LABORATORY CHARACTERIZATION OF ASPHALT CONCRETE MIXTURES USING DYNAMIC MODULUS TEST

A Thesis

of

Master of Science

Submitted By

Yasir Ali

(NUST-2012-60946-MSCEE-15112F)

Department of Transportation Engineering

National Institute of Transportation

School of Civil and Environmental Engineering

National University of Sciences and Technology

Islamabad, Pakistan

(2014)

This is to certify that the

thesis entitled

LABORATORY CHARACTERIZATION OF ASPHALT CONCRETE MIXTURES USING DYNAMIC TEST

Submitted by

Yasir Ali

Has been accepted towards the partial fulfillment

of the

requirements for

Master of Science in Transportation Engineering

____

Dr. Muhammad Irfan, Ph.D

Department of Transportation Engineering

National Institute of Transportation

School of Civil and Environmental Engineering

National University of Sciences and Technology, Islamabad

LABORATORY CHARACTERIZATION OF ASPHALT CONCRETE MIXTURES USING DYNAMIC MODULUS TEST

by

Yasir Ali

(2012-NUST- 60946-MSCEE-15112F)

A Thesis

of

Master of Science

Submitted to

Department of Transportation Engineering

National Institute of Transportation

School of Civil and Environmental Engineering

National University of Sciences and Technology

Islamabad

In partial fulfillment of the requirements for the degree of

Master of Science Transportation Engineering

2014

Dedication

This thesis is dedicated to my beloved

TEACHERS

&

PARENTS

Who taught me the value of education and have never failed to give me financial and moral support for giving all my needs during the time I developed my system and for teaching me that even the largest task can be accomplished if it is done one step at a time. I'm deeply indebted to them for their continued support and unwavering faith in me. .

ACKNOWLEDGEMENT

It is impossible to express my gratitude in a limited number of words. This Acknowledgments section symbolizes my humble attempt at thanking those who have taught me anything and everything I have learned during my graduate studies.

The completion of this thesis would not have been possible without the guidance, help, patience and perseverance of a number of people, who in one way or the other extended their valuable assistance in the continuation and completion of this research. Most of all this piece of work would never have been accomplished if it wasn't for the benevolence of one above all of us, the all-pervading Allah, for answering my prayers and for giving me the strength to trudge on despite my resolve wanting to wane and throw in the towel, thank you so much Dear Lord.

First and foremost I would like to thank my thesis supervisor, Dr. Muhammad Irfan, for urging me on and on, inducting me in National Highway Authority (NHA) research Project. If it was not for his support and encouragement it would not have been possible for me to come over all obstacles I faced in the course of my research.

Secondly I would like to thank all my committee members Dr Tariq Mahmood, Dr Shahab Khanzada and Dr Sarfraz Ahmed for sharing their valuable insights and helpful whenever I required their assistance.

I also would like thank my fellows Muhammad Zeeshan and Muhammad Aniq Gul for their help in determination of optimum bitumen content for mixes. I am also grateful to transportation lab staff for their continuous support during this course of time.

Last but not the least, I would like to thank my family from all my heart, for putting up with me in my most annoyed phases in the completion of this document, and for urging me on at every point. Mom, Dad and Siblings, this would never have been possible without you.

Yasir Ali

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AASHTO	- American Association of State Highway and Transportation Officials
AMPT	- Asphalt Mixture Performance Tester
ANOVA	- Analysis of Variance
ASTM	- American Society for Testing and Materials
HMA	- Hot Mix Asphalt
LVDTs	- Linear Variable Differential Transformer
MAPE	- Mean Absolute Percentage Error
ME	- Mechanistic- Empirical
MEPDG	- Mechanistic- Empirical Pavement Design Guide
NCHRP	-National Cooperative Highway Research Program
NHA	-National Highway Authority
NMAS	-Nominal Maximum Aggregate Size
PG	- Performance Grading
SGC	- Superpave Gyratory Compactor
SPT	- Simple Performance Tester
VA	- Air Voids
VFA	- Voids Filled with Asphalt
VMA	- Voids in Mineral Aggregates

ABSTRACT

The dynamic modulus test correlates with the field performance of hot mix asphalt (HMA), complements the mix design criteria, and considered as a key material characterization input parameter in the Mechanistic-Empirical (M-E) design of pavement structures. This study investigated the dynamic response and fatigue behavior of various asphalt concrete (AC) mixtures subjected to compressive sinusoidal loading. Eight (08) AC mixtures (four wearing and four base course) were selected including Superpave, asphalt institute manual series (MS), dense bituminous macadam (DBM) and national highway authority (NHA)'s class A & B gradations. Marshall mix design method was employed to determine the optimum bitumen content of all mixes and specimens were fabricated using superpave gyratory compactor (SGC) for performance testing. The dynamic modulus (|*E**|) test at various temperatures (4.4 to 54.4 °C) and frequencies (0.1 to 25 Hz) was conducted using asphalt mixture performance tester (AMPT). Statistical analysis of two-level factorial was employed to regulate the factors affecting the AC mixtures. The analyses result revealed that an increase in temperature (from 21.1 to 37.8 °C), translated into 45% and 43% drop in |*E**| values on average while 80% and 67% of variation in |*E**| values was attributed to the sweep of frequency (from 25 to 0.1 Hz) for wearing and base course mixes, respectively. The sensitivity of the dynamic modulus to the variation in the HMA mix properties using different aggregate gradation, diverse loading frequencies and temperature, or a combination of those were evaluated and results exhibited that NHA-A wearing course mix and DBM base course mix had relatively higher dynamic modulus values than other mixes. Non-linear regression models were developed to express the dynamic modulus as a function of test temperature, loading frequency and mixture volumetric parameter. Also, indicators of dynamic response and viscous (or elastic) properties of the mixtures were used to derive fatigue parameter to estimate the resistance to fatigue and results revealed that Superpave wearing mix and NHA-B base course mix had relatively better resistance to fatigue for evaluated mixtures. This study also presents the catalog for default dynamic modulus values for all mixes at various temperatures and frequencies by generating the master curves which in turns provide the basis for the implementation of mechanistic-empirical analysis and design - an approach which is more appropriate for heavy axle load/ tyre pressure and climatic conditions of Pakistan.

Chapter 1

INTRODUCTION

1.1 Background

Transportation plays pivotal role in the daily life of human being and better transportation facilities is sign of developed countries. Pakistan is one of the developing countries where transportation infrastructure is serving a major contribution to movement of people, fleet and goods. The total road network of Pakistan is over 260,000 km and most of the national highways and motorways are usually of asphalt pavements or hot mix asphalt (HMA) pavements.

Asphalt pavements are very common these days around the globe. The asphalt pavements are not new idea as it has been started a century ago. The emphasis is made on the quality and service life of the pavement for their long lasting and provides the ease of accessibility and desired level of comfort and services for which they are intended to construct. The main constituents of HMA pavements are aggregate and asphalt binder. For the performance of HMA pavements, it is imperative to develop the relation between the constituents of HMA i-e aggregate and binder.

Various researchers have worked on establishing the relationship between aggregates and binder. Marshall and Hveem had successfully attempted to link the relationship between HMA constituents and determine volumetric properties of the mixes i-e stability and void analysis. But with time it has been realized that these methods do not predict field performance which makes pavement viable to failure prior to completion of its design life. These methods are based on the empirical design approach which does not cater the aforementioned problem.

The problems in the current methods and necessity to overcome such obstacles, efforts were made to determine the basic mechanical properties of HMA. A research program named strategic highway research program (SHRP) was carried out in USA in early 1990's and the final product of this research was performance based grading (PG) and superior performing asphalt pavements (Superpave). With the advent of this method, previously used method like Marshall and Hveem were outdated around the globe and Pakistan is still making move toward the performance based grading system. This testing procedure simulates the field conditions better than previously used method with the gyratory compactor which

simulates the field conditions with no of gyration.

As the superpave is being widely used and overcome the deficiencies of previous methods, the basic need arises of the characterizing the mechanical properties of HMA, for which national cooperative highway research program (NCHRP) carried out various studies and end result is dynamic modulus which best characterize the mixes and complement superpave volumetric design using superpave gyratory compactor. Dynamic modulus is one of the basic design input parameter in the AASHTO Guide for mechanistic-empirical design of new and rehabilitated pavements surfaces (NCHRP 1-37A).

The pavement structural design is very important and in the very beginning it has been estimated through field experience i-e AASHO road test which is based on certain set of conditions and with different conditions this approach poses problems and does not cater these problems. The most of the US agencies follow the AASHTO 1986 and 1993 which both are empirical in nature. Due to failure of the pavement within few years of its construction is because of the empirical design procedures adopted which could not predict the life of the pavements. Soon this problem become more pronounced and need of new design procedures evolved.

The premature failure of the HMA pavements within few years of construction has been major problem arising these days and it's because of not predicting the future performance of asphalt pavement. Hence it is necessary to develop mechanistic approach which appropriately predict and give acceptable performance. Mainly mechanistic portion of design uses the developed model to predict performance and encounter certain factors which were missing in empirical approach like environmental conditions and traffic and temperature.

In this regards, AASHTO took step forward and initiated study with NCHRP in 2002 and outcome was mechanistic-empirical design guide which was supporting tool for pavement engineers in terms of acceptable performance. This design procedure entertain site conditions as well as traffic characteristics which helps the engineer to play with design thickness of various layers pavement based on the traffic characteristics and material properties incorporated in order to reduce the distresses within first few years of construction which cause the premature failure of pavement and provide desired performance.

This approach is relatively new for Pakistan and yet to be fully implemented and prior to implementation it is very important to carry out laboratory evaluation of different HMA mixes and predict their field response and correlate laboratory results with field results. In this regards, dynamic modulus is lead candidate as performance test and only test which completely characterize the asphalt mixes as it can be done on range of temperature from -10 to 60 °C temperature and six different frequencies starting from 0.1 to 25 Hz. It can also be used to evaluate the predictive equations and their potential to predict accurately and also one of the basic input parameter for the implementation of new M-EPDG approach based on the superpave performance based mix design.

1.2 Problem Statement

Transportation infrastructure is getting handsome amount annually for its overall roads of 260,000 km which includes motorways and national highways. After such huge investment for construction, maintenance and rehabilitation of highways, it is frequently observed that desired level service is not achieved due to distresses. These distresses cause the premature failure of newly constructed asphalt pavements in form of cracking and permanent deformation. This is because of empirical design approach followed while designing phase which did not cater the effect of the distresses in design life of the pavement and ultimately poses the problem of failure. If the level of severity of distresses is being catered while designing, it will help pavement engineers to minimize the distresses by compensating mix and material properties. The M-EPDG can be used in order to cater the climate, pavement response to traffic loading and effect of material properties to pavement performance.

These problems justify the need of study which in facilitate turn the implementation of mechanistic and empirical design approach and caters problems related to implementation. In this regards, National Highway Authority (NHA) of Pakistan has carried out research project “Improvement of asphalt mix design technology for Pakistan” to implement the mechanistic-empirical design approach and dynamic modulus testing is one aspect of that project in which various asphalt wearing and base course mixes are to be tested.

1.3 Objectives of the study

The implementation of the M-EPDG needs the complete characterization of laboratory prepared HMA mixes along with the field results.

The objectives of this study are:

- To conduct the simple performance test i-e Dynamic modulus test on the specimens prepared using superpave gyratory compactor (SGC).

- To investigate the factors affecting dynamic modulus (stiffness parameter) in order to compare different asphalt concrete mixes (local and global gradations).
- To develop the master curves for different asphalt concrete mixes.
- To estimate the resistance to fatigue of different asphalt concrete mixes.
- To calibrate regression model of dynamic modulus for wearing and base course mixes

1.4 Scope of the Study

A methodology was planned in order to achieve the study objectives which is already stated above and few errands has been highlighted. To start with the already research carried out on the dynamic modulus, insight of literature review is done which covers the testing, findings, correlation and also research carried out in Pakistan. This study consists of eight different gradations i-e four for the asphalt wearing course and four for the asphalt base course. The binder source is attock refinery limited (ARL) 60/70 and aggregate material has been from the acquired from margalla quarry. In initial stages optimum bitumen content and volumetric properties were determined using standard marshall method and based on the results performance testing is done for which superpave gyratory specimens were fabricated. Each mix is tested for dynamic modulus at four different temperatures starting from 4.4, 21.1, 37.8 and 54.4°C and six different frequencies i-e 0.1, 0.5, 1, 5, 10 and 25 Hz.

Table 1.1 Test Matrix for Dynamic Modulus Evaluation of Asphalt Mixtures

Gradations	Layer	Temperatures (°C)			
		4.4	**21.1**	**37.8**	**54.4**
		Frequency (Hz)			
		0.1,0.5,1,5,10,25	**0.1,0.5,1,5,10,25**	**0.1,0.5,1,5,10,25**	**0.1,0.5,1,5,10,25**
NHA A	Wearing Course	03 Replicate specimens			
NHA B		03 Replicate specimens			
Superpave 1		03 Replicate specimens			
MS 2		03 Replicate specimens			
NHA A	Base Course	03 Replicate specimens			
NHA B		03 Replicate specimens			
Superpave 2		03 Replicate specimens			
DBM		03 Replicate specimens			

The table 1.1 shows the test matrix for research study. This table indicates the scope of study which includes the type gradation, aggregate source and binder type and source, testing temperature and frequencies.

1.5 Thesis Organization

This research study is organized into five chapters. Chapter one describes the background of the HMA mix and structural design procedures, problem statement, objectives, scope of the study. The second chapter of literature review covers the brief description of the dynamic modulus and complex modulus as well as concept of viscoelastic materials, previous research findings, determination of the dynamic modulus and various researchers worked over it, development of master curves using the laboratory results and concept of master curves and dynamic modulus predictive models. The third chapter includes the methodology to laboratory testing for optimum calculation and performance testing, sample preparation, testing equipment. The chapter four of results and analyses describe the laboratory results and master curve development based on the laboratory results along with properties the statistical analysis which includes the full factorial design of experiment, regression model development, estimation of resistance to fatigue and sensitivity analysis. The chapter five presents the conclusion and recommendations on the basis of the current study results and future research. The thesis organization can also be illustrated by figure 1.1.

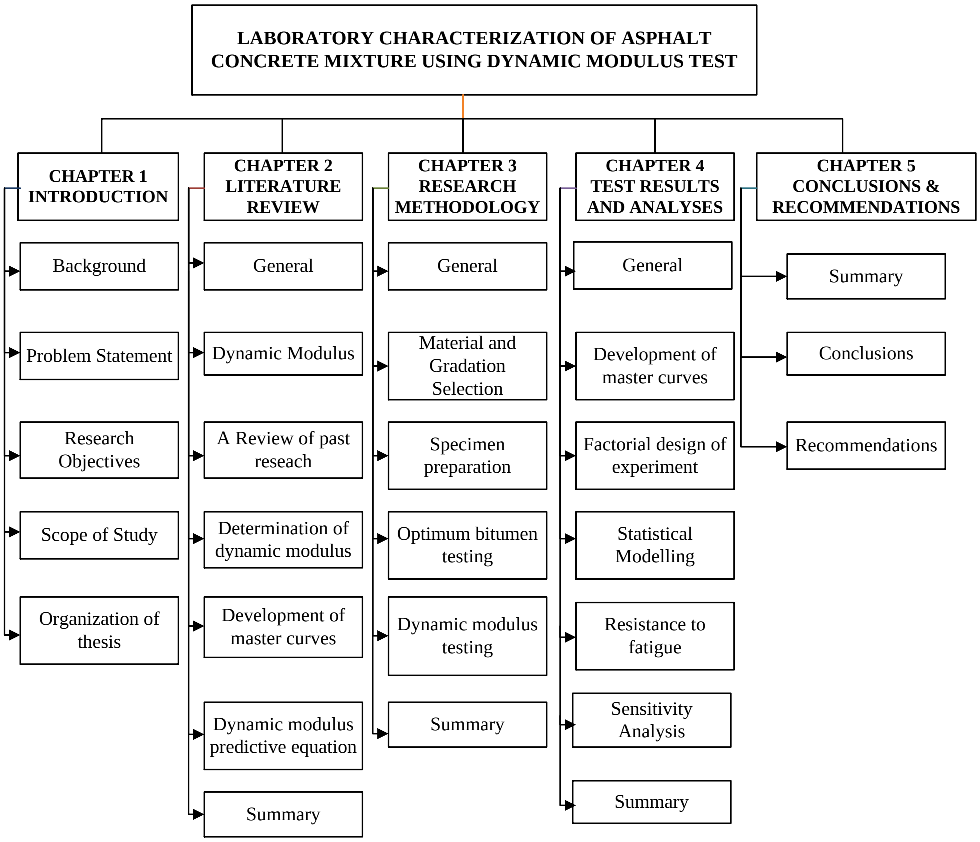


Figure 1.1 Organization of thesis

Chapter 2

LITERATURE REVIEW

2.1 General

Hot mix asphalt (HMA) consists of mainly aggregate and asphalt binder. By varying the aggregate, the properties of HMA also vary and same is case with change in asphalt binder. It has been generally observed that pavements fail before due course of time and do not complete their service life. The premature failure may be due to distresses like rutting, fatigue, cracking, stripping etc. To arrest these distresses during design stage of pavement, dynamic modulus |*E**| of HMA should be evaluated which will be helpful in pavement thickness design and for evaluating pavement performance. Dynamic modulus of HMA is material property which defines the time and temperature addiction of HMA. Therefore it is necessary to gain insight the dynamic modulus |*E**| and the influencing factors over it. The ensuing paragraph will elaborate the dynamic modulus, its testing procedures, dynamic modulus predictive models and factor affecting the dynamic modulus and master curve development with the help of the previous literature.

2.2 Dynamic Modulus |*E**|

A complex modulus can be defined as "ratio of stress to strain for a linear viscoelastic material", or it can be defined as it shows the relationship of stress-strain for linear viscoelastic material, while the dynamic modulus can be described as "the ratio of maximum stress (δ_o) to recoverable axial strain (ε_o) under sinusoidal loading". It is the normal value of the complex modulus which can be calculated by above stated ratio (AASHTO, 2007). Mathematically dynamic modulus can expressed by equation 2-1.

$$|E^*| = \frac{\delta_0}{\varepsilon_0} \qquad (2\text{-}1)$$

Where

δo = Maximum (peak) stress

ε_o = Peak recoverable strain

The complex modulus is consisting of two parts. First part exemplifies the elastic stiffnes while other part describes the material's internal dampness (Huang, 2004). Mathematically it can be written by equation 2-2 (Witczak et al. 2002).

$$E^* = E' + i E'' \quad (2\text{-}2)$$

Where:

E' = storage or elastic modulus

E" = loss or viscous modulus

$i = \sqrt{-1}$

If the material is purely elastic hence E" is zero and dynamic modulus will be equal to E'. The phase angle can be defined as "angle by which axial strain fall behind the compressive stress". It is direct indicator of the viscoelastic properties of the mix and can be represented by equation 2-3 (Witczak et al. 2002).

$$\phi = \frac{ti}{tp} \times 360 \quad (2\text{-}3)$$

Where

ti = time lag between a cycle of stress and strain (s);

tp = time for a stress cycle (s)

i = imaginary number

When Φ = 0 (for purely elastic material) then complex modulus (E*) will be equal to dynamic modulus whereas Φ=90 for viscous material. Dynamic modulus is ratio of sinusoidal stress to resulting strain which is characterize by angular velocity ω, time t, which infers that phase angle represents the time reliance of HMA and can be illustrated by figure 2.1. Loading frequency is the one of factor upon which HMA is dependent and equation 2-4 (Huang, 2004) suggests that stress and resulting strain are function of angular frequency which is related to the loading frequency.

$$\omega = 2 \pi f \quad (2\text{-}4)$$

Where:

ω = angular frequency (rad/s)

f = loading frequency (Hz)

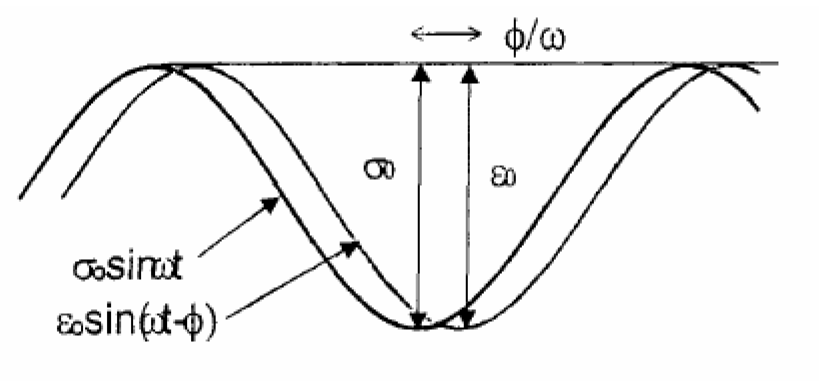


Figure 2.1 Dynamic (complex) modulus test (Dougan et al. 2003)

2.3 A Review of Past Research

Viscoelastic behavior of HMA was firstly described by the Papazian in 1962 when he carried out extensive laboratory testing over cylindrical specimens under controlled environment and temperature at different loading frequencies and amplitudes. As the load is applied on certain frequency sinusoidal stress is produced accompanied by the resulting strain which is measured at frequency. This study concludes that HMA viscoelastic behavior is applicable performance and design of HMA (Papazian, 1962).

Later on, in 1970, Kallas carried out study regarding the compression, tension and compression-tension loading. HMA testing was conducted under tension and tension-compression sinusoidal loading to determine the dynamic modulus and compared to compression loading as well. Furthermore the difference in dynamic modulus was more pronounced at frequency 1 Hz and range of temperature 21 to 38 °C (Kallas, 1970).

For evaluation of dynamic modulus of HMA when design is based on elastic theory, all three testing i-e tension, compression and tension-compression modes were done. If the viscoelastic theory is basis of the design and dynamic modulus & phase angle are considered as design variables then the original loading conditions should be used i-e tension-compression test (Witczak & Root, 1974).

