overlay	Hot Mixed, Hot Laid AC, Dense Graded	1.7
			AC Binder Course	Hot Mixed, Hot Laid AC, Dense Graded	2.3
			Treated Base	HMAC	11.8
			Treated Base	Open Graded, Hot Laid, Central Plant Mix	4
			Subgrade Soil	Fine-Grained Soils: Silty Clay	
Ohio	39-0202-1 (PC)	Delaware	Original Surface Layer	Portland Cement Concrete (JPCP)	8.3
			Granular Base	Crushed Stone	5.8
			Subgrade Soil	Fine-Grained Soils: Silty Clay	

Table A – 1 Contd.

States	Section ID Number	County	Layer Type	Material Type	Thick-ness (in)
Ohio	39-0204-1 (PC)	Delaware	Original Surface Layer Granular Base Embankment Layer Subgrade Soil	Portland Cement Concrete (JPCP) Crushed Stone Fine-Grained Soils: Silty Clay Fine-Grained Soils: Silty Clay	11.1 5.8 16
Ohio	39-0205-1 (AC)	Delaware	Original Surface Layer Treated Base Subgrade Soil	Portland Cement Concrete (JPCP) Lean Concrete Fine-Grained Soils: Silty Clay	8 6.2
South Dakota	46-0804-1 (AC)	Campbell	AC Overlay Granular Base Subgrade Soil	Hot Mixed, Hot Laid AC, Dense Graded Crushed Stone Fine-Grained Soils: Silty Clay	7.2 12

Table A – 1 Contd.

States	Section ID Number	County	Layer Type	Material Type	Thick-ness (in)
Minne-sota	27-1018-1 (AC)	Morrison	AC Overlay AC Binder Course Granular Base Subgrade Soil	Hot Mixed, Hot Laid AC, Dense Graded Hot Mixed, Hot Laid AC, Dense Graded Gravel (uncrushed) Coarse-Grained Soils: Poorly Graded Sand with Silt	1.6 2.8 5.2
Minne-sota	27-1028-1 (AC)	Otter Tail	AC Overlay AC Binder Course AC Binder Course Subgrade Soil	Hot Mixed, Hot Laid AC, Dense Graded Hot Mixed, Hot Laid AC, Dense Graded Hot Mixed, Hot Laid AC, Dense Graded Coarse-Grained Soils: Poorly Graded Sand with Silt	1.6 2 6
Minne-sota	27-6251-1 (AC)	Beltrami	AC Granular Base Subgrade Soil	Hot Mixed, Hot Laid AC, Dense Graded Gravel (uncrushed) Coarse-Grained Soils: Poorly Graded Sand with Silt	7.4 10.2