Bonnaure et al. (1977) determined the dynamic modulus of the asphalt mixtures using two point bending apparatus which is developed by the shell laboratories. They conducted test on trapezoidal specimen which is fixed at the bottom and exposed to haversine (sinusoidal) loading at the free end. Stiffness modulus of specimen can be evaluated from the load deformation plot at the free end or it can be calculated by measuring the strain at the span of beam using strain gauge. Shell nomographs are developed by which stiffness modulus can be calculated. They also stated the relationship of temperature and loading in terms of dynamic modulus. It increases with decrease in the temperature and vice versa. They also discovered the dynamic modulus master curves at different frequencies and temperatures and their superposition which is commonly known as time-temperature superposition principle. This principle has gained very importance today as the entire laboratory results are shifted to one reference temperature and master curve is generated as it is done in M-EPDG.

Lee et al. (2002) carried out research on different asphalt mixtures with granite which is mostly common in Korea. Dynamic modulus was evaluated for range of temperatures from -10 °C to 55 °C and master curves were generated from laboratory obtained results. Specimens were prepared using superpave gyratory compactor (SGC) for different aggregate sizes (13 mm, 19 mm) with controlled air voids and optimum bitumen content. Laboratory dynamic modulus results were compared the predictive equations stated by the NCHRP 1-37A in M-EPDG.

There are standard procedures by which modulus of asphalt mixtures can be evaluated. American society of testing materials (ASTM) specification "D3497-79 Standard test method for determining dynamic modulus of asphalt mixtures" which defines the testing of cylindrical specimens prepared using superpave gyratory compactor (SGC) or kneading compactor at different test temperature i-e 5, 21.6 and 40 °C and at different frequencies i-e 1, 4 and 16 Hz. Dynamic modulus is calculated by applying sinusoidal load to specimen and measuring the strain using strain gauges at the mid span of specimen and then with ratio of stress over axial strain gives the dynamic modulus of that specimen (ASTM, 2003).

AASHTO also provide the standard for evaluation of dynamic modulus which is provisional standard AASHTO TP 62-07 which recommends the testing of SGC prepared specimen for a range of temperatures from -10 to 60 °C and six different frequencies 0.1, 0.5, 1, 5, 10 and 25 Hz. Axial strain is obtained using linear variable differential transformer (LVDTs) mounted on the test specimen. Dynamic modulus can be calculated by the ratio of the stress to axial strain. This method is most populous for determining the dynamic modulus in the laboratory (AASHTO, 2007).

Another study carried out by U.S department of transportation Washington D.C in 2009, there was three main objectives of the study. First the current standard for determining dynamic modulus AASHTO TP 62-07 was reviewed to check the accuracy the test and if necessary, recommend the improved test procedure with more precision. The second objective of the study was testing and comparison of plant produced and laboratory prepared specimens of various HMA mixtures and prepare the dynamic modulus catalog for use in mechanistic-empirical pavement design guide (M-EPDG). The third objective was to check the precision of two dynamic modulus models namely Witczak and Hirsch model. This study concluded that correlation was developed using results between dynamic modulus, fatigue cracking and rutting of various asphalt mixtures (Bennert & Aboobaker, 2009).

Numerous studies describe the use of modifiers in HMA to alter its properties and to cater desired distresses. A similar study is presented herein which elaborates the use of modifiers in HMA to control its dynamic response ad fatigue resistance. This research incorporates three different types of fibers namely polyester fiber, cellulose fiber and mineral fiber with percentage of 0.3%, 0.3%, and 0.4% respectively by weight of HMA. Based on the aforesaid content of modifiers, performance testing was carried out on these blends and control mixes. Testing program includes dynamic modulus and indirect tension fatigue test. This research concludes that dynamic modulus along with phase angle decrease with addition of fibers. Fatigue resistance of HMA can be estimated using fatigue parameter ($|E^*| \times \sin\delta$) which is derived from dynamic response of HMA. The results indicated that fatigue parameter decreased with addition of modifier which shows that fiber modifiers improves the fatigue property of HMA. By comparing results of both modified and control mixes, fatigue test suggested that fiber modified mixtures performed better in contrast to control mix (Ye et al. 2009).

Another study describes the HMA laboratory's behavior is compared with field measured pavement response by use of dynamic modulus test. The focus of this study was to compare and validate the field measured longitudinal strains with laboratory determined dynamic modulus using simple performance test equipment. Hot laid 3 (HL3) was tested in laboratory under constant frequency of load, the resulting dynamic modulus was found to be exponentially decreasing with increase in the temperature of the asphalt. At the constant speed of the truck, controlled wheel load experiments were performed on HL3 asphalt, longitudinal strains found to be exponentially increasing with asphalt mid span depth temperature. This study concluded that exponential relationship showed that laboratory obtained dynamic modulus is inversely proportional to the field measure pavement response of the asphalt longitudinal strains (Bayat & Knight, 2010).

Mun and Lee carried out research in South Korea for the characterization of bituminous mixes at low temperature. This research elaborates that at low temperature the fatigue behavior of HMA can be evaluated. Researchers conducted the dynamic modulus test for characterization of material stiffness while constant cross-head rate tension test was performed to categorize fatigue cracking resistance. Dense graded alongwith lime added mixtures were used for the performance testing. This research concludes with development of algorithm based on the measured and calculated stress & strain recorded in said performance testing which is carried out at low temperatures and formulates the methods to determine the optimum asphalt content of bituminous mixes to rally resistance to fatigue cracking and its evaluation (Mun & Lee, 2010).

Various researches around globe have been carried for unconventional mixes in which mineral filler is used in hot mix asphalt and performance testing is being carried out. In similar way, a laboratory research has been conducted in which granulated copper slag has been used as fine aggregate in hot mix asphalt. In various blends of aggregate prepared, up to 40% of copper slag was added and marshall mix design was performed. On prepared blends dynamic modulus test was performed on frequencies varying from 0.1 to 16 Hz and temperatures ranging 25 to 60 °C. Based on the obtained results, Master curves and shift factors were acquired for both control and slag mixed blend. Further these curves were compared to dynamic modulus predictive models. This research concludes that with the increase in addition of slag percentage, strength of mix reduces significantly when it is compared to control mixes. To demonstrate the stripping potential of slag mixes, indirect tensile strength was performed and results revealed that strength reduces but ratio of tensile-strength increases when it is compared to control mixes (Hassan & Al-Jabri, 2011).

The characterization of HMA is important phenomena while determining its behavior when exposed to loading conditions. Addition of modifier is very often nowadays as many researches illustrated the use of modifiers with HMA to change its properties. A research carried out in India which highlighted dynamic mechanical behavior of asphalt mixes with the addition of crumb rubber and styrene butadiene styrene (SBS) polymer. Blends were prepared and performance testing was carried out which includes dynamic modulus, static and dynamic creep test at different temperatures. Master curves were developed for both unmodified and modified asphalt binder mixes. Regression analysis was used to estimate the creep parameters which explained enduring deformation of HMA mixes. This study concluded that the dynamic modulus have higher values for SBS and reduced rate of deformation when exposed to higher temperatures compared to unmodified and crumb rubber asphalt binder. Statistical analysis i-e mutli-level factorial analysis of variance was used and determined frequency, temperature and asphalt binder significantly affect the dynamic mechanical behavior of asphalt behavior (Kumar & Veeraragavan, 2011).

Zhu et al. (2011) conducted dynamic modulus to evaluate the influence of the modifier on the enactment of AC mixtures. The effect of temperature, confining pressure and frequency was investigated and subsequently master curves were developed and interpreted. The laboratory results was correlated with Witczak model and results indicated that model predictive ability is better in predicting values. This study concluded that highest mixture stiffness is obtained by use of polymer modifiers, especially Domix and higher dynamic modulus values are obtained at high frequency, high confining pressure and low temperature.

The reuse of asphalt pavements is not relatively new technique and various researches have been conducted on recycled asphalt pavement (RAP). A study is enlightened in which influence of RAP material on the asphalt pavement performance was investigated. RAP percentages like 15, 35, and 50% were selected for said study while in hot mix drum plant the percentage of RAP was not more than 30%. Based on these specifications, mixes were prepared alongwith virgin material and performance testing was carried out on both blends, the testing program includes asphalt pavement analyzer (APA) rutting, dynamic modulus and modified lottman. This study concludes that with addition of RAP, rutting is decreased by 24% while resilient modulus is increased by 52% on average in RAP mixtures which were under study. The addition of aggregate and RAP binder causes the stiffening of mixtures when exposed to higher temperatures and heavier traffic loading conditions. Dynamic modulus values increased with addition of RAP and statistical analysis showed dynamic modulus variability was significant at high RAP content (Colbert & You, 2012).

Mun and Lee (2012) investigated the fatigue resistance of AC mixture using viscoelastic continuum damage analysis. The testing procedure included indirect tension test and dynamic modulus test for characterization. For numerical computation viscoelastic convolution integral, the state-variable approach is be used. For the determination of damage parameter of a stiffness reduction function, Nelder–Mead simplex search was used. Resistance to fatigue was determined as a function of loading rate, asphalt binder content, modifier (e.g.

usage of hydrated lime), and temperature, and results revealed that these factors have strong effect on fatigue resistance.

HMA mixes can be characterized by various performances testing like dynamic modulus, flow number and resilient modulus, fatigue life test and many more. Keeping this in view, a study is framed by various researchers which focus on the dynamic modulus testing, flow number and uniaxial repeated load permanent deformation test. This research illustrate the comparison of flow number, dynamic modulus and uniaxial repeated load permanent deformation laboratory test results which define the rutting susceptibility of HMA and presented idea that based on obtained results and correlation, one test method may substitute other and develop the relationship among the results if possible. Rut resistance of HMA is elaborated in this research which is based on notion of flow number index which characterize the rutting resistance. This research concluded that flow number index which lieu to flow number (cycles) has good correlation to dynamic modulus and uniaxial repeated load permanent deformation test (Zhang et al. 2013).

Unconventional mixes like warm mix asphalt (WMA), Stone mastic asphalt (SMA) is under research around the globe. A study is enlightened in which stone mastic/matrix asphalt (SMA) performance of basalt and limestone basalt is evaluated. Three different types of mixes were incorporated (basalt course and fine aggregate B-SMA, basalt course and limestone fine aggregate BL-SMA and limestone course and fine aggregate L-SMA). Dynamic modulus test was performed on these mixes. This study concludes that B-SMA has best rutting resistance mixture while BL-SMA and L-SMA followed B-SMA respectively. Resistance to cracking at low temperature and moisture vulnerability was evaluated and found reverse sequence to rutting resistance. Statistical analysis showed that aggregate type has significant effect on rutting behavior of mixes. Dynamic modulus master curves were developed and results indicated that B-SMA has highest dynamic modulus when compared to L-SMA and BL-SMA mixtures (Cao et al. 2013).

To reduce the cost of bridge, asphalt surfacing is nowadays is frequently used. A research study revealed that dynamic modulus and flexural stiffness was evaluated of different surfacing material placed orthotropic steel deck bridge. The material includes polymer modified asphalt, gussasphalt concrete and epoxy asphalt concrete. Master curves were developed and flexural stiffness was obtained and difference in said material was investigated. This research concludes that for material classification, both dynamic modulus and flexural stiffness can be used. At low frequency and/or high temperature, dynamic modulus master curves are significantly higher when it is compared to flexural stiffness for all type of surfacing material (Yao et al. 2013).

2.4 Determination of the Dynamic Modulus

In recent years, Pavement performance has gained a lot of attention of the researchers as it serve the basis for the mechanistic-empirical design practice which is nowadays very common and most agencies are shifting from empirical design approach to M-E approach. Dynamic modulus is one of the feature of the M-E design approach which predicts the pavement performance during its design and used in the structural design of the pavement and also as used as design input in M-EPDG. Dynamic modulus is under focus of various research studies in past years and researchers have reported that the dynamic modulus is temperature and frequency dependent and found out that dynamic modulus has inverse relation with temperature and loading frequency (Bonnaure et al. 1977; Lee et al. 2002; Robbins, 2009; Bennert & Aboobaker, 2009). Beside these two major paramters, properties of aggreagte and binder and their interaction plays a vital role in determination of dynamic modulus.

Various department of transportation (DOT's) of USA combined together and pooled funded project started by the Connecticut department of transportation with the support of U.S department of transportation and federal highway authority (FHWA) to check the precision of dynamic modulus test and problem occurring while implementing it and defined test protocols and problem solutions. The outcome of this 30 months project was round Robin test for protocols and necessary changes in it (Dougan et al. 2003).

Minnesota DOT conducted research to evaluate the complex dynamic modulus and the phase angle. Four different asphalt mixtures were under study from different sites and tested at six temperatures and five frequencies. Data obtained from the laboratory results were evaluated to nonlinear analysis to generate master curve of dynamic modulus and phase angle and also compare these results with Witczak predictive model. This study concluded that that dynamic modulus has direct relation with frequency and inverse relation with temperature and model generated from the experimental data was best fit and recommended that dynamic modulus can be used as design parameter and simple performance test (Clyne et al. 2003).

Another research work at university of Florida determined the correlation of dynamic modulus and numerous factors affecting the dynamic modulus i-e viscosity, gradation and rutting resistance. The main objectives of the study were to evaluate the dynamic modulus predictive equation i-e Witczak (2002) and to evaluate the effect of gradation and type of aggregate used in the determination of dynamic modulus and comparison of static creep test with short term dynamic modulus measurements (Ekingen , 2004).

National cooperative highway research program (NCHRP) documented in their report that dynamic modulus is ratio of stress over recoverable strain under sinusoidal loading. Furthermore, this study elaborated the determination of dynamic modulus practically in laboratory using simple performance test in accordance with the AASHTO TP 62-07 "Standard test method for determining the dynamic modulus". Dynamic modulus for various asphalt mixtures were performed at three replicate specimens of each mixture and tested at four different temperatures i-e 4.4, 21.1, 37.7, 54.4 °C and loading frequencies of 0.1, 0.5, 1, 5, 10 and 25 Hz. Stress controlled mode is observed during test which produce strains smaller than 200 micro-strains. The axial deformation was measured by linear variable deformation transformers (LVDT's) fixed on metal studs. These studs were glued for forty five minutes on specimens at same distance to top and bottom. Before preparing the test specimen the laboratory blended mixture was placed in oven as per the AASHTO standard for short term aging for four hours up to temperature of 135 °C (Witczak, 2005).

The new M-EPDG has three levels of inputs to fully depict the material properties of the asphalt mixtures and dynamic modulus has huge importance as it is the first input level and entails highest precision and reliability. In order to develop procedure for Oklahoma DOT (ODOT), a study was framed at Oklahoma state university (OSU) to obtain dynamic modulus master curves without performing detailed dynamic modulus testing for each of the mix in pavement system. The factors affecting the dynamic modulus and mix properties were the main objective of this study. Master curves were developed based on the results of the asphalt binder, aggregate type and nominal maximum aggregate size. Samples of twenty one mixtures was collected and testing was performed in accordance with AASHTO TP 62-07. This study concluded that the use of reclaimed asphalt pavement (RAP) and PG binder grade has influencing effect on the dynamic modulus (Cross & Jakatimath, 2007)

The complete characterization of asphalt pavements is one of the fundamental aspects of the M-EPDG which initiated another project in Virginia USA for new and rehabilitated pavements. The objective of this project was to implement the M-EPDG in Virginia by complete characterization of hot mix asphalt (HMA) mixtures which includes the testing of surface and base mixes. Dynamic modulus was examined for HMA material as it is required by M-EPDG and thermal cracking which can be predicted by creep amenability and tensile strength. Resilient modulus was also conducted to develop correlation between dynamic modulus and resilient modulus. Eleven (11) samples were collected from different plants across Virginia and specimens were prepared using superpave gyratory compactor (SGC). From the investigation carried out in project, it can be inferred that mechanical behavior of HMA can be successfully be evaluated by dynamic modulus because of its range of temperatures and loading frequencies. The mix constituents (aggregates, asphalt content, RAP percentage etc.) affected the dynamic modulus (Flintsch et al. 2007).

Researchers have reported that numerous factors affecting the dynamic modulus and properties of the asphalt mixture. An investigation conducted by Louisiana DOT on the effect of the aggregate size of various asphalt mixtures commonly used in the Louisiana. The scope of this research consists of thirteen different plant produced mixtures having different grade, aggregate size and source also. Out of thirteen, 10 mixes were superpave designed for high, low and intermediate type roads while two were Marshall designed for high type roads and one of stone mastic asphalt (SMA) for high roads and all mixes have different design methodology. Dynamic modulus was conducted in accordance with the AASHTO TP 62-07 (AASHTO, 2007). From the investigation, it is concluded that the nominal maximum aggregate size (NMAS) has direct relation with dynamic modulus and with increase in particle with RAP, higher dynamic modulus values are obtained at high temperature (Mohammad et al. 2007).

Dynamic modulus can be determined by either laboratory testing or predictive equations. Various researchers have proposed different equation and models for determining the dynamic modulus. In this regards, a study has been carried out in which micromechanical model is developed to predict the dynamic modulus of various asphalt mixtures. The model is developed on the basis such that HMA is a composite mixture in which mastic-coated aggregate are embedded into HMA mixtures by equal medium. From the model, equations were derived for the prediction of the dynamic modulus. These equations were sensitive to gradation and air voids distribution. The model verified using laboratory results and laboratory testing is done for mastic and HMA mixtures to obtain the dynamic modulus values. For the cross check, using developed model and dynamic modulus of mastic as input, dynamic modulus of the laboratory prepared HMA is predicted and it is concluded that predicted dynamic modulus was merely close to measured dynamic modulus at high frequencies (Shu & Huang, 2008).

A study carried out at Auburn University, USA which highlighted that dynamic modulus can be determined by the laboratory testing and predictive equations as well. The comparison among the Hirsch, Witczak 1-40D and 1-37A was done and results showed that measured dynamic modulus values can be accurately predicted by Hirsch |E*| model while Witczak 1-40D over predicted values and Witczak 1-37A varied inconsistently. Furthermore, M-E design was validated and optimized in order to connect the pavement performance to the material response in the field (Robbins, 2009).

Usually laboratory testing of dynamic modulus is done by asphalt mixture performance tester (AMPT) or Simple performance test protocols (SPT). Researchers have determined dynamic modulus of various asphalt mixture using various other techniques. Similarly a research conducted for the determination of dynamic modulus using ultrasonic pulse test. The objective was this study was to elaborate the experimental procedure alongwith evaluation of dynamic modulus using ultrasonic pulse test at indicated temperature. Limestone and dolerite aggregate was used for specimen preparation of porous and dense asphalt mixtures. Furthermore a comparison was carried out between dynamic modulus obtained from ultrasonic transmission at frequency of 65 kHz and dynamic modulus obtained from standard test procedure at test frequencies of 2, 5, 8 and 10 Hz. The research concluded that dynamic modulus obtained from ultrasonic transmission has higher magnitude than that of standard test procedure. It can be inferred that specimens subjected to ultrasonic transmission test increase dynamic modulus and has direct relation with frequency used during the test (Contreras et al. 2010).

Cho and his colleagues worked in Korea for the Korean M-E pavement design guide and suggested that the dynamic modulus is material property of the asphalt mixtures and important factor for analysis in M-EPDG because it counter both temperature and time dependency of the asphalt mixtures. Various asphalt mixtures were under objective of study and predictive equation for Korean M-E pavement design guide was the main aim of the study. Performance grade (PG) binder was used to test at five different temperatures (-10, 5, 21, 40, 55 °C) and six different frequencies (0.1, 0.5, 1, 5, 10 and 25 Hz). The outcome of this research was a predictive equation which is verified by measured and predictive dynamic modulus and results shows that there is correlation of predictive equation with measured values (Cho et al. 2010).

Laboratory determination is the various researchers' objectives as different asphalt mixtures are tested using asphalt mixture performance tester (AMPT). Dynamic modulus was conducted on various asphalt mixtures which were mostly practiced in Wisconsin. Twelve asphalt mixtures were selected for the study and these mixtures were differentiated on the basis of the aggregate sources and asphalt binder. Dynamic modulus test was performed at three different test temperatures i-e 4, 20 and 35 ºC and three different frequencies of 0.1, 1 and 10 Hz. This research concluded that same aggregate sources did not the affect the dynamic modulus much. Furthermore, it is also concluded that aggregate sources having higher dynamic modulus has higher limiting minimum dynamic modulus and when it is compared with other sources it is less (Bonaquist, 2010).

There are many factors affecting the dynamic modulus and various studies have been conducted to describe the effect of the different factors. In this regards, a research has been done on aggregate packing influence on the dynamic modulus using three dimensional discrete element methods. As the dynamic modulus is considered as the indicator for the field fatigue and pavement performance stated in the M-EPDG and stress-strain response can be evaluated. This study focused on the aggregate size distribution, angularity distribution and their effect on the dynamic modulus using 3D discrete element method (DEM). Ball clumping approach was used to generate the angular particles using image data from which number of ball is reduced significantly and particle shape effect is captured. Using angularity distribution, the particle size is allocated to DEM dynamic modulus specimen based on the actual experimental specimen. With the use of data, 3D DEM dynamic modulus is generated which is also calibrated from the same data. From the calibrated model, it is evaluated that how packing of different aggregate with change in angularity and particle shape distribution resulted change in the dynamic modulus (Yu & Shen, 2011).

Apeagyei (2011) conducted Flow number test to investigate the rutting propensity of AC mixtures expressed as function of dynamic modulus and gradation. Sixteen (16) AC mixtures (eight surface mixes, five base mixes, and three stone matrix asphalt) produced in Virginia were used to evaluate onset of tertiary flow. Multiple linear regression models were developed to pronounce the relationship among FN, gradation, and dynamic modulus. The results revealed that dynamic modulus values had strong correlation with FN at 38°C, and gradation for the selected AC mixtures. With the help of previously published data, the reliability of the relationship of FN as a function of gradation and dynamic modulus was verified for 12 mixtures.

In another study, dynamic modulus is recommended as one of the important factor for evaluating field response of asphaltic concrete. New M-EPDG used the triaxial dynamic modulus to fully depict temperature and time dependency of asphalt pavements. This study is focused on the construction of model for the triaxial dynamic modulus master curve. The confining pressure on dynamic modulus was considered by vertical shifting technique which is important parameter of the study. Model was developed for shift factor which considered reduced frequency and confining pressure as independent variable. Three asphalt mixtures were evaluated using developed model at various confining pressures, test temperatures and loading frequencies (Zhao et al. 2012).

Another study conducted by Waraich in which seven plant produced mixtures were collected from different sites of Pakistan. These seven mixtures were brought to laboratory and SGC specimens were prepared but before preparation these mixtures were reheated to certain temperature for short term aging for three to four hours. A total of eighty four samples were prepared and dynamic modulus test was performed using simple performance tester (SPT). This research carried out at four different temperatures 4.4, 21.1, 37.7 and 54.4 °C and six different frequencies 0.1, 0.5, 1, 5, 10 and 25 Hz. Master curves were developed based on the laboratory results. Two different dynamic modulus prediction models were also evaluated. This research concluded the prediction error range for Witczak and Hirsch model was 48% and 72% respectively. Furthermore the relationship between mixture compositions was established and observed that temperature and frequency has relation with dynamic modulus of HMA while nominal maximum aggregate size (NMAS) found to be insignificant (Waraich, 2012).

Rafique (2013) carried out reseacrh over evaluation of mositure susceptibility of dense graded asphalt mixture using dynamic modulus test and indirect tensile test. Specimens were prepared with varying proportion of fines (3%, 6% and 9%) and bitumen content was also determined for each proportion. Hydrated Lime was used as antistripping agent as it removes the deleterious material which causes damage to the pavement while percentage of antistripping agent was kept 1.5 % by weight of dry aggregate. The scope of study consists of Pen grade of 60/70 bitumen and NHA class B gradation while optimum bitumen content was calculated using marshall mix design method and cylinderical specimens were prepared using

SGC. Conditioning was done as per standard ASTM D4867. The research concluded that hydrated lime is an effective antistripping agent and improve strength of asphaltic concrete.

Ghosh et al. (2013) conducted the dynamic modulus for the implementation of M-E design using ASHTOWare design software. Two bituminous mixes namely concret grade-2 and DBM were used, respectively and master curves were developed. Thias study concluded that utmost sections failed to qualify the design prerequisite and thickness was calculated using software which was found to be greater than calcluated by Indian Roads Congress.

Khattab et al. (2014) carried out research for the implementation of M-E design in Kingdom of Saudi Arabia and developed a database for various AC mixtures. Further, the predictive models namely NCHRP 1-37A and 1-40A were verified using developed database and results indicated the performance of models is affected by variation in temperature and method of characterizing the binder. This study concluded that NCHRP 1-37A model produced most accurate and least biased results.

The above researches indicates that dynamic modulus is important property which is used to characterize the HMA mixture and depict the viscoelastic behavior of asphalt mixtures. The importance of dynamic modulus can be estimated as it is required in first level of design input new M-EPDG which has highest level of precision and accuracy and make the laboratory evaluation of dynamic modulus as importance to fully characterize the asphalt mixtures. Most of the states in USA has adopted the M-EPDG and superpave design methodolgy and now its time for Pakistan to make shift to latest design procedures which are globally being used.

2.5 Development of Master Curves

Generally Master curves represent the range of temperatures and frequencies to a reference temperature to make comparison. Time-temperature superposition principle is used for development of the master curves. This principle stated that, for a range of temperatures and frequencies, all data is shifted horizontally to a referenced temperature and merge various curves to form a single curve which is called master curve. Time-temperature principle is applicable on assumption that asphalt mixtures are thermo-rheological material (Ekingen, 2004).

The shift factor a(T) can be defined as shift at a given temperature. Reduced frequency f_r can be calculated as ratio of actual frequency to shift factor. Mathematically it can be expressed equation 2-4,

$$f_r = \frac{f}{a(T)} \text{ or } \log(f_r) = \log(f) - \log[a(T)] \quad (2\text{-}4)$$

Where

f_r = Reduced frequency

a(T) = shift function

f = actual frequency.

At any referenced temperature Tr, all data is to be shifted for asphalt mixture and master curve can be generated. Shift factor a(T) =1 at the reference temperature. In general, master curve be mathematically represented by sigmoidal function which is given in equation 2-5.

$$\left[\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log Tr)}}\right] \quad (2\text{-}5)$$

δ = minimum value of |E*|

$\delta + \alpha$ = maximum value of |E*|

β, γ = parameters describing the shape of the sigmoidal function

The shift factor can be expressed by equation 2-6.

$$a(T) = \frac{t}{tr} \quad (2\text{-}6)$$

Where,

a(T) = shift factor as a function of temperature

t = time of loading at desired temperature

tr = reduced time of loading at reference temperature

T = temperature of interest

For precision, a second order polynomial relationship between the logarithm of the shift factor i.e. log $a(T_i)$ and the temperature in degree Fahrenheit is used. The relationship can be expressed by equation 2-7:

$$\text{Log } a(T_i) = aT_i^2 + bT_i + c \quad (2\text{-}7)$$

Where,

$a(T_i)$ = shift factor as a function of temperature T_i

T_i = temperature of interest, °F

a, b and c = coefficients of the second order polynomial

2.6 Dynamic Modulus Prediction Equations

As it is mentioned in above researches that the dynamic modulus can be found out using laboratory test experiment or can be determined by the predictive equations which predict |E*| from mix volumetric properties. Due to requirement of skilled personnel which handle the equipment, time and cost required to perform this test. Hence researchers have developed equations for the determining the dynamic modulus. Bari & Witczak (2006) has reported the dynamic modulus prediction equations from the past research carried out in few decades has been listed in table 2.1.

Table 2.1 List of Dynamic Modulus Predictive Models (Bari & Witczak, 2006)

S.No	Dynamic Modulus Prediction Model	Year of Publishing
1	Van der Poel Model	1954
2	Shook and Kallas Model	1969
3	Witczak's Early Model 1972	1972
4	Bonnaure Model	1977
5	Witczak and Shook's Model	1978
6	Witczak's 1981 Model	1981
7	Witczak, Miller and Uzan's Model	1983
8	Witczak and Akhter's Model	1984
9	Witczak, Leahy, Caves and Uzan's Model	1989
10	Witczak and Fonseca's Model	1996
11	Andrei, Witczak and Mirza's Revised Model	1999
12	Hirsch Model of Christensen, Pellinen and Bonaquist	2003

Most commonly being used models are Andrei, Witczak and Mirza's models which is commonly populous by Witczak Model and Bonaquist, Pellinen and Christensen commonly known as Hirsch Model.

2.6.1 Witczak Model

Various attempts have been made to develop the prediction model due to cumbersome laboratory test and time consuming activity also. Hence various models have been developed but Witczak revised model is one of the fine regression models to predict the dynamic modulus using the mix volumetric properties. The dynamic modulus illustrated in equation 2-8 describes the prediction ability of the model to predict the dynamic modulus for range of temperatures, loading frequencies and aging condition which can be obtained from binder tests and mixture volumetric properties. This model is based on the over 2800 asphalt mixtures tested in asphalt institute laboratory, FHWA, and the University of Maryland (Ekingen , 2004).

$$\text{Log}E^* = -1.249337 + 0.029232(p_{200}) - 0.001767(p_{200})^2 - 0.00284(p_4) - 0.05809Va - 0.802208\frac{Vb_{eff}}{Vb_{eff} + Va} + \frac{3.871977 - 0.0021P_4 + 0.003958P_{38} - 0.000017P_{(38)^2} + 0.00547P_{34}}{1 + e^{[(-0.603313 - 0.313351\log(f) - 0.393532\log\langle\eta\rangle]}}$$

(2-8)

Where

E^* = dynamic modulus of mix, 10^5 psi

ή= viscosity of binder, 10^6 psi (Refer Equation 2-9)

f = loading frequency, Hz

p_{200} = % passing # 200 sieve

p_4 = cumulative % retained on # 4 sieve

p_{38} = cumulative % retained on 3/8 in. sieve

p_{34} = cumulative % retained on 3/4 in. sieve

V_a = air voids, % by volume

V_{beff} = effective binder content, % by volume

The above equation represents that the most of the input parameters are from mix volumetric properties and can be directly put from the job mix formulae. However binder viscosity can be taken from relation of log temperature and log-log viscosity defined in equation 2-9.

$$\text{Log} \log ή = A + VTS \log T_R \qquad (2\text{-}9)$$

Where as

ή = binder viscosity, centiPoise (cP)

A = regression intercept

VTS (viscosity temperature susceptibility) = slope of the line

T_R = temperature, degree Rankine

The above model is based on over 2700 data values and for range of temperatures of 0 to 130 °F and loading frequency of 0.1 to 25 Hz. Twenty five mixtures were for modified and unmodified binder to develop the model which includes 14 different modified binders and 9 different unmodified binders. A total of thirty nine aggregate types were used and mixtures were prepared using SGC and kneading compactor both.

2.6.1 Hirsch Model

Christensen et al. (2003) developed a model for predicting the dynamic modulus on the basis of the law of composite mixtures which was developed by the Hirsch. Eighteen (18) different asphalt mixtures were used to depict the dynamic modulus from binder shear modulus (G*) and volumetric properties i-e Voids in mineral aggregate (VMA) and Voids filled with asphalt (VFA). The Hirsch model is shown by equation 2-10 which is simpler than Witczak due to less number of variables.

$$|E^*| = Pc[4200000(1-\frac{VMA}{100}) + 3|G^*|_b(\frac{VFAxVMA}{10000})] + \frac{(1-Pc)}{[\frac{1-\frac{VMA}{100}}{4200000} + \frac{VMA}{3VFA|G^*|_b}]} \quad (2\text{-}10)$$

Where

$$Pc = \frac{(20 + \frac{VFAx3|G^*|_b}{VMA})^{0.58}}{650 + (\frac{VFAx3|G^*|_b}{VMA})^{0.58}} \quad (2\text{-}11)$$

|E*| = dynamic modulus, psi

VMA = voids in mineral aggregate, %

VFA = voids in aggregate filled with asphalt, %

$|G^*|_b$ = dynamic shear modulus of binder, psi

Hirsch model was developed using over 200 data values from 18 different mixtures which were tested to develop above model. Mixture on which testing were performed consists of aggregate size and gradation between 9.5 mm (3/4 inch) to 37.5 mm (1.5 inch). Laboratory testing was done for range of temperatures from 4 to 38 °C and loading frequency of 0.1 and

5Hz. The above data model has air voids ranging from 5.6 to 11.2%; VFA ranges from 38.7 to 68% and VMA ranges 13.7 to 21.65%.

2.7 Summary

Dynamic modulus as described previously is material property which describes the viscoelastic behavior of the HMA. Dynamic modulus can be defined as the absolute value of complex modulus or ratio of stress to peak recoverable strain for sinusoidal loading for continuous time period. Viscoelastic nature of HMA is characterized by the time and temperature of dynamic modulus. Various tests were performed as stated in the above literature to evaluate the dynamic modulus but mostly used method is defined by AASHTO TP 62-07.

Researchers have found out the temperature and frequency is the main factors on which dynamic modulus of HMA are dependent. However, other factors affecting dynamic modulus are mix volumetric properties; aggregate size, gradation, shape, packing, binder grade and bitumen content have been reported in various researches. Fatigue resistance can be calculated by continuum damage analysis as reported in literature. Various correlation is also presented for |E*| and reported as rutting as function of dynamic modulus and gradation. The dynamic modulus predictive equations are validated for different regions by developing database stated in previous literature. It is also mentioned in literature that new AASHTOWare design software calculates higher thickness in comparison to local procedures. Dynamic modulus master curves are developed and mixtures are compared on basis of master curves which is reported in previous researches.

Dynamic modulus can be determined by laboratory as well as predictive equations and various researches have correlated the laboratory results with developed models. The two models discussed above namely Witczak and Hirsch have been reported precise. These models predict the dynamic modulus without laboratory testing and input depends on the mix volumetric properties. The Witczak viscosity based model is bit lengthy as there are number of variable while Hirsch model is simpler having less variable. These models have been developed for one set of conditions and calibrated accordingly for regional use.

The dynamic modulus is one of the important parameter in AASHTO 2002 mechanistic-empirical pavement design guide (M-EPDG). It is used as design input in M-EPDG. Furthermore, it is only simple performance test which counterpart the superpave mix design methodology. The M-EPDG has three stage design process to input material based on the design accuracy required by the designer. Level 1 is most accurate and reliable as it needs the laboratory determined dynamic modulus while Level 2 and 3 are based on the predictive equations to depict the dynamic modulus. The predictive equations are applicable to areas/regions where they were developed and Pakistan has yet not adopted the model based on the conditions of the country.

The dynamic modulus is important parameter during design phase as it predict the performance of asphalt mixture and very helpful in structural design of the pavement. The laboratory testing completely characterize the HMA as it has temperature ranges -10 to 60 °C and loading frequency from 0.1 to 25 Hz as per AASHTO TP 62-07. However the test temperatures 4.4 and 21.1 °C, at frequency of 5 Hz is fracture resistance indicator while 37.8 and 54.4 °C test temperatures have been reported as rutting indicator. The master curves developed from the laboratory testing represent the single curve in which all test temperatures are to be shifted to reference temperature i-e 21 °C.

Chapter 3

RESEARCH METHODOLOGY AND TESTING

3.1 General

This chapter focuses on the research methodology adopted for the study including selection of gradations and asphalt mixtures. Furthermore, specimen preparation, equipment and laboratory test performed have been discussed herein detail. This research emphasize on the laboratory prepared specimens of various hot mix asphalt mixtures of different gradations used for asphaltic wearing and base course mixes subjected to dynamic loading. This study incorporates eight (08) different gradations i-e four (04) for wearing course and four (04) for base course. The marshall mix design method used for calculating optimum bitumen content for above stated mixtures is elaborated in this chapter. The volumetric properties; flow, stability, VMA, VFA and AV are determined as per the MS-2 manual. Based on the optimum bitumen content calculated using marshall mix method, the specimens were fabricated using superpave gyratory compactor (SGC) for both wearing and base course mixes. The performance testing i-e Dynamic modulus test using asphalt mixture performance tester AMPT (commonly known as simple performance tester SPT) was carried out on the specimens prepared for said mixes. The further elaboration of gradations, compaction methods and conditioning of specimens is also described in ensuing paragraphs.

The research methodology is illustrated by figure 3.1. This figure shows that in initial stages, mixtures were selected while later on optimum bitumen content is calculated using Marshall standard procedure. This Marshall procedure includes determination of volumetric properties and flow & stability which provide basis for the performance testing. The optimum bitumen content is then used to prepare the gyratory specimen which was further polished and sawed to required size for testing. The dynamic modulus test is performed on the gyratory specimens and results is extracted from simple performance tester software which is input for statistical analyses in statistical software and development of master curves using solver add-in.

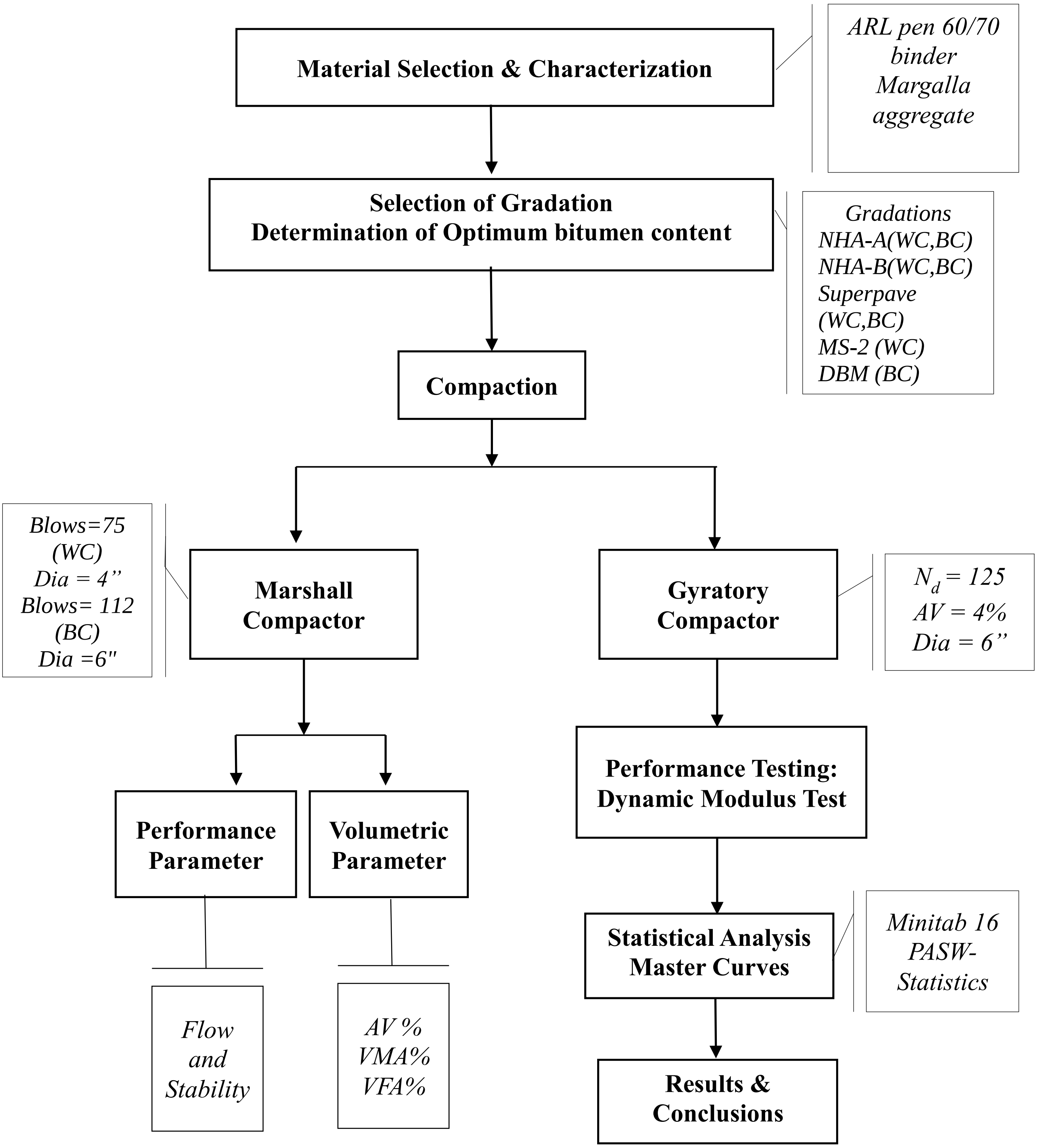


Figure 3.1 Flow chart for research methodology

3.2 Selection of Material

As this research is part of NHA Project "Improvement of asphalt mix design technology for Pakistan", so aggregate material source is margalla and bitumen is pen grade 60/70 of Attock refinery limited (ARL), which is mostly commonly used in Pakistan.

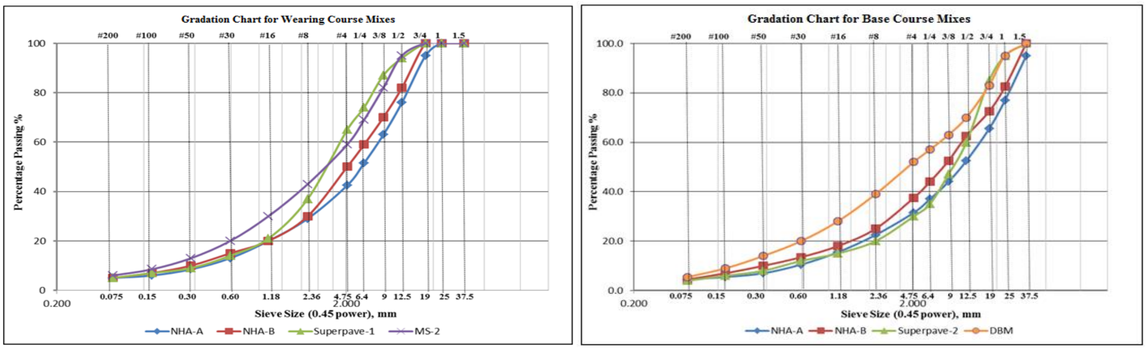
3.2.1 Gradations

The appropriate proportion of aggregate in gradation is very important for proper hot mix asphalt mixture. Four (04) different types of gradations are used for wearing and base course mixes. For wearing course gradations are NHA Class A, NHA Class B, Superpave Class A-1, and Asphalt Institute MS-2 while for base course are NHA class A, NHA Class B, Superpave Class A-2, and Dense Bituminous Macadam (DBM). The table 3.1 shows gradation for base and wearing course mixes.

Table 3.1 Gradations for Wearing and Base Course Mixes

Sieve Size	Asphalt Wearing Course Gradations				Asphalt Base Course Gradations			
	Cumulative Percentage Passing (%)				Cumulative Percentage Passing (%)			
	NHA-A	**NHA-B**	**Superpave A**	**MS-2**	**NHA-A**	**NHA-B**	**Superpave A**	**DBM**
37.5 mm	100	100	100	100	95	100	100	100
25.4 mm	100	100	100	100	77	82.5	94	95
19 mm	95	100	100	100	65.5	72.5	86	83
12.5 mm	76	82	94	95	52.5	62.5	73	70
9.0 mm	63	70	87	82	44	52.5	65	63
6.4 mm	51.5	59	74	69	37	44	53	57
4.75 mm	42.5	50	65	59	31.5	37.5	44	52
2.36 mm	29	30	37	43	22.5	25	25	39
1.18 mm	20	20	21	30	15.5	18	16	28
0.6 mm	13	15	14	20	10.5	13.5	11	20
0.3 mm	8.5	10	9	13	7	10	7	14
0.15 mm	6	7	7	8.5	5.5	7	5	9
0.075mm	5	5	5	6	4.5	4.5	4	5.5
Pan								

The above table contains commutative passing from which commutative retained can be calculated by subtracting from 100 and then individual retained percentage is calculated by subtracting lower value from upper value and similarly weights on each sieve can be calculated from these retained percentages.