APPENDIX B

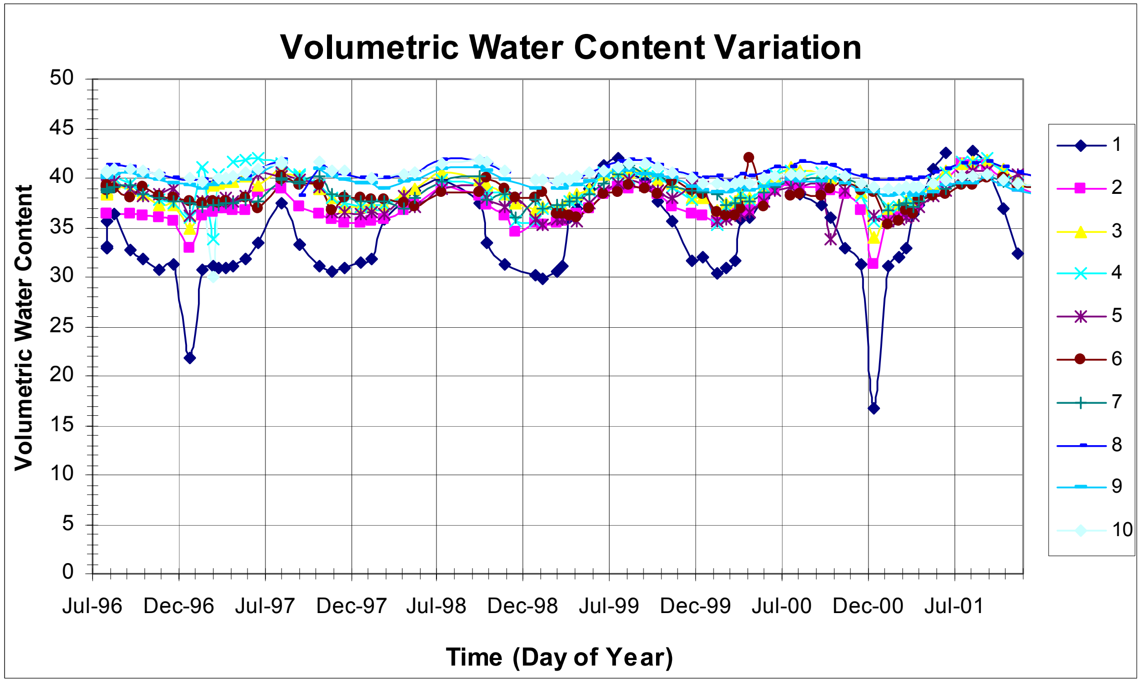


FIGURE B -1 Seasonal Variation of Volumetric Water Content Observed from Sensors Installed in Section 390104 in Ohio

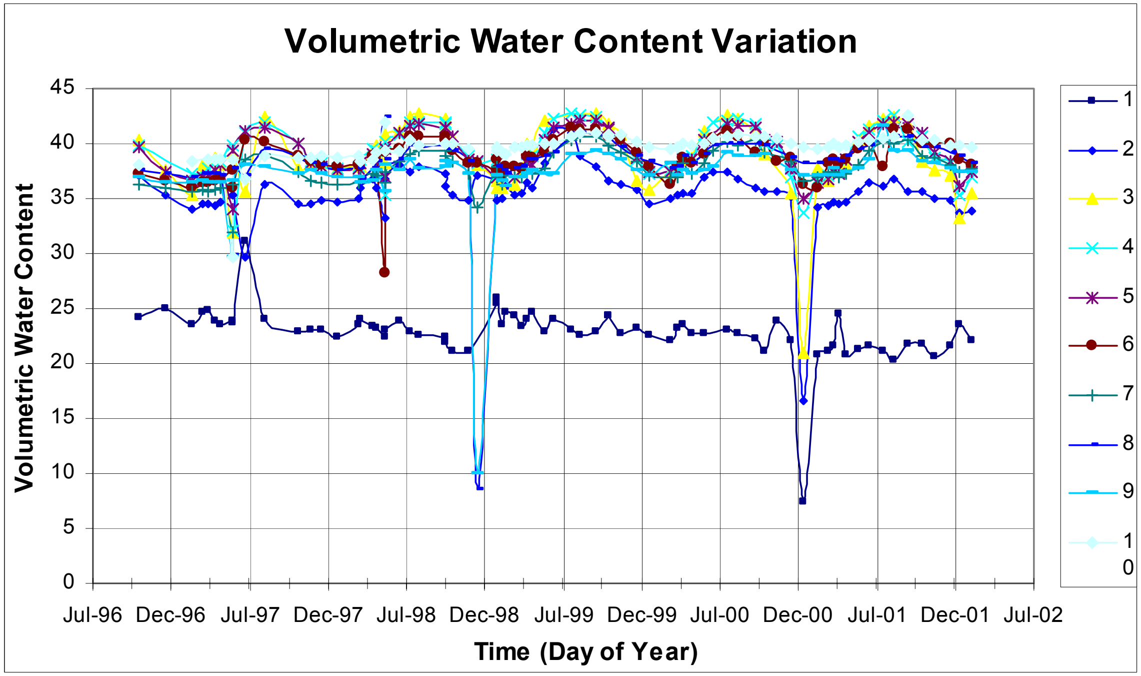


FIGURE B -2 Seasonal Variation of Volumetric Water Content Observed from Sensors Installed in Section 390204 in Ohio