(a) Wearing mixes **(b) Base mixes**

Figure 3.2 Gradation charts for asphalt mixtures

From above gradation table, gradation charts are generated for both wearing and base course mixes. The figure 3.2 contains curves for all types of gradations and on X-axis there is size size raised to power 0.45 while on Y-axis there is percentage passing. From these charts the percenatge of the missing sieves can be calculated.

3.3 Optimum Bitumen Content Calculation

The optimum bitumen content calculation is initial step towards performance testing and volumetric properties were calculated using marshall mix design method. The procedure is described in the ensuing paragraphs.

3.3.1 Preparation of Specimens

The preparation of bituminous mixes for wearing and base courses is carried in accordance with the ASTM D6929, standard practice for the preparation of specimens using marshall apparatus. It is worth mentioning here that for wearing course the standard or normal marshal method is used (i-e 4" sample) while for base courses modified marshal method is used (i-e 6" sample). For each type of the gradation, duplicate specimens were prepared and tested accordingly.

3.3.2 Testing of the Specimens

The specimens prepared using marshall apparatus were tested for the determination of volumetric properties of the mixes i-e Air voids (Va), Voids filled with mineral aggregate (VMA), Voids filled asphalt (VFA), theoretical maximum specific gravity (Gmm) and Bulk Specific gravity (Gmb), Flow and Stability. Flow and stability using marshal apparatus is determined in accordance with ASTM D6927-06 while theoretical maximum specific gravity (Gmm) and Bulk specific gravity are determined using ASTM D2041 and ASTM D2726 respectively.

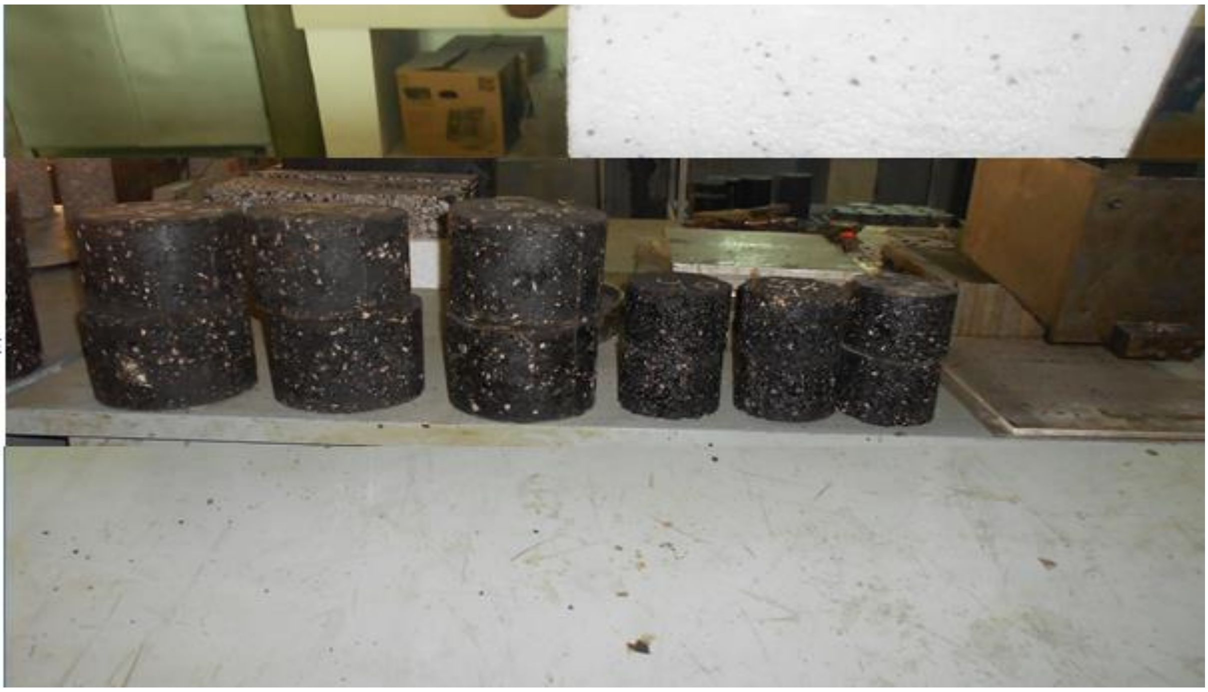


Figure 3.3 Specimens for the base and wearing course mixes.

Table 3.2 Wearing Course Volumetric Properties Results

Optimum Bitumen Content Results of Wearing Course for Different Gradations									
Mix Type	**AC (%)**	**G_{sb}**	**G_{mb}**	**G_{mm}**	**Air Voids (%)**	**VMA (%)**	**VFA (%)**	**Stability (Kg)**	**Flow (0.25 mm)**
ARL 60/70 NHA-A	3.5	2.614	2.382	2.513	5.22	12.07	56.77	1330	9.634
	4.0	2.614	2.399	2.500	4.04	11.90	66.01	1451	11.356
	4.5	2.614	2.417	2.481	2.58	11.70	77.91	1276	12.954
	4.0	**2.614**	**2.392**	**2.498**	**4.24**	**12.15**	**65.08**	**1362**	**12.035**
ARL 60/70 NHA-B	3.5	2.611	2.330	2.503	6.91	13.89	50.22	1499	12.140
	4.0	2.611	2.360	2.483	4.96	13.23	62.54	1471	13.380
	4.5	2.611	2.399	2.468	2.81	12.27	77.09	1531	14.388
	4.1	**2.611**	**2.370**	**2.482**	**4.51**	**12.95**	**65.16**	**1291**	**12.650**
ARL 60/70 SP-A	4.5	2.604	2.312	2.467	6.28	15.21	58.68	1247	14.476
	5.0	2.604	2.335	2.448	4.62	14.82	68.83	1544	12.530
	5.5	2.604	2.348	2.418	2.90	14.79	80.42	1409	14.626
	5.0	**2.604**	**2.338**	**2.449**	**4.53**	**14.70**	**69.18**	**1424**	**13.550**
ARL 60/70 MS-2	4.5	2.606	2.308	2.470	6.55	15.41	57.52	1609	12.352
	5.0	2.606	2.350	2.448	3.99	14.32	72.12	1836	11.772
	5.5	2.606	2.369	2.411	1.73	14.08	87.74	1876	15.894
	4.8	**2.606**	**2.340**	**2.455**	**4.68**	**14.52**	**67.73**	**1554**	**13.120**

Table 3.3 Job Mix Formula (JMF) for Wearing Course Mixes.

Parameters	Gradations			
	NHA-A	NHA-B	Superpave	MS-2
Optimum Asphalt Contents (%)	4.0	4.1	5.0	4.8
Air Voids (%)	4.0	4.0	4.0	4.0
VMA (%)	12.15	12.95	14.70	14.52
VFA (%)	66.08	65.16	69.18	67.73
Stability (Kg)	1362	1291	1424	1544
Flow (mm)	12.035	12.650	13.550	13.120

The table 3.2 illustrates the volumetric properties of wearing course mixes and it can be inferred from table 3.3 that optimum asphalt content of NHA-A and NHA-B mixes are 4.0 and 4.1 % respectively which is less as compared to superpave and MS-2 mix because these are coarser gradations and for coarser particles bitumen requirement is low because it possess small surface area while finer particles have large surface area thus requiring relatively high asphalt content in case of superpave and MS-2 mixes. Alongwith optimum asphalt content table 3.2 also presents the G_{mm}, G_{mb}, Flow and stability. These results are well within limits which are prescribed by MS-2 manual for marshall mix design hence satisfying the minimum criteria.

Table 3.4 Base Course Volumetric Properties Results

Optimum Bitumen Content Results of Base Course for Different Gradations									
Mix Type	**AC (%)**	**G_{sb}**	**G_{mb}**	**G_{mm}**	**Air Voids (%)**	**VMA (%)**	**VFA (%)**	**Stability (Kg)**	**Flow (0.25mm)**
ARL 60/70 NHA-A	3.0	2.621	2.397	2.528	5.19	11.29	54.02	2816	22.724
	3.5	2.621	2.417	2.507	3.57	10.99	67.50	3031	17.942
	4.0	2.621	2.435	2.496	2.45	10.81	77.31	2687	18.216
	3.3	**2.621**	**2.402**	**2.510**	**4.30**	**11.38**	**62.19**	**2650**	**19.250**
ARL 60/70 NHA-B	3.5	2.618	2.390	2.514	4.95	11.91	58.43	3287	16.836
	4.0	2.618	2.411	2.495	3.36	11.60	71.01	2731	20.860
	4.5	2.618	2.419	2.475	2.26	11.76	80.75	2909	17.000
	3.7	**2.618**	**2.396**	**2.505**	**4.35**	**11.87**	**63.33**	**2905**	**18.650**
ARL 60/70 SP-B	3.0	2.621	2.368	2.530	6.41	12.36	48.16	2302	19.244
	3.5	2.621	2.395	2.512	4.67	11.82	60.53	2276	20.408
	4.0	2.621	2.425	2.497	2.89	11.18	74.17	2175	23.102
	3.6	**2.621**	**2.388**	**2.504**	**4.63**	**12.17**	**61.93**	**2295**	**21.550**
ARL 60/70 DBM	3.5	2.611	2.358	2.510	6.04	12.84	52.97	4059	16.674
	4.0	2.611	2.386	2.491	4.22	12.27	65.62	3308	20.504
	4.5	2.611	2.422	2.477	2.20	11.41	80.70	3013	22.020
	3.9	**2.611**	**2.380**	**2.500**	**4.80**	**12.40**	**61.33**	**3496**	**18.120**

Table 3.5 Job Mix Formula (JMF) for Base Course Mixes

Parameters	Gradations			
	NHA-A	**NHA-B**	**Superpave-B**	**DBM**
Optimum Asphalt Contents (%)	3.3	3.7	3.6	3.9
Air Voids (%)	4.0	4.0	4.0	4.0
VMA (%)	11.38	11.87	12.17	12.40
VFA (%)	62.19	63.33	61.93	61.33
Stability (Kg)	2650	2905	2295	3496
Flow (mm)	19.25	18.65	21.55	18.12

The table 3.4 illustrates the volumetric properties of base course mixes and it can be seen from table 3.5 that optimum asphalt content is on lower side as compared to wearing mixes which due to fact that base course generally incorporated large size aggregate which has small surface are thus requiring less asphalt content. All other properties are also meeting the specified criteria as well.

3.4 Specimen Preparation for Dynamic Modulus Test

The optimum bitumen content calculated from marshall method is used for preparation of the specimens using superpave gyratory compactor (SGC). The specimens were prepared in accordance with ASTM D3496-99, "Standard Practice for Preparation of Bituminous Mixture Specimens for Dynamic Modulus Testing". Triplicate specimens were prepared for each mix of wearing and base course mixes. The figure 3.4 shows the specimens prepared from gyratory compactor with approximate height of 170 mm and diameter of 150 mm.

These specimens are labelled as per their gradation and with suffix of "W" for wearing and "B" for wearing while triplicate specimens were named by numeric like (NHA W-1). After the preparation of specimens from gyratory compactor, these specimens were cored from center and trimmed in order to meet specification of testing prescribed in AASHTO TP 62-07. A 100 mm diameter core was made using coring machine. The height was trimmed from 170 mm to 150 mm using saw cutter. As per the specification, the height to diameter ratio required is 1.5 which is obtained by coring and saw cut the specimens. Figure 3.5 show the specimens cored and trimmed to desired ratio alongwith waster rings.

During this process, it was ensured that specimens should be compacted upto desired air voids with allowable limit not exceeding ± 0.5%. Triplicate specimens were prepared for each mix and tested at different temperatures. Three replicate specimen for each mix and total of twenty four specimens which includes twelve (12) for four gradations of wearing and same for the base course. Figure 3.6 shows the specimens stacked for the testing.

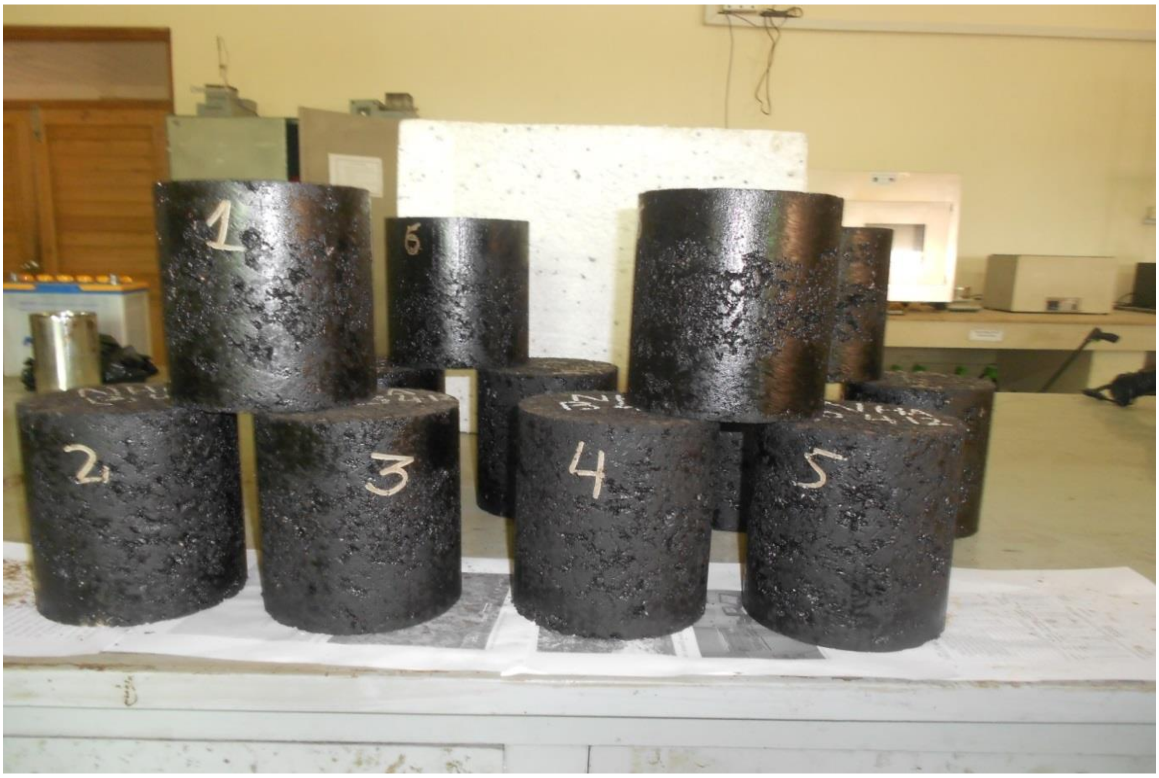


Figure 3.4 Specimens prepared using gyratory compactor

Figure 3.5 Cored and trimmed specimen alongwith waster rings.

After the preparation of specimens to desired dimensions and air voids, gauge points (studs) were fixed using 5 minutes epoxy glue. These studs on specimens helped to measure axial deformation/ strain during test using linear variable differential transformer (LVDT). These studs were fixed to specimens using gauge point fixing jig which is illustrated by the figure 3.7.

The gauge point fixing jig machine applies pressure for forty five (45) minutes on the studs so that the glue got hardened completely around the studs. After the fixing of studs, the specimens were removed from the fixing jig and fixed with the clamps. These clamps are designed in such a way to accommodate the LVDTs for measuring axial deformation as shown by the figure 3.8. The LVDT’s are checked by computer software as it can measure the deformation or not. If the bars of LVDT’s are in motion and within range (i-e 0.49 mm), it can measure the axial deformation.

Figure 3.6 Specimens gathered in laboratory for dynamic modulus test

The specimen is then left in environmental chamber to equilibrate with testing temperatures as stated in AASHTO TP 62-07. At higher temperatures, the studs start to loosen up as glue starts to become soft. Hence, greater care should be taken while performing test at higher temperatures.

Figure 3.7 Gauge point fixing jig

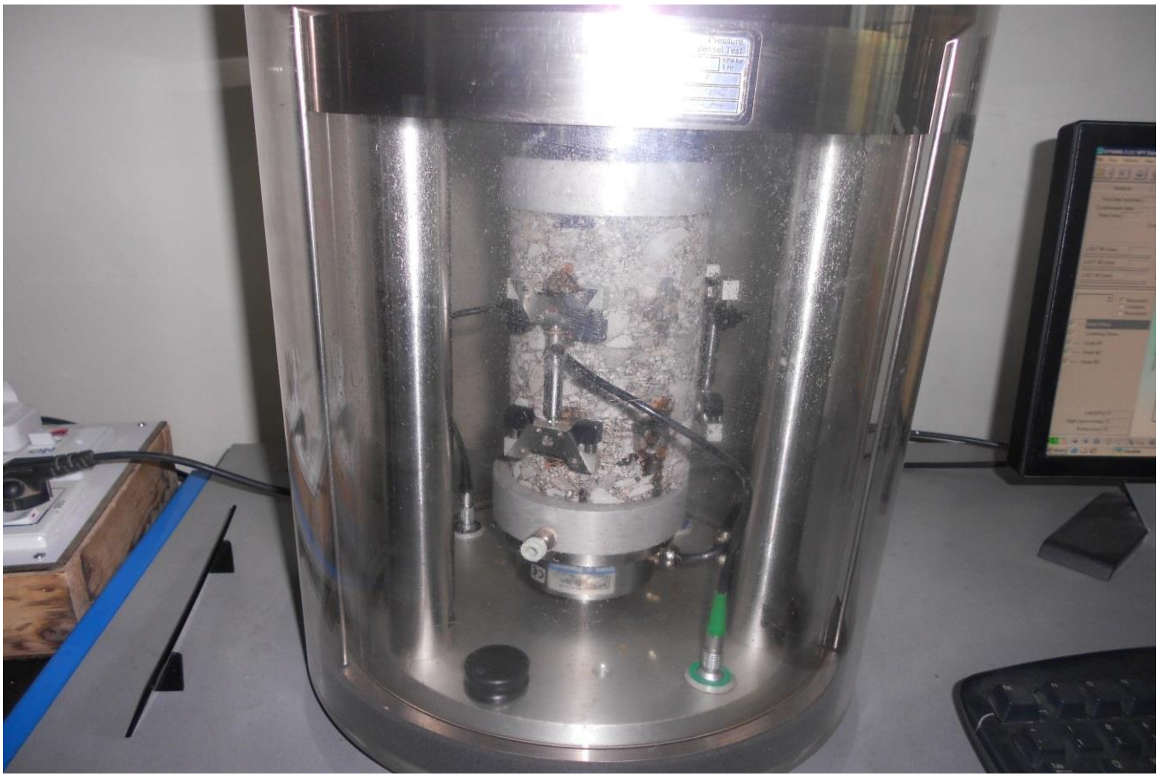


Figure 3.8 LVDTs mounted on the specimen alongwith transducers

3.5 Laboratory Testing

The AASHTO TP 62-07 standard was used for performing dynamic modulus test which requires cylindrical specimen upon which sinusoidal load is applied and dynamic modulus alongwith phase angle is calculated at required frequency and temperature. With the application of sinusoidal compressive stress, the ratio of stress to axial recoverable strain gives the dynamic modulus in results alongwith the phase angle. Simple performance tester (SPT) is equipment used for conducting dynamic modulus test which is elaborated in further subsections.

3.5.1 Testing Equipment and Procedure

The apparatus used for dynamic modulus testing is asphalt mix performance tester (AMPT) which is commonly known as simple performance tester (SPT). This apparatus has a trail axial cell, hydraulic actuator alongwith pump, an environmental chamber for maintaining temperature and placing specimen for testing, refrigeration for reducing temperature while heating unit for raising temperature and computer system attached to it for controlling and data collection system. Figure 3.9 shows the dynamic modulus testing machine i-e AMPT. Dynamic modulus test is operated by computer by using UTS 6 software.

Figure 3.9 Simple performance tester (AMPT)

After fixing studs, the specimen is placed in environment chamber and mounted transducers and LVDT's at three points which are at 120^{o} apart. The environmental chamber is closed and left to equilibrate with given test temperature and AASHTO TP 62-07 guidelines has been followed while performing test and minimum equilibrium time of temperature is defined in table 3.6 given below.

Table 3.6 Recommended Temperature Times (As per AASHTO, 2007)

Specimen Temperature (°C)	Time from Room Temperature (Hrs)	Time from Previous test temperature (Hrs)
-10	Overnight	Overnight
4	Overnight	4 Hrs or overnight
21	1	3
37	2	2
54	3	1

After completing equilibrium temperature times, test is started on the specimen using UTS 6 software, once required temperature is attained, the desired frequencies are selected from option menu and in this case 25, 10, 5, 1, 0.5, 0.1 Hz frequencies were selected and before starting the test, the software requires the initial modulus value which is obtained by tuning option of software in which haversine load is applied for 9 cycles which gives initial modulus value. The test procedure setup is such that it starts from highest frequency and proceed to lowest frequency i-e from 25 Hz to 0.1 Hz. After completion of test, the software automatically generates the output which contains dynamic modulus value and phase angle at given test temperature and selected frequencies. Figure 3.10 shows the general interface of the output of UTS 6 software after completion of the test.

The same procedure of performing dynamic modulus test is revised for triplicate specimens which are tested at four different temperature i-e 4.4, 21.1, 37.8 and 54.4 °C. The results of this test are utilized in development of master curves for both wearing ad base course mixes.

3.5.2 Development of Master Curves

In M-EPDG, dynamic modulus master curves are sole representative and present full characterization of asphalt mixtures. The dynamic modulus master curve is developed on the basis of time-temperature superposition principle, which states that dynamic modulus is mainly dependent upon on the reduced frequency, which is function of temperature and frequency.

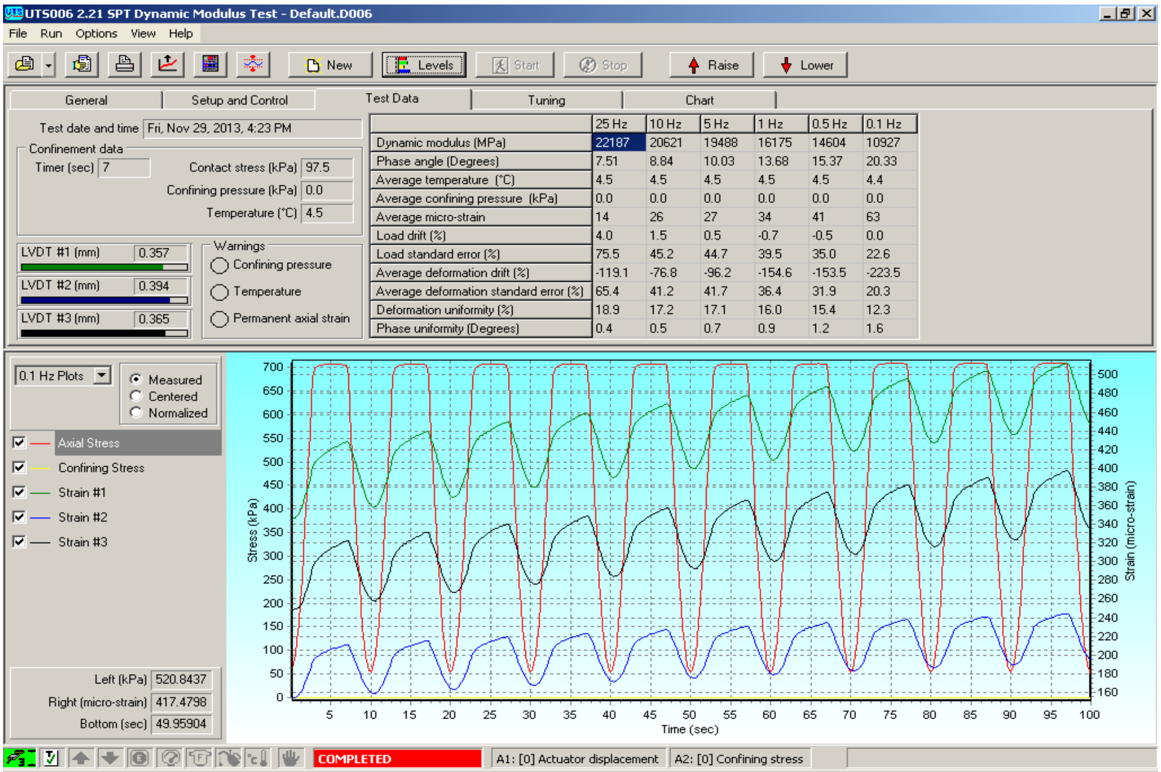


Figure 3.10 General interface of the output of the SPT

At different test temperatures and loading frequencies, the dynamic moduli are obtained which is combined using time-temperature superposition principle and single curve is generated known as master curve. Generally a master curve is generated at temperature of 21°C. After selecting the reference temperature, the underlying phenomena is to shift the data of different temperature with respect to frequency until smooth single function curve is obtained. Dynamic modulus master curve is function of frequency which describes the frequency dependency of material while temperature dependency of material is defined by its amount of shifting which is required to form master curve.

Master curves for each mix is to be generated at a reference temperature of 21 ºC using time-temperature superposition principles. This procedure requires three test temperatures and four loading frequencies. Master curves parameters can be determined using Equation 3-1.

$$\log|E^*| = \log(\min) + \frac{(\log(Max) - \log(Min))}{1 + e^{\beta + \gamma\left\{\log\omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \qquad (3\text{-}1)$$

Where

$|E^*|$ =Dynamic modulus, MPa

ω_r = reduced frequency, Hz

Max = limiting maximum modulus, ksi

Min = limiting minimum modulus, ksi

β, and γ = fitting parameters

The required reduced frequency is computed using Arrhenius equation shown in equation 3-2 (Bonaquist, 2008).

$$\log \omega_r = \log \omega + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \qquad (3\text{-}2)$$

Where:

ω_r = reduced frequency at the reference temperature

ω = loading frequency at the test temperature

T_r = reference temperature, °K

T = test temperature, °K

ΔE_a = activation energy (treated as a fitting parameter)

3.6 Summary

This chapter covers the detail of methodology adopted for the research and flow chart shows the methodology. The laboratory mixtures selected for the study is also mentioned in detail. Four different types of mixes were prepared for wearing course and also for base course. Only one aggregate source i-e Margalla quarry is selected for the study. The type of gradation used in this study is also is presented in tabular form. The wearing course mixes has nominal maximum aggregate size of 19 mm and 12.5 mm while in base course it is 37.5 mm and 25 mm. The pen grade of ARL 60/70 is used.

The test specimens were fabricated using gyratory compactor. These specimens extracted from gyratory compactor were more than the size required for the test so cylindrical specimen of 100 mm diameter and 150 mm height was cored and then trimmed using saw cutter to conform the AASHTO TP 62-07.

The sample preparation for marshall mix design is also outlined in this chapter. Furthermore for each mix optimum bitumen content is determined using standard ASTM procedures which include the calculation of theoretical maximum specific gravity, Bulk specific gravity, flow and stability. Same procedure is revised every time for each mix and volumetric properties are also presented in tabular form in this chapter.

Dynamic modulus test is conducted using AMPT on range of four temperatures from 4.4, 21.1, 37.8 and 54.4 °C while six frequencies are 25, 10, 5, 1, 0.5 and 0.1 Hz. As stated in AASHTO TP 62-07, the tested cannot be performed below 4 °C due to inability of the test equipment. The software details and software output is also discussed herein.

Furthermore the specification regarding to testing, preparation of specimens, conditioning are also discussed in this chapter. The data obtained from dynamic modulus test at different temperatures is shifted to a reference temperature of 21°C and master curve is developed for each mix. MS Excel add-in Solver is used to develop the master curve which minimized error sum of squares (SSE) in such a way to develop a single smooth curve.

Chapter 4

TEST RESULTS AND ANALYSES

4.1 General

This chapter mainly consists of dynamic modulus and phase angle experimental test results and based on obtained results, statistical analysis is presented herein. Various factors affecting the dynamic modulus like temperature, frequency and mixture properties are also discussed in detail. Master curves have been developed for each mix and presented collectively for wearing and base course mixes. Statistical analysis mainly includes the design of experiment i-e full factorial design; analysis of variance (ANOVA), interaction plot and sensitivity analysis is also part of this chapter. Dynamic modulus statistical models have been also developed using statistical software. Resistance to fatigue is also calculated for both wearing and base course mixes.

4.2 Dynamic Modulus Test results

The dynamic modulus is obtained using simple performance tester (SPT) and this test is conducted at four different temperatures i-e 4.4, 21.1, 37.8 and 54.4 °C and seven different loading frequencies i-e 25, 10, 5, 1, 0.5, 0.1 and 0.01 Hz. Triplicate specimens were tested at said loading frequencies and test temperatures. The results of dynamic modulus test for each mix is presented in appendix-A from table 1 to 8. Based on these laboratory results master curves were generated which is elaborated in ensuing paragraphs.

4.2.1 Development of Master Curves

The results obtained from laboratory performed test using AMPT is used to develop master curve which ultimately helps in determining the pavement response during design process. Triplicate specimens were tested at each temperature and average is taken of triplicate specimen for each temperature and used while developing master curve for average |E*| at reference temperature of 21°C using the time-temperature superposition principle in which each temperature |E*| is shifted to reference temperature to get a smooth uniform curve. As it is has been already discussed that AMPT cannot perform test below 4 °C hence for -10 °C temperature test, condensed method is used to develop master curve which is elaborated in phase IV of NCHRP project 9-29 (Bonaquist, 2008).

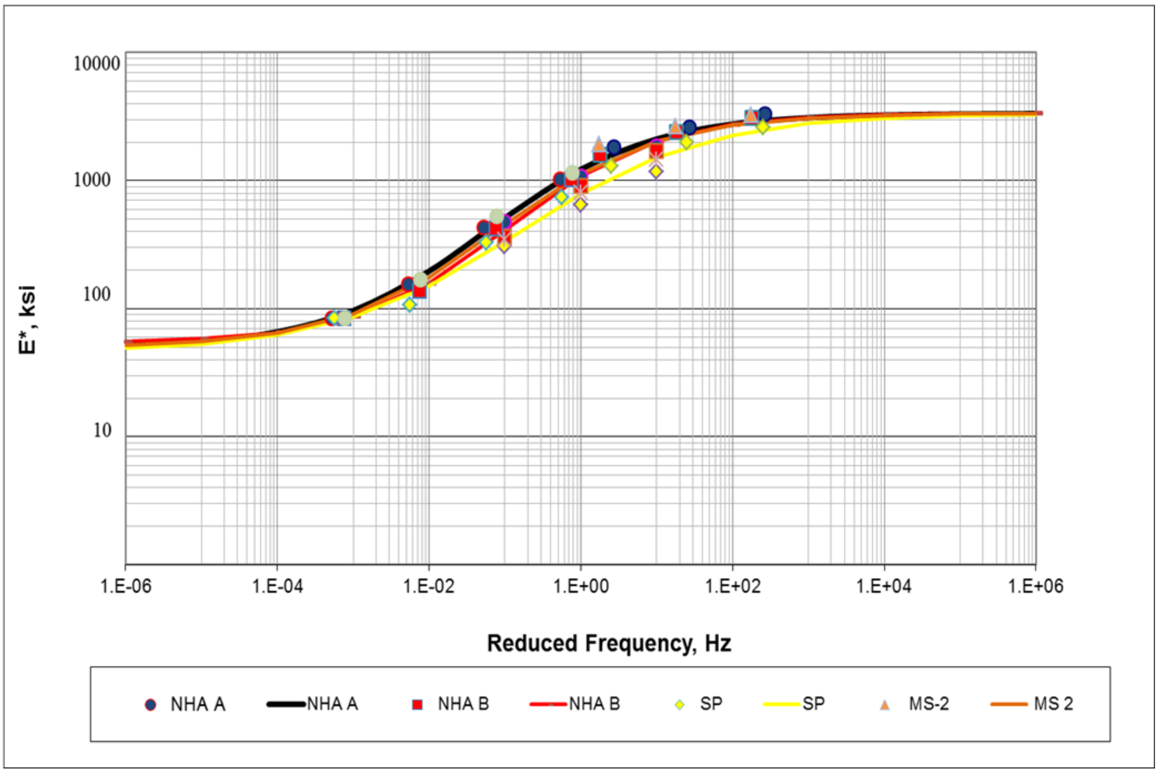


Figure 4.1 Dynamic modulus master curve for wearing course mixes

Master curves are developed using microsoft excel sheet which was developed under NCHRP project 9-29. This excels sheet uses the add-in tool i-e Solver which regress/minimize the sum of square of error (SSE) in such a way to fit in curve. This excel sheet uses the sigmoidal function to develop master curves illustrated by equation 2-5. This function captures the physical variation of mix for a range of temperature. At lower temperatures, mixture's stiffness is governed by binder stiffness while at higher temperature; mixture's stiffness is indicated by the aggregate interlocking (Pellinen & Witczak, 2002). The master curve for wearing course mixes is presented in figure 4.1 which shows that all mixtures are closer to each other. From this graph, it is evident that dynamic modulus is higher for higher frequency and higher frequency is similar lower temperatures and vice versa while temperature is considered. Furthermore, this figure indicated that all curves of mixtures are merged to one and no variation is observed at higher and lower frequency. Even though it is hard to distinguish between the lines, the graph shows that the NHA–A mix has the highest dynamic modulus values at all frequencies while superpave mix has the lowest dynamic modulus values at all frequencies. This indicates that the dynamic modulus test is sensitive to variation in the mix volumetric properties, gradation type and OBC. The master development for HMA mixes for pavements will help to select best mix for wearing course and facilitate while designing process and implementation of new design procedure i-e M-E approach in the Pakistan.

Figure 4.2 illustrates the dynamic modulus master curve for base course mixes, developed by master Solver excel worksheet using excel add-in solver. It can be inferred that there is no variation at lower and higher frequencies as curves are merged but significant variation can be observed at intermediate frequencies due to descent in |E*| values from 21.1 to 37.8°C and same variation in intermediate frequency may be attributed to effect of temperature and aggregate interlocking which causes differ in mechanical behavior of mix when exposed to higher temperatures.

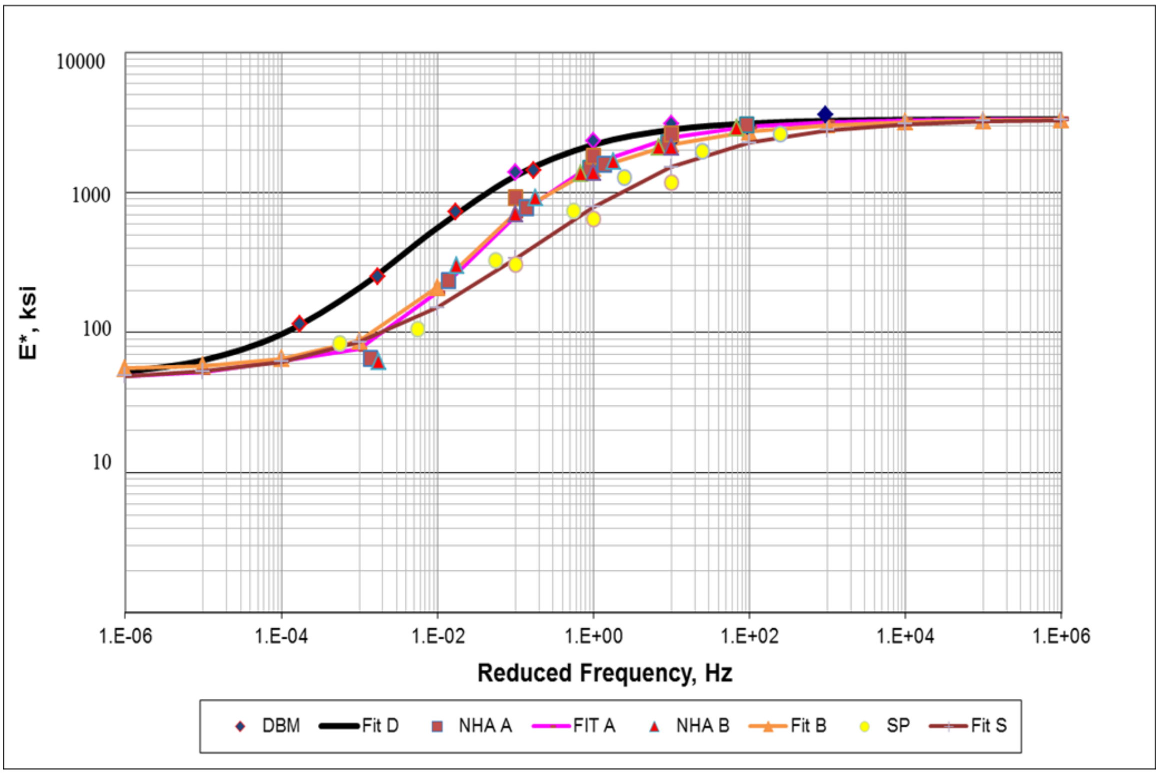


Figure 4.2 Dynamic modulus master curve for base course mixes

The complete detail of shift factors and reduced frequency of each mix for both wearing and base course is described in tabular form in appendix B which is obtained using master solver excel worksheet. The statistics for goodness of fit for master curves for each type of mix is present in table 4.1. The value of R^2 equal to 0.99 or above and Se/Sy equal to 0.05 or less is plausible for master curves. It can be perceived from table that some mixes do not comply with said criteria it is because solver tries to regress or minimize the error and find global minimum while in this case it stuck finding local minimum instead of global minimum.

Table 4.1 Goodness of Fit for Master Curves

Mixes	Mix type	R^2	Se/Sy
NHA A	AWC	0.98	0.10
NHA B	AWC	0.96	0.13
SP	AWC	0.94	0.18
MS 2	AWC	0.87	0.25
NHA A	ABC	0.99	0.07
NHA B	ABC	0.99	0.04
SP	ABC	0.94	0.18
DBM	ABC	0.98	0.10

4.2.2 Design of Experiment for Dynamic Modulus

The design of experiment is combination of various variable selected for a study in order to know the effect of these variables to response. It is very useful technique because instead of studying the effect of single factor to response variable individually and for each & every variable separate testing is done so it will be difficult to study when number of factors are greater so to minimize the effort and for better understanding, design of experiment method is adopted which takes all factors into account at the same time and exhibit its effect to response variable i-e |E*|).

In this study, two-level factorial design is adopted using statistical software Minitab 16. Two-level factorial design means each factor has two level values i-e high and low value. For selected study, dynamic modulus is response/Y variable and all other affecting parameters/X are temperature, frequency, air voids (AV), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), optimum bitumen content and nominal maximum aggregate size (NMAS). Initially, all these variable were included and input in Minitab 16 software and results shows that most of the factors are insignificant hence to keep it simple, significant variable are presented here while insignificant variable are omitted after running the test for first time. The factor after first run which is included is presented in table 4.2 alongwith their abbreviation, high and low values.

The below table presents the abbreviation for each factor considered for study alongwith its measured units. Low level and high level values are also presented herein. It can be seen in table that only significant change is in NMAS of wearing course to base course; in case of wearing course low level value is 12.5 mm while in base course mixes it is 25 mm and same is case in high level values i-e 19 and 37.5 mm for wearing and base course mixes respectively.

Table 4.2 Factors for Two-Level Factorial Design for Wearing and Base Course Mixes

Factors	Abbreviation	Units	Low Level		High Level	
			WC	BC	WC	BC
Temperature	A	°C	4.4	4.4	54.4	54.4
Frequency	B	Hz	0.1	0.1	25	25
Nominal Max Aggregate Size	C	mm	12.5	25	19	37.5

WC = Wearing course *BC= Base course*

The estimates of main effect and interaction effect is given in table 4.3 obtained from running factorial design in minitab 16 software. The effect can defined as it is mean difference in response of any factor at given two extreme values i-e low level and high level value while interaction effect can be defined as mean difference between effect of one factor at extreme values i-e high and low level values of other factor or in other words, it can be said that it is difference in effect of one factor at high level of other factor and effect one factor at low level of other factor. It is also observed from factorial design software output that effect estimate is double the value regression coefficient of each factor.

Table 4.3 Effect Estimates for Dynamic Modulus - Wearing Course Mixes

One factor			Two Factors			Three factors		
Main factors	Effects	p-value	Interaction	Effects	p-value	Interaction	Effects	p-value
Temp	-16398	0	Temp*Freq	-2211	0.098	Temp*Freq *NMAS	256	0.847
Freq	7591	0	Temp*NMAS	-573	0.606			
NMAS	1791	0.033	Freq*NMAS	752	0.448			

The temperature, frequency and NMAS effect estimates of wearing course are presented in table 4.3 which represent that temperature and frequency have higher values as compared to NMAS which means these two factors affect the dynamic modulus most while NMAS has little or no significant effect on the dynamic modulus while the arithmetic sign i-e (+, -) shows nature of relationship of effect. The positive sign shows that it has direct relation i-e with increase in frequency dynamic modulus increase and vice versa while negative sign shows inverse relation which means with increase in temperature dynamic modulus decrease and vice versa. The design of experiment was conducted at 95% confidence interval with significance level of α =0.05 for said design. The significance of any factor can be judged be comparing its p-value to significance level, if p-value is less than 0.05, the factor is said to be significant. From table 4.3, it can be inferred that individual effect of temperature, frequency and NMAS are significant at given significant level while in 2-way interaction, temperature & frequency has little or no significant effect on response i-e dynamic modulus. While other interactions like temperature & NMAS, frequency & NMAS has no effect because their p-value is greater than given significance level and it does not fall into rejection zone (i-e significance of variable). A same phenomenon is attributed to 3-way interaction having high p-value.

Table 4.4 Effect Estimates for Dynamic Modulus - Base Course Mixes

One factor			Two Factors			Three factors		
Main factors	**Effects**	**p-value**	**Interaction**	**Effects**	**p-value**	**Interaction**	**Effects**	**p-value**
Temp	-14921	0	Temp*Freq	-960	0.463	Temp*Freq *NMAS	271	0.836
Freq	9443	0	Temp*NMAS	1206	0.271			
NMAS	492	0.546	Freq*NMAS	692	0.478			

The table 4.4 contains the main and interaction effect estimates for base course mixes which shows same trend analogous to wearing course. The temperature and frequency has higher values than other factors which means temperature and frequency has significant influence on the dynamic modulus while nominal maximum aggregate size (NMAS) has little or no effect. The arithmetic sign represents the nature of relationship as negative sign denotes the relationship between temperature and dynamic modulus is inverse i-e with increase in temperature, dynamic modulus decrease which is infact is observed in isothermal graph presented in ensuing paragraph while positive sign denotes that there is direct relationship between frequency and dynamic modulus; as frequency is decreased the dynamic modulus is decreased and vice versa. The above design of experiment method was also run at same significance level of $\alpha = 0.05$. The significance of any parameter can be estimated by comparing its p-value (Table 4.4) to significance level. If the p-value of any factor is greater than 0.05 then that parameter is said to be insignificant because it does not fall into rejection zone (Rejection zone means parameter is significant) and does not affect the response and vice versa. In this study, the temperature and frequency has p-value less than $\alpha = 0.05$ then it is rejected means the parameters are significant while NMAS has p-value greater than $\alpha = 0.05$ hence it is in fail to reject and does not affect the dynamic modulus. The two way interaction effect also seem to be insignificant as their p-value is higher than α = 0.05 which put them in fail to reject zone and same phenomena is observed for three way interaction which includes all three factors at once and their effect is insignificant by looking its p-value which is greater than α=0.05.

The table 4.5 represents the analysis of variance (ANOVA) of observed data for dynamic modulus of wearing course mixes upto three way interaction effects. It can be noticed from table 4.5 that degree of freedom for main effect is three (03) which means there are three parameters explaining the variation of dynamic modulus i-e temperature, frequency and NMAS. The significance of factor is judged by comparing p-value to α = 0.05 and value of *F* (generally greater than 10 considered to be significant). Here the main effect is observed as significant as p-value is less and *F* is also greater than 10 while rest of the interaction does not affect much on the dynamic modulus as their p-value is greater than α =0.05.

Table 4.5 ANOVA for Dynamic Modulus - Wearing Course Mixes

Sources	DF	Sum of Sq	Mean Sum of Sq	*F*	P
Main Effects	3	2424073352	808024451	92.69	0
2-Way Interaction	3	29429816	9809939	1.13	0.343
3-Way Interaction	1	325426	325426	0.04	0.847
Residual Errors	88	767111642	8717178		
Pure Error	48	104448215	2176004		
Total	95	4496636630			

Table 4.6 illustrates the analysis of variance for dynamic modulus of base course mixes. A similar trend of results is obtained only differ by values in comparison to wearing course mixes. Main effect in only significant as its *F* is higher than 10 and p-value is less than α =0.05 while two way interaction and three way interactions do not seem to be significant as their *F* is smaller and p-value is greater than significance level. The significance level is assumed to be α =0.05. The degree of freedom for main effect is three (03) as there are three parameters involved in explaining the variation of dynamic modulus which is already stated above. While two interaction has degree of freedom three (03) which means there are two factors at once explaining variation and three different combination are there hence degree of freedom is three while three way interaction has degree of freedom is one in which three factor explaining collectively variation in dynamic modulus.

Figure 4.3 represents the cumulative normal probability plot of dynamic modulus for wearing course mixes. The confidence interval is 95% and it includes all model parameters i-e main and interaction effect.

Table 4.6 ANOVA for Dynamic Modulus - Base Course Mixes

Sources	DF	Sum Of Sq	Mean Sum of Sq	*F*	P
Main Effects	3	2284593364	761531121	90.29	0
2-Way Interaction	3	24367854	8122618	0.96	0.414
3-Way Interaction	1	364699	364699	0.04	0.836
Residual Errors	88	742197263	8434060		
Pure Error	48	277989631	5791451		
Total	95	4521415234			

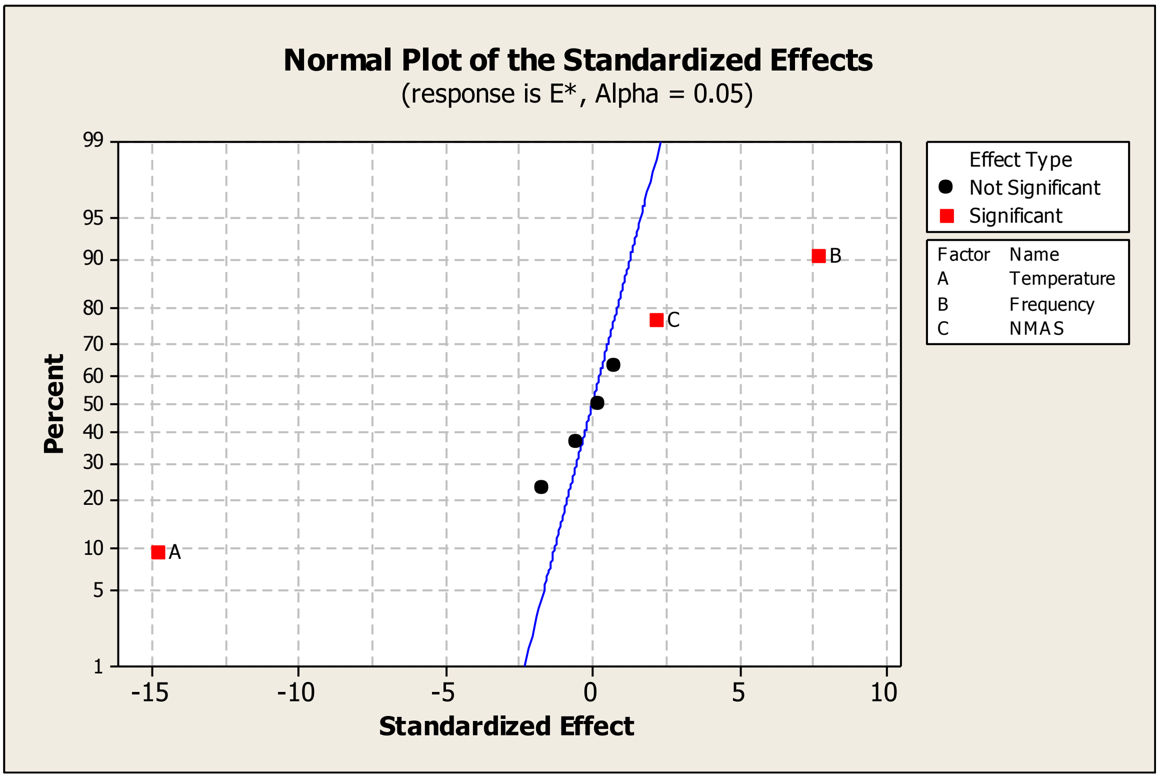


Figure 4.3 Cumulative normal plot for dynamic modulus - Wearing course mixes

The figure 4.3 indicates the factors selected for study of wearing course mixes are significant or otherwise. The black dot denotes that factor is insignificant while red squares shows factor is significant as it is represented in figure 4.3 legand. The temperature and frequency has significant influence on the dynamic modulus and their strength can be judged by their distance away from reference line while temperature is on negative sign which means it has inverse effect to dynamic modulus and same is case with frequency which is on positive side and has direct relation with dynamic modulus. The NMAS has no or little effect on the dynamic modulus as it can be inferred from the plot given above while two way and three way interaction do not pose any significant effect on the dynamic modulus which is already stated in previous paragraphs.

The figure 4.4 illustrates the cumulative normal probability plot of effect estimates for dynamic modulus of base course mixes at 95% confidence interval with indulgence of all model parameters.

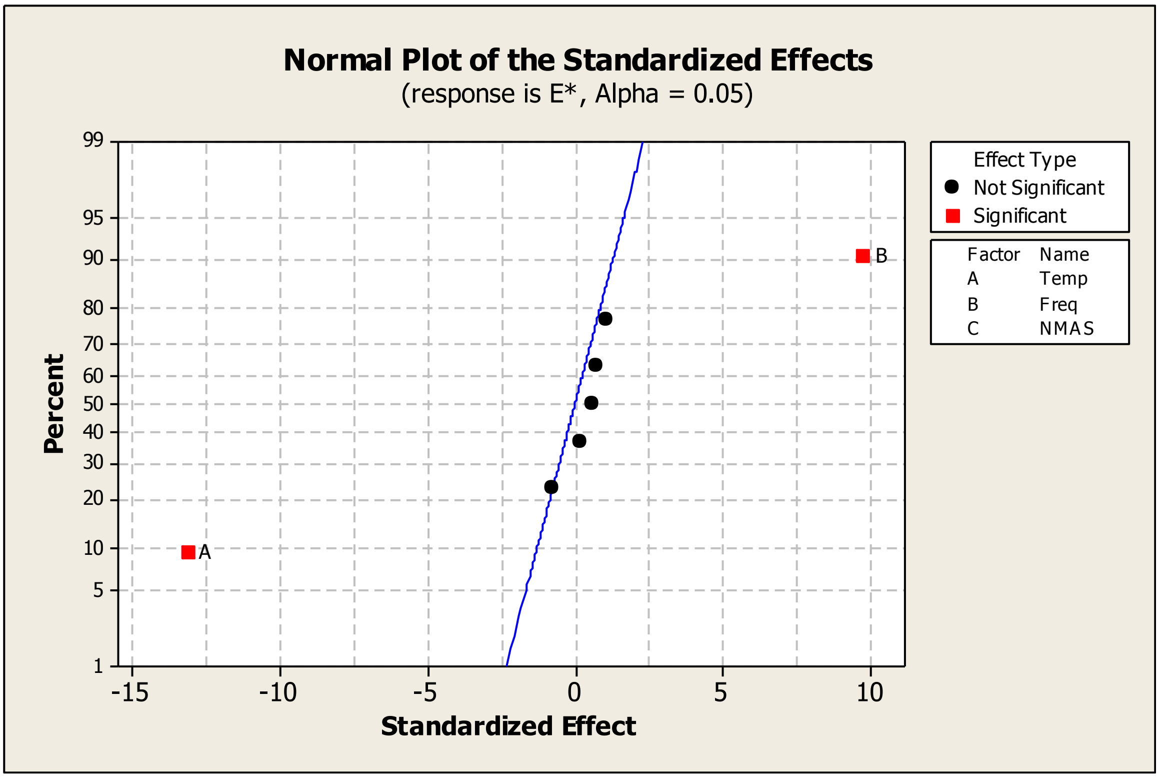


Figure 4.4 Cumulative normal plot for dynamic modulus - Base course mixes

It can be inferred from plot that temperature and frequency significantly influences the dynamic modulus while their nature of relation is indicated by negative and positive sign. The strength is indicated as their distance from reference line. NMAS has little or no effect on dynamic modulus while two-way and three-way interactions are close to reference line but not significant as they are denoted by black dot which means factor is insignificant.

The figure 4.5 shows the main effect plot for dynamic modulus of wearing course mixes. This figure expresses that main effect is plotted versus high and low levels of factors considered for study and the sharp slope of line shows that there is strong relation between parameter and response variable. Temperature has sharp slope line which notifies that temperature is significant variable and affects dynamic modulus inversely as suggested by the slope of line while frequency is also significant parameter explaining changes in dynamic modulus as it also represented by the sharp slope of line and line ascends which denote that frequency is directly related dynamic modulus. The NMAS has little or no significant impact on dynamic modulus as line does not show any notable slope.

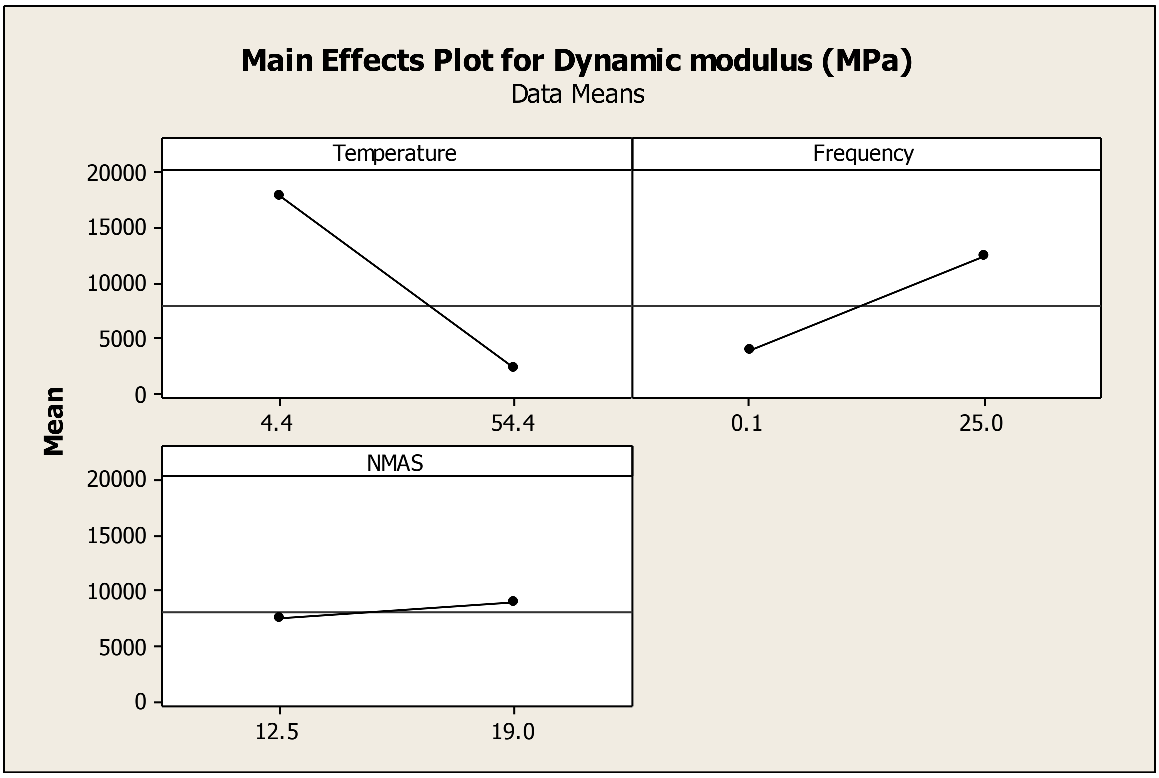


Figure 4.5 Main effect plot for dynamic modulus - Wearing course mixes

The figure 4.6 illustrates the main effect plot for dynamic modulus of base course mixes. This plot is analogous to wearing course mix plot. This figure shows that main effect is designed against high and low levels of factors considered for study. Here, it is clear from plot that base course mixes are significantly influenced by the temperature and frequency as both are denoted by sharp slope of line, only differing by nature of their relationship to dynamic modulus i-e temperature has inverse relation while frequency is directly related to temperature. The NMAS has negligible effect on the dynamic modulus as it is represented by almost straight line which shows there is no significance change in dynamic modulus with change in NMAS considered for base course mixes.

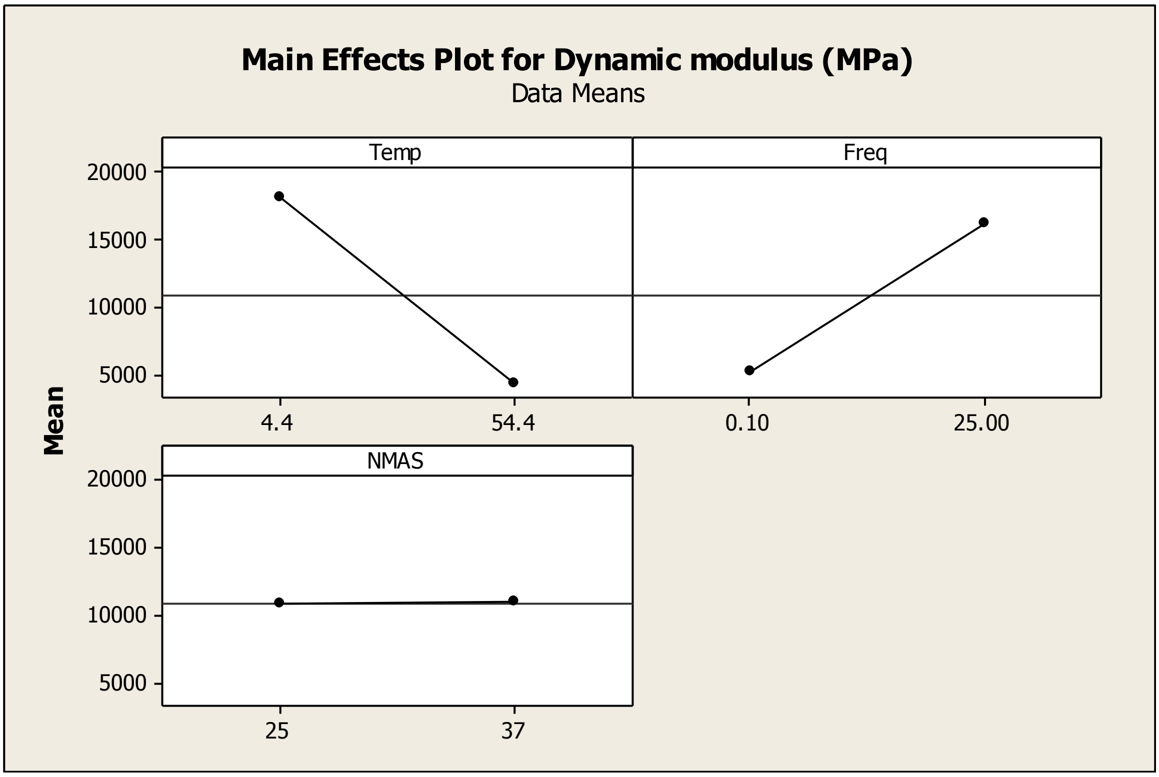


Figure 4.6 Main effect plot for dynamic modulus - Base course mixes

The figure 4.7 illustrates the interaction effect plot of factor affecting dynamic modulus for selected wearing course mixes. The interaction between two factors can be explained as effect of one factor to high and low level of other factor for mean response. The significance of interaction between two factors can be identified by non-parallel line which means interaction effect exists between selected factors while parallel line show that interaction is insignificant which means there is no interaction effect present between factors. The steepness of slope of line shows the strength effect of interaction.

The figure 4.7 shows the interaction effect plot for dynamic modulus of wearing course mixes selected for study. From above plot, it can be inferred that interaction effect between temperature & frequency has no or little impact as line is almost parallel while interaction effect temperature & NMAS and frequency & NMAS is insignificant which is illustrated by parallel which indicates that there is no relation exists between these factors and also implies that similar trend will occur in response at different levels of other factor.

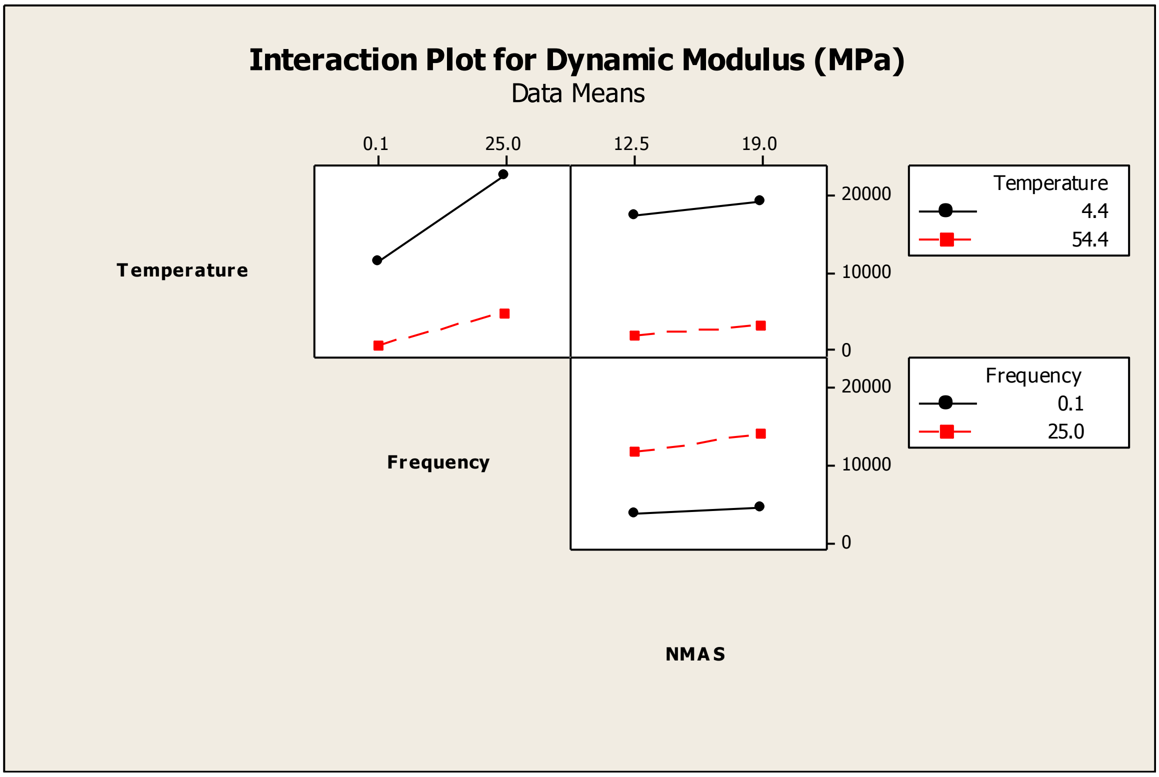


Figure 4.7 Interaction effect plot for dynamic modulus - Wearing course mixes

The figure 4.8 illustrates the interaction effect plot for dynamic modulus of base course mixes. It is evident from figure that all lines are parallel which indicates that there is no relationship between temperature & frequency, temperature & NMAS and frequency & NMAS. All these interaction are insignificant as it is shown in figure which implies that there will be no impact and similar kind of drift will be observed in mean response at extreme values i-e high and low level values. Although it is interaction plot but if single line is observed it shows the relationship of temperature and other factors to dynamic modulus. The sudden drop of line from one end to other end shows the applicability and impact of factor on the dynamic modulus.

The figure 4.9 represents the pareto chart for dynamic modulus of wearing course mixes. The pareto chart defines the significance of factor as well as interaction effect to mean response. Pareto chart also shows the relative importance of factor effect. This chart contains the standardized effect of each factor i-e amalgamation of factors for mean response and for selected significance level i-e 5%, t-critical reference line is drawn on the chart which indicates that bars crossing the reference line are significant while those bars which are not crossing reference line termed as insignificant. The figure 4.9 notifies that temperature, frequency and NMAS are significant parameters as bars of all these parameters are crossing the t-critical line which suggest that these parameters influence the dynamic modulus while interaction effect of temperature & frequency has little or no effect as its bar is close to t-critical reference line while other interaction like temperature & NMAS and frequency & NMAS are insignificant which is confirmed by bars which are behind the reference line which implies that interaction effect of factors do not have any significantly impact on the dynamic modulus while individually these factor affect the dynamic modulus which is cross checked by the pareto chart.

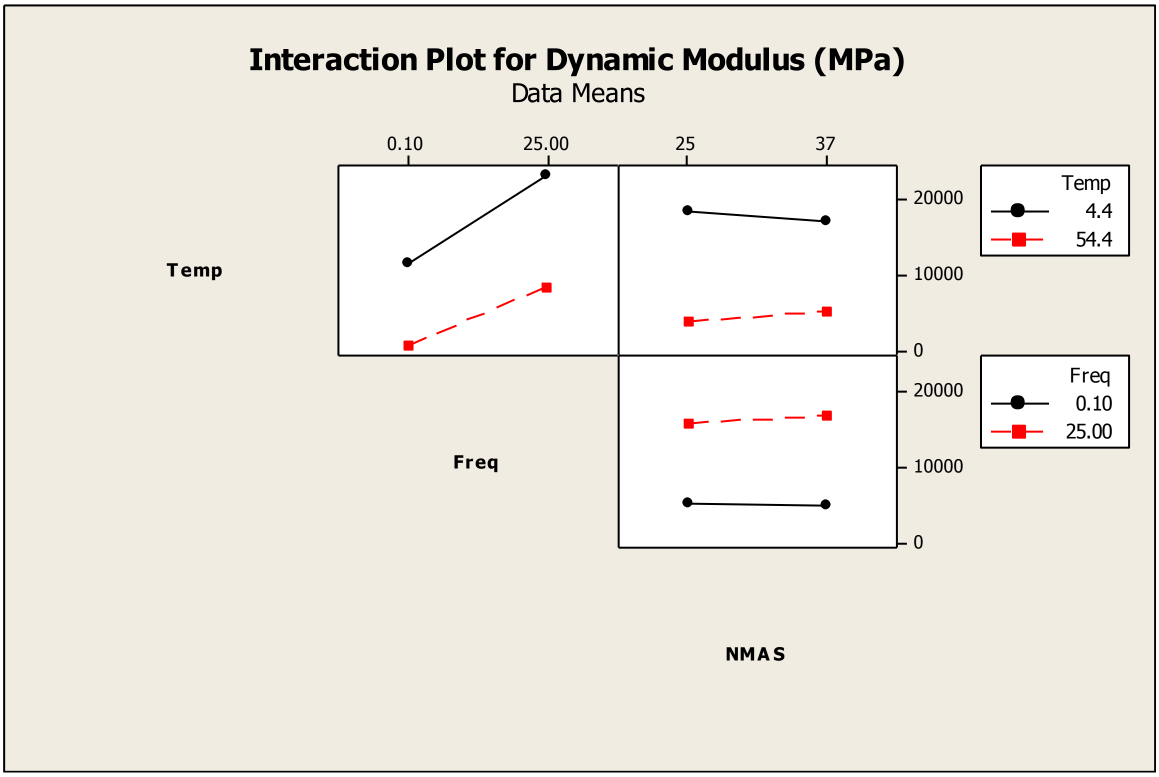


Figure 4.8 Interaction effect plot for dynamic modulus - Base course mixes

The significance of factor effect and interaction effect for base course mixes is given by figure 4.10 i-e pareto chart. It is observed that for base course mixes, temperature and frequency are significant parameters that affect the dynamic modulus as their bars are crossing the t-critical value for 95% confidence interval and NMAS is insignificant term which does not affect the dynamic modulus. It is also evident from pareto chart that no any other bar is crossing the t-critical reference line which means interaction effect in case of base course mixes in negligible.

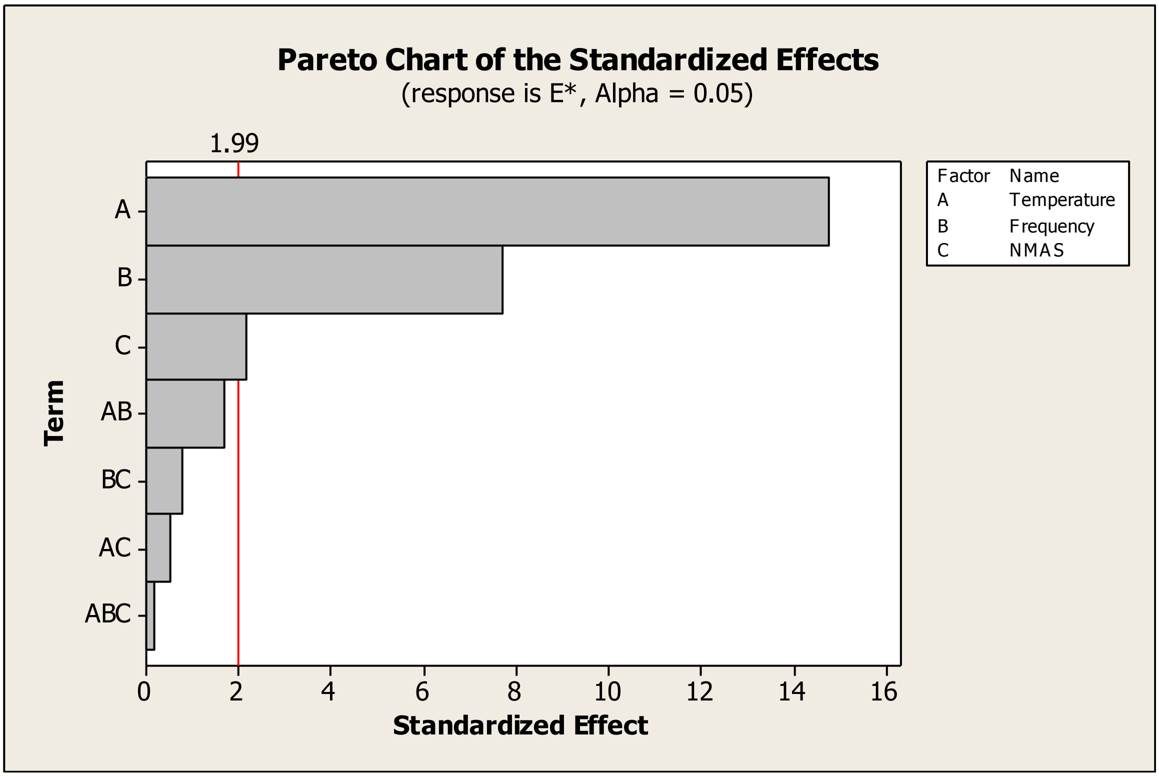


Figure 4.9 Pareto chart for dynamic modulus - Wearing course mixes

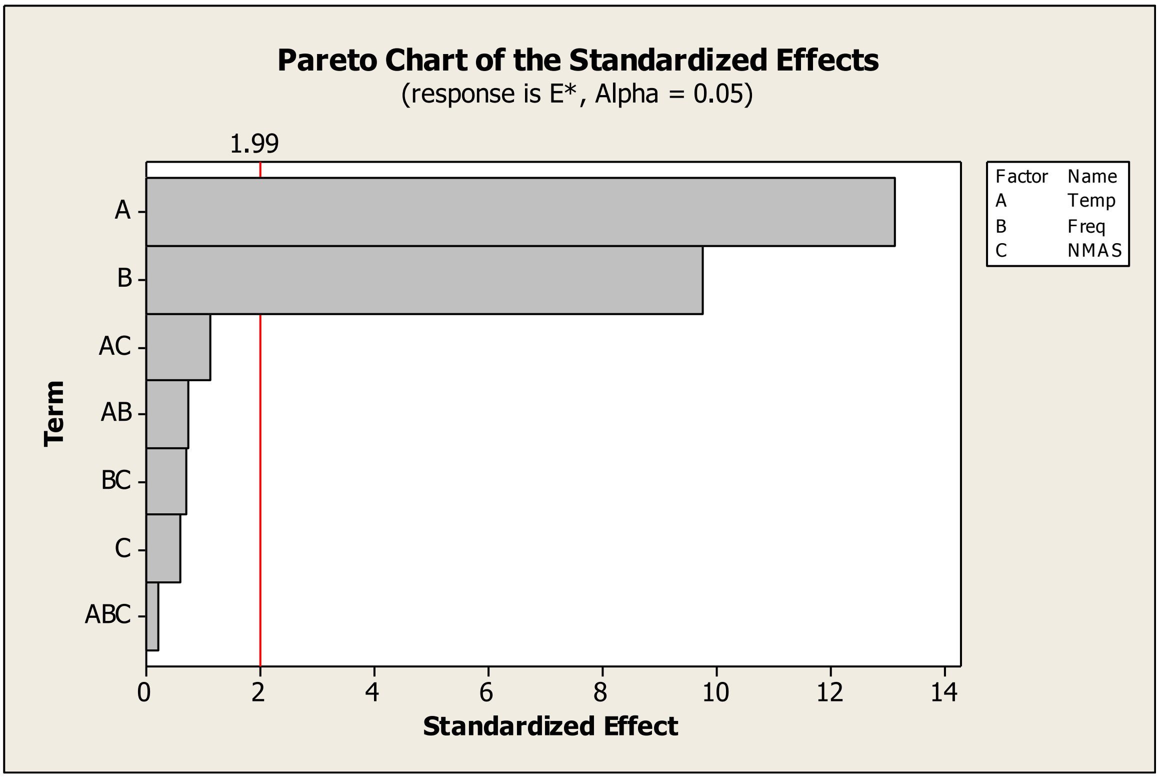


Figure 4.10 Pareto chart for dynamic modulus - Base course mixes

It is clear from normal plot and pareto chart of wearing course mixes that temperature, frequency and NMAS are significant variable while 2-way and 3-way interaction of these factors is insignificant. It is clear from figure 4.11 that highest dynamic modulus is achieved when temperature is 4.4 °C and frequency is 25 Hz while NMAS is 19 mm. The resultant dynamic modulus is high because at low temperature, material become stiff and strain produced are less which tends dynamic modulus to increase while lowest dynamic modulus is observed when temperature is 54.4 °C and frequency is 0.1 Hz and NMAS is 12.5 mm, because at high temperature material becomes flexible and viable to produce more strains which ultimately reduces the dynamic modulus. The change of dynamic modulus from low level of frequency and temperature is more prominent. This plot conform that temperature, frequency and NMAS affect the dynamic modulus.

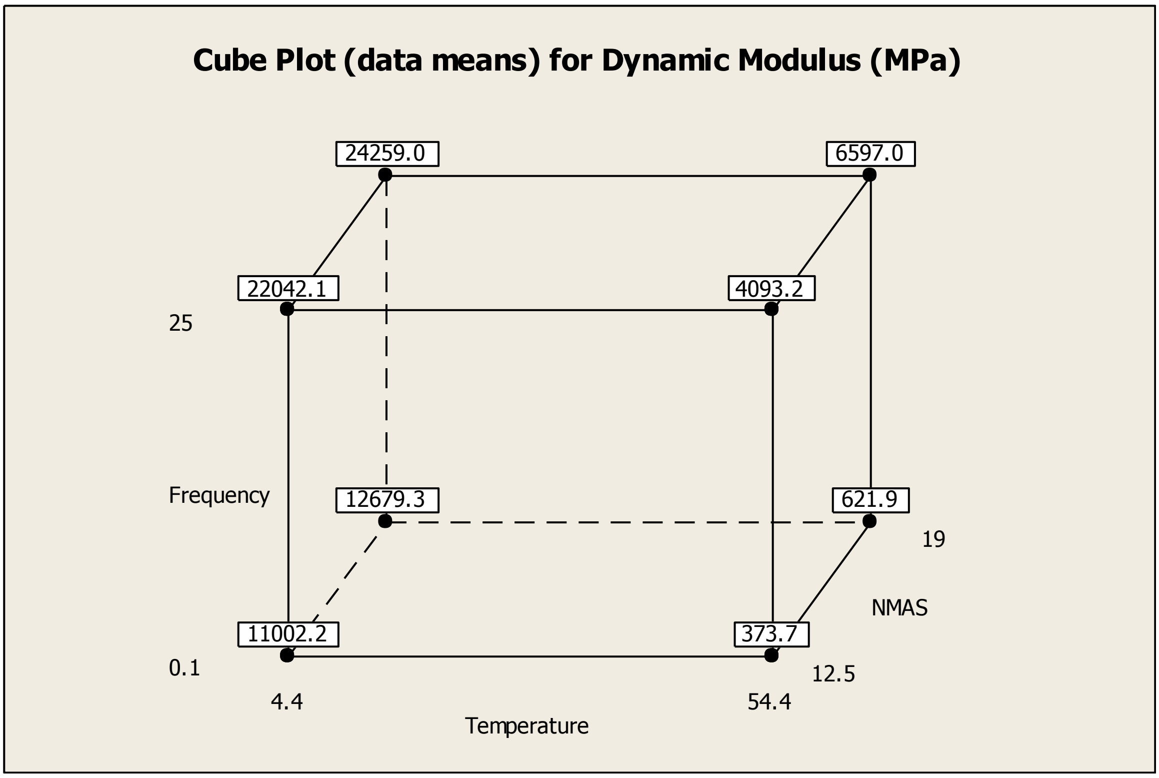


Figure 4.11 Cube plot for dynamic modulus - Wearing course mixes

The figure 4.12 illustrates the cube plot for dynamic modulus of base course mixes. By looking at the plot, it can be inferred that highest dynamic modulus is obtained 4.4 °C with NMAS of 25 mm and frequency of 25 Hz while lowest dynamic modulus is obtained at 54.4 °C temperature, frequency of 0.1 Hz and NMAS of 25 mm. hence this provide evidence that temperature, frequency and NMAS are significant parameter affecting the dynamic modulus of base course mixes.

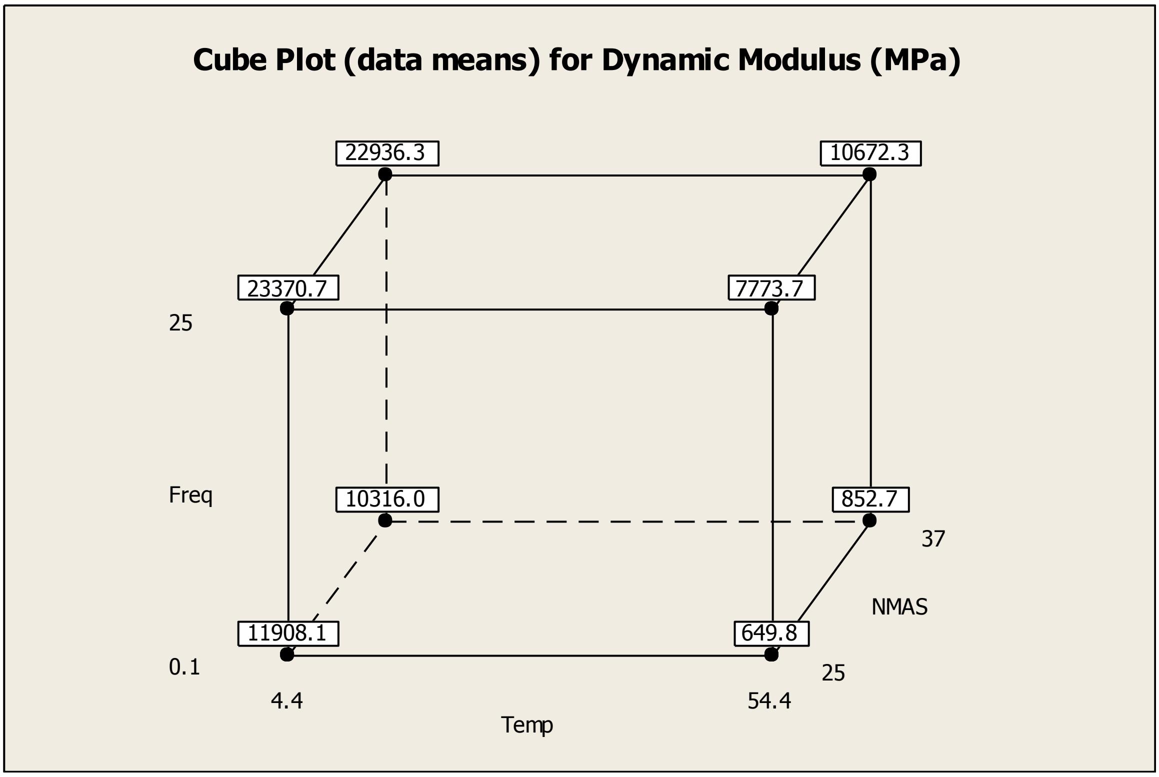


Figure 4.12 Cube plot for dynamic modulus - Base course mixes

Response/Contour plot helps in determining the desirable values of response at any value of depending factors simply by interpolating. The figure 4.13 shows the response surface for dynamic modulus of wearing course mixes with low level values of temperature and frequency and keeping NMAS as hold value.

The figure 4.13 represents the response plot which indicates series of experiments on various wearing course mixes. The dynamic modulus values increase in frequency and decrease with increase in temperature. The best way to interpret the plot like a topological map with these lines indicating the contours of equal dynamic modulus. The curvature of line shows the interaction between temperature and frequency at low level. By keeping the temperature constant, the dynamic modulus value can be predicted at any frequency. It can be done by drawing a line parallel to the frequency axis across the contour plot. Similarly, by keeping the loading frequency constant, dynamic modulus can be obtained at any point of temperature by drawing line parallel to the vertical axis.

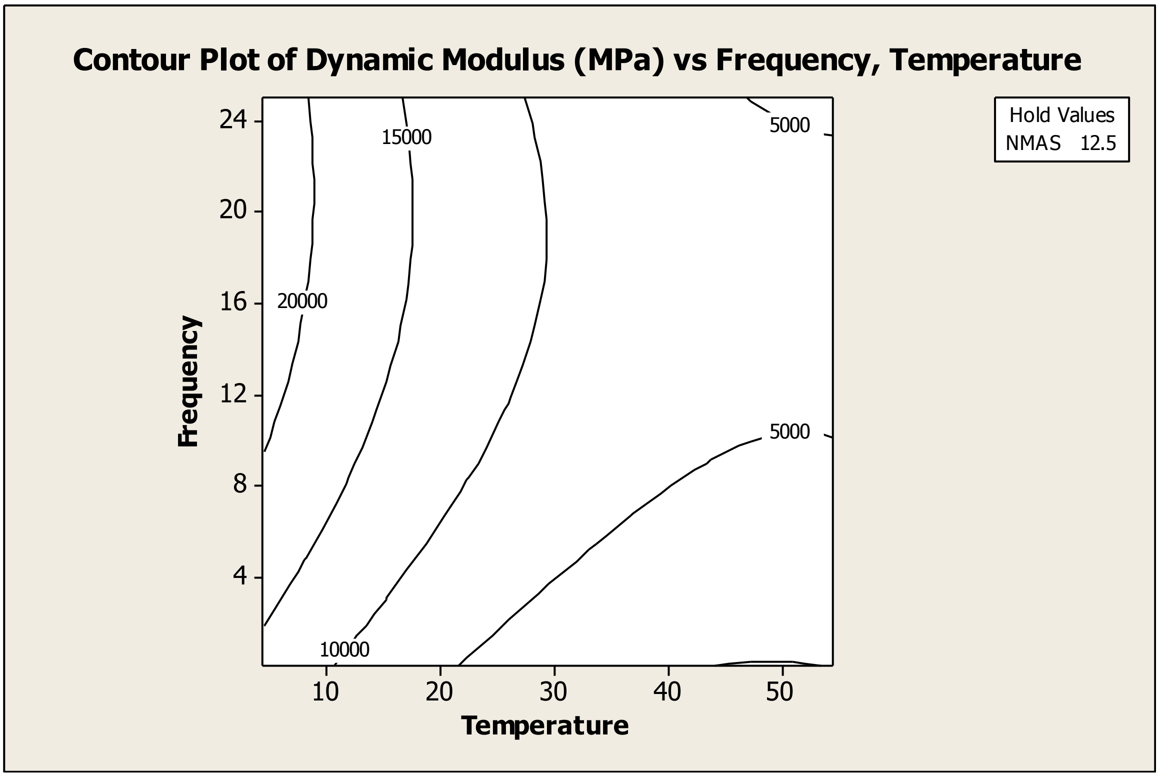


Figure 4.13 Response plot at low level of Temp: & Freq: - Wearing course mixes

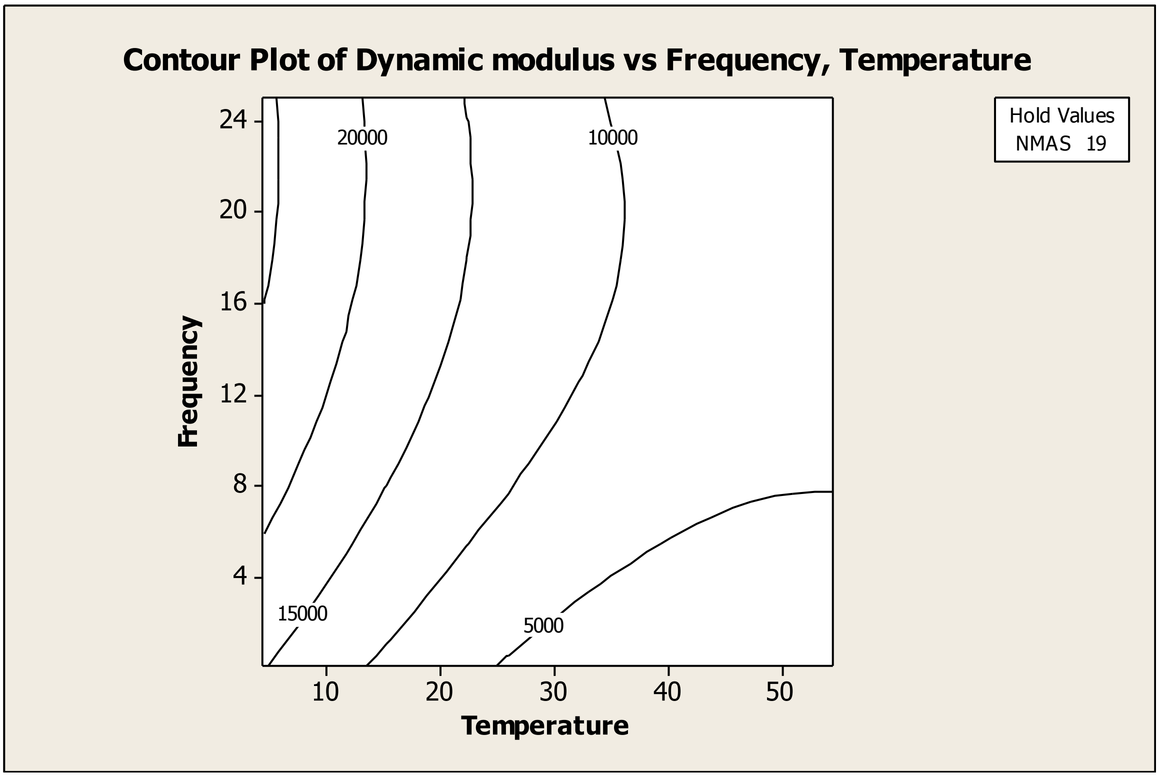


Figure 4.14 Response plot at high level of Temp: & Freq: - Wearing course mixes

The figure 4.14 illustrates the response surface plot. It can be interpreted in same way but only difference that it incorporated the high level value of temperature and frequency. The figure 4.15 represents that three dimensional (3D) view of dynamic modulus versus temperature and frequency by keeping NMAS as hold value. From this plot, it can inferred that dynamic modulus increase with decrease in temperature and decrease with decrease in frequency while dynamic modulus can be predicted for temperature and frequency values other than specified in the test simply by drawing line from required frequency and temperature onto the dynamic modulus. This plot is useful for determining the intermediate and desirable values for response vaiable.

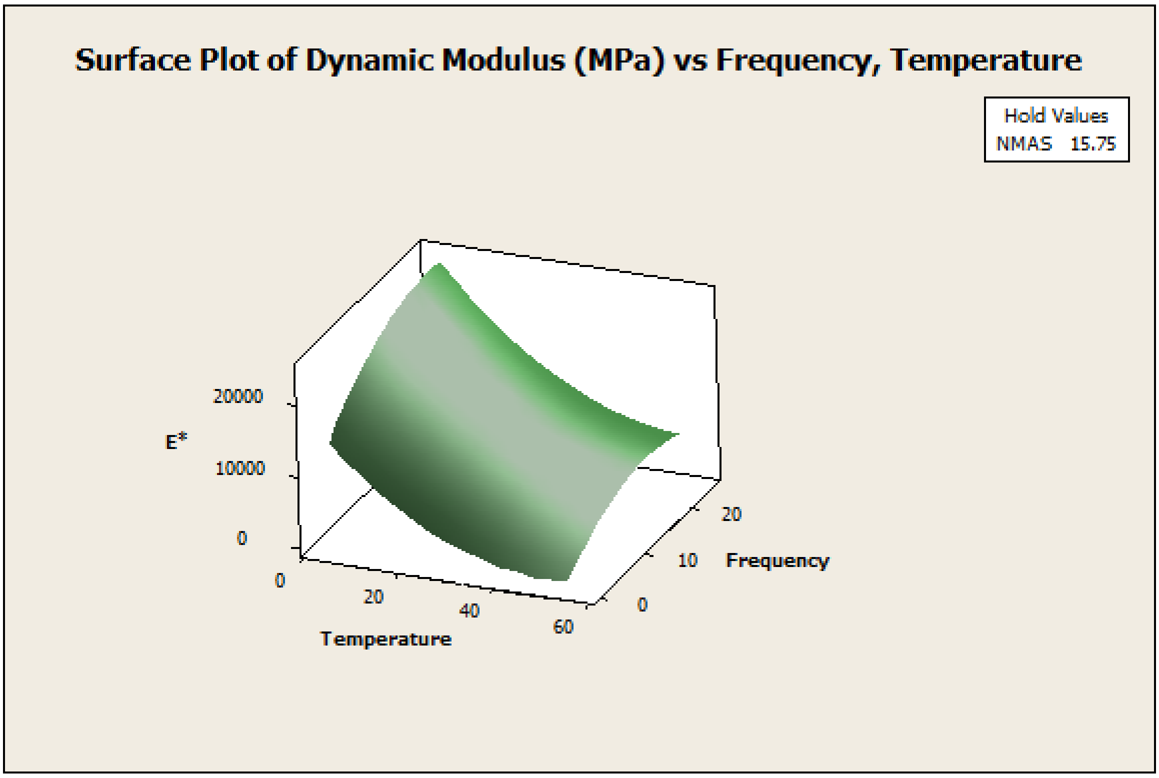


Figure 4.15 3D Surface plot - Wearing course mixes

The figure 4.16 represents the surface plot for dynamic modulus at low levels of temperature and frequency for various base course mixes by keeping NMAS as hold value. The curvature of line denotes that there is little interaction effect between temperature and frequency. The interpretation of plot is analogous to wearing course mixes. By keeping the temperature constant, the dynamic modulus value can be predicted at any frequency. It can be done by drawing a line parallel to the frequency axis across the contour plot. Similarly, by keeping the loading frequency constant, dynamic modulus can be obtained at any point of temperature by drawing line parallel to the vertical axis.

The figure 4.17 illustrates the response surface plot. It can be interpreted in same way but only difference that it incorporated the high level value of temperature and frequency.

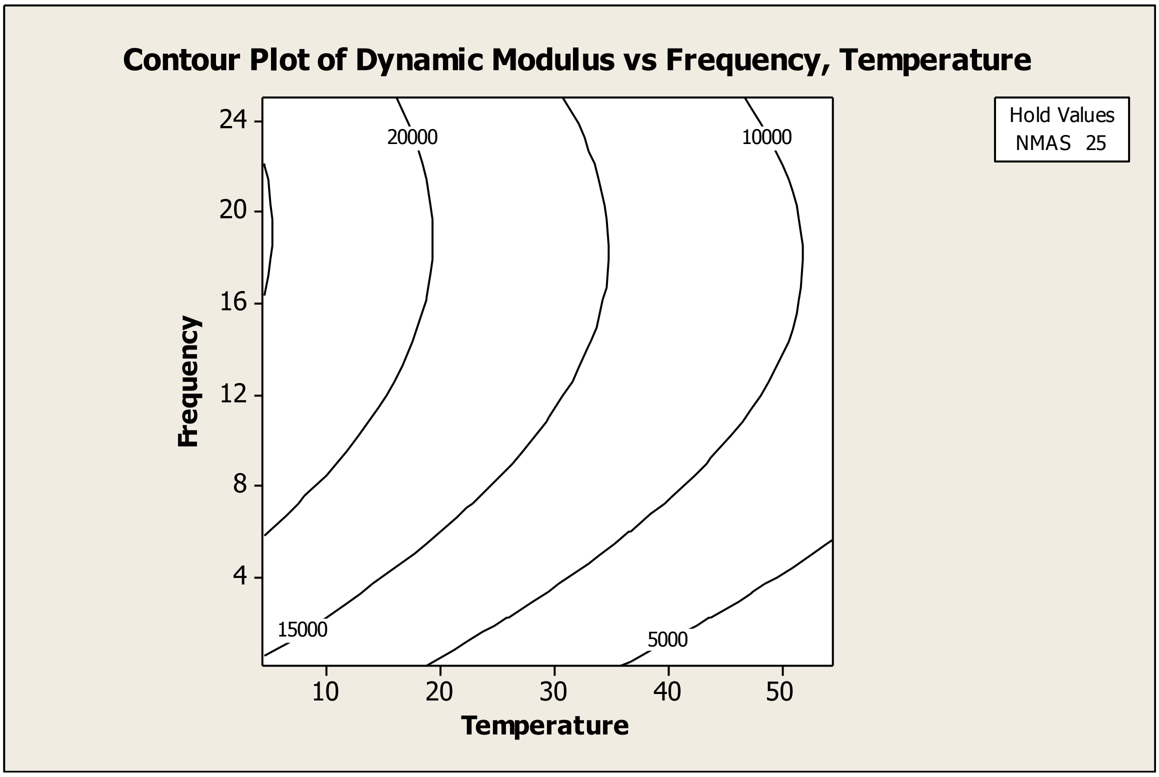


Figure 4.16 Response plot at low level of temperature & frequency - Base course mixes

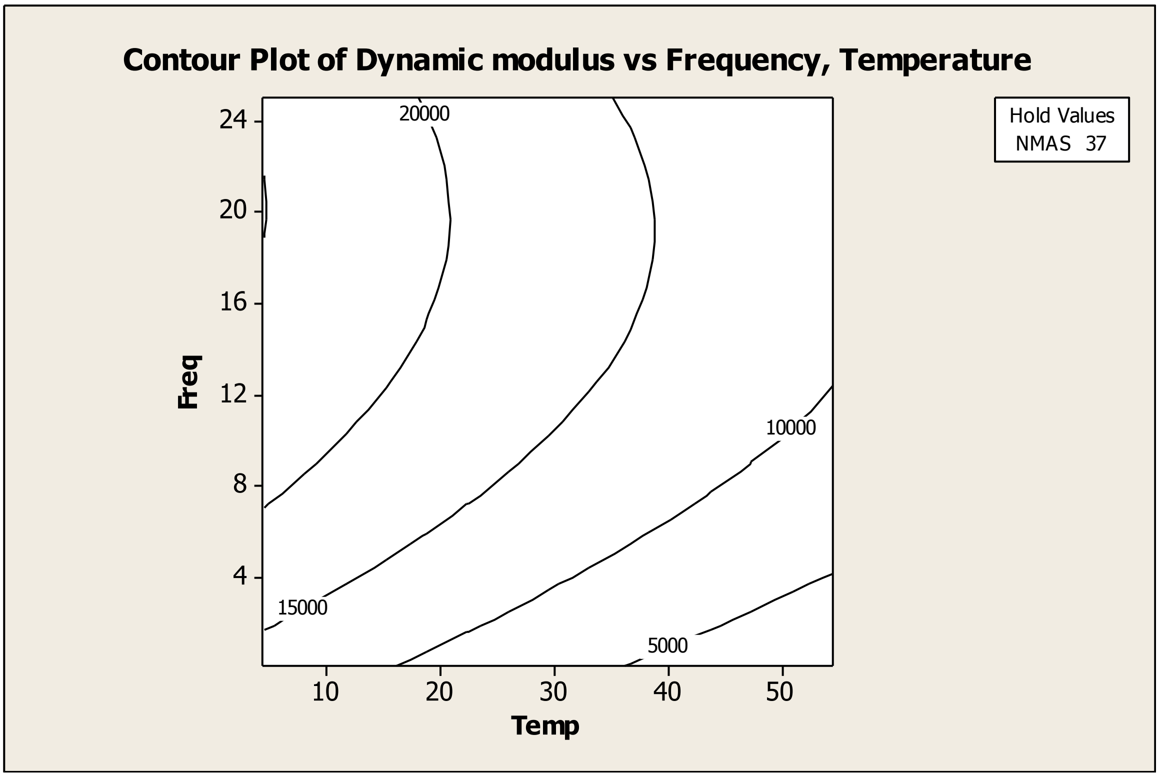


Figure 4.17 Response plot at high level of temperature & frequency - Base course mixes

The figure 4.18 illustrates the three dimensional (3D) response surface plot for dynamic modulus against average temperature and frequency values by keeping NMAS as hold value.

This plot gives clear idea of variation in dynamic modulus due to temperature and frequency. The dynamic modulus can be predicted at any point on any value of temperature and frequency. This plot infact facilitate for interpolating the intermediate value of frequency and temperature as per requirement.

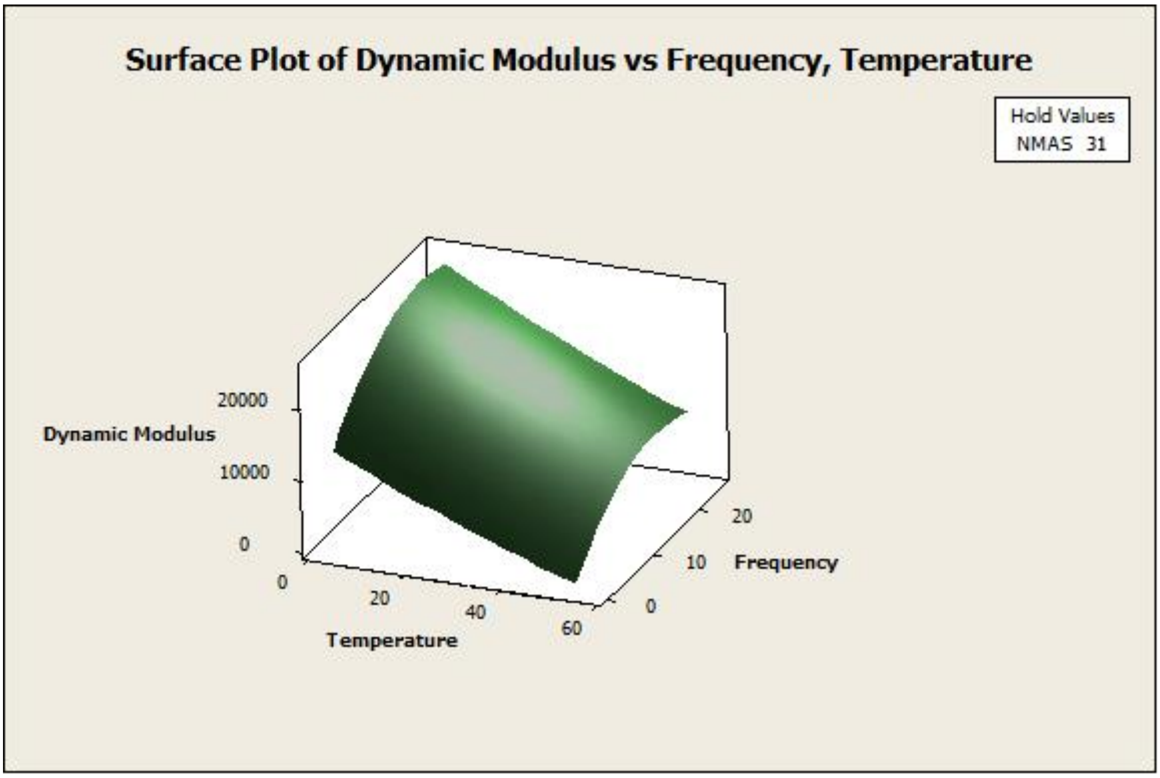


Figure 4. 18 3D Surface plot - Base course mixes

4.2.3 Performance Modelling

The performance is measure of behavior of pavement when exposed to different factors like weather conditions, loading, temperature etc. The mechanistic part of newly developed AASHTO 2002 M-EPDG design guide is based on the development of models to predict distresses like cracking, fatigue etc. Therefore it is imperative to predict pavement performance at design stage for longevity of pavement life. In this case, dynamic modulus is performance indicator and depends on the loading frequency, test temperature and mix volumetric parameter.

Dynamic modulus = *f* (temperature, loading frequency, Mix volumetric parameter)

The data acquired from laboratory testing is used for development of model to predict the dynamic modulus. Initially hit & trail method was adopted and scatter plot were generated to conform the best relation of dynamic modulus to its affecting variables. By iterating process, many functional forms like exponential and logarithmic emerge as good but problem arises when model validation is done as it over predict the response. So Cobb-Douglas functional form is selected. This functional form is widely used to illustrate the interaction of two or more inputs having different functional forms and also used in cost based empirical studies. This functional form is very popular in engineering economics concepts as it has advantage to capture economies of scale ascribed to variation. The parameters/ coefficients of independent variables presented in Equation (4-1) are not restricted to unity but, rather, left free to be determined by statistical estimation. This mathematical specification helped to identify any non-linearity in prediction of dynamic modulus. The general generic functional form of Cobb-Douglas model is

$$Y = \alpha \times {X_i}^{\beta_i} \quad (4\text{-}1)$$

Where i = Number of variables = 1, 2, 3,…., n

This functional form can be rewritten for this study as is given below

$$|E^*| = \alpha \times T^{\beta_1} \times F^{\beta_2} \times V^{\beta_3} \quad (4\text{-}2)$$

Where,

$|E^*|$ = Dynamic modulus, MPa

T = Temperature, Degrees (4.4 to 54.4 ^{o}C)

F = Loading Frequency, Hz (0.1 to 25 Hz)

V = Mix volumetric parameter (VMA in percentage)

α, β_1, β_2, β_3 = Regression Coefficients

Non-linear regression analysis approach is used to develop the models for the mixes used in the study. Initially multiple linear regression was used to generate model but it does not give desirable coefficient of determination (R^2), so non-linear regression was adopted which appropriately fit the data. Non-linear regression was done using PASW 18 to develop the general model for wearing and base course mixes incorporating the mix volumetric parameter as variable and model output is presented in appendix D. The parameters statistics for wearing course model are presented in table 4.7.

Table 4.7 Wearing Course Model Summary

Parameter	Estimate	Std. Error	t-Stat	R^2 (%)	95% Confidence Interval	
					Lower Bound	Upper Bound
α	714298	29590	24.10	89.7	656301	772294
β_1	-0.603	0.016	-37.68		-0.634	-0.571
β_2	0.152	0.008	19.00		0.137	0.168
β_3	-1.133	0.160	-7.08		-1.447	-0.819

The above table shows the model parameters and statistics. It can be inferred that model is capturing 89 percent of variation in dynamic modulus while all the independent variables are significant as their t-stat are greater than critical value of t-stat at 95% confidence level i-e 2.308. The 95% confidence interval values are also presented in table 4.8.

Table 4. 8 Base Course Model Summary

Parameter	Estimate	Std. Error	t-Stat	R^2 (%)	95% Confidence Interval	
					Lower Bound	Upper Bound
α	1609273	105562	15.24	77	1402371	1816175
β_1	-0.333	0.015	-22.22		-0.361	-0.304
β_2	0.164	0.009	18.22		0.145	0.182
β_3	-1.670	0.265	-6.30		-2.192	-1.148

It can be observed from above table that R^2 of these models is above 77% means most of variation in dynamic modulus is explained by the variation in the temperature and frequency and mix volumetric parameter. The above table also presents the t-stats of parameter estimates which show that all the parameters are significant at 95% confidence level.

4.2.4 Model Validation

Model validation is a technique to measure the applicability/approach to predict the observed data by use by the regression model. There are many methods of model validation but for this study, mean absolute percentage error (MAPE) is used which can be defined as it is mathematical difference between observed and fitted data value divided observed value and taking average of that gives mean absolute error and if 100 is multiplied, it will yield error in percentage.

$$\text{MAPE} = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \qquad (4\text{-}3)$$

Where,

A_t = Actual value

F_t = Fitted value

The MAPE of wearing course model is 15%. The figure 4.19 shows the validation plot for wearing course model. The more data values close to 45° line more better the model predictive capability would be and it is evident from figure that most of the data values are close to line which shows that model is good.

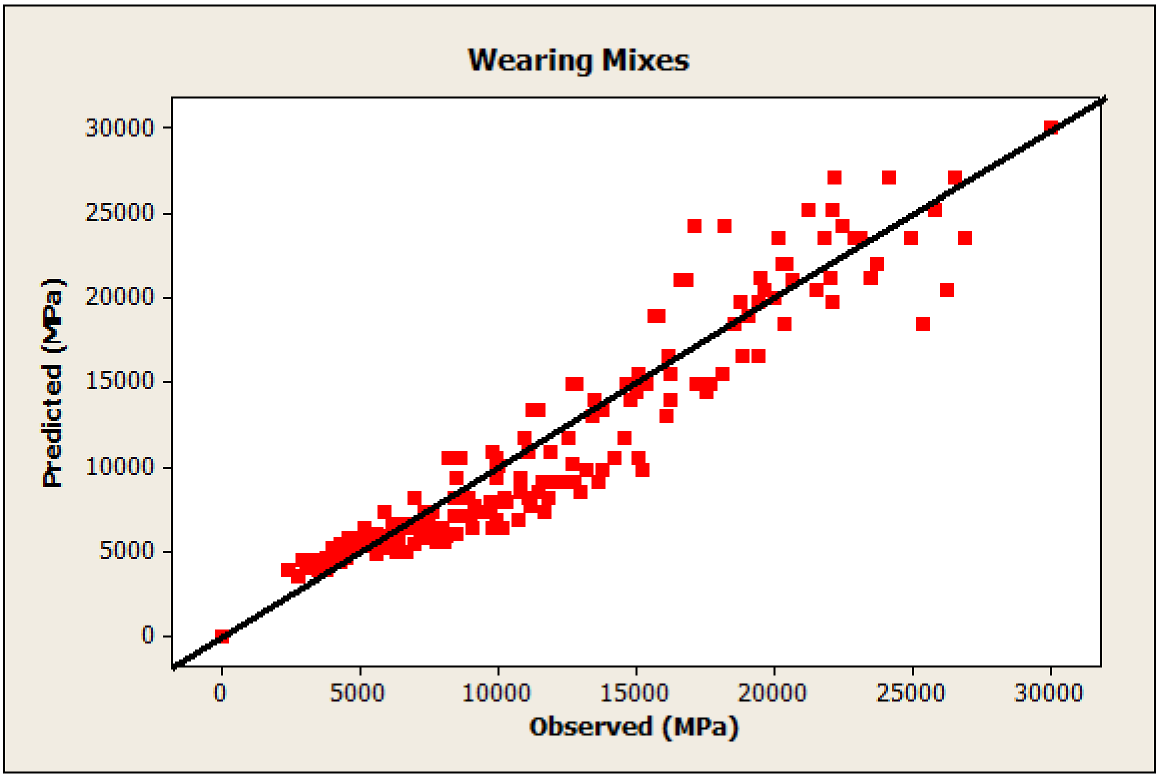


Figure 4.19 Validation plot for wearing course model

The figure 4.20 shows the validation plot for base course model. The MAPE value for base course mixes model is 19%. It can be inferred from the figure that most of values are close to line which defines the model predictive ability.

4.2.5 Sensitivity Analysis

Sensitivity analysis is used to define the impact of different independent variables (Input) on the dependent (Output) under given predefined set of conditions. This analysis is performed under certain boundaries condition which will define for input variable and based on the input variables; sensitivity analysis suggests that how much output is sensitive to specific input variables or change in the input parameters. It can be very useful while testing the robustness of the models or output which is based on the certain input parameters. For this study, the input parameters are the frequency and temperature while output is dynamic modulus.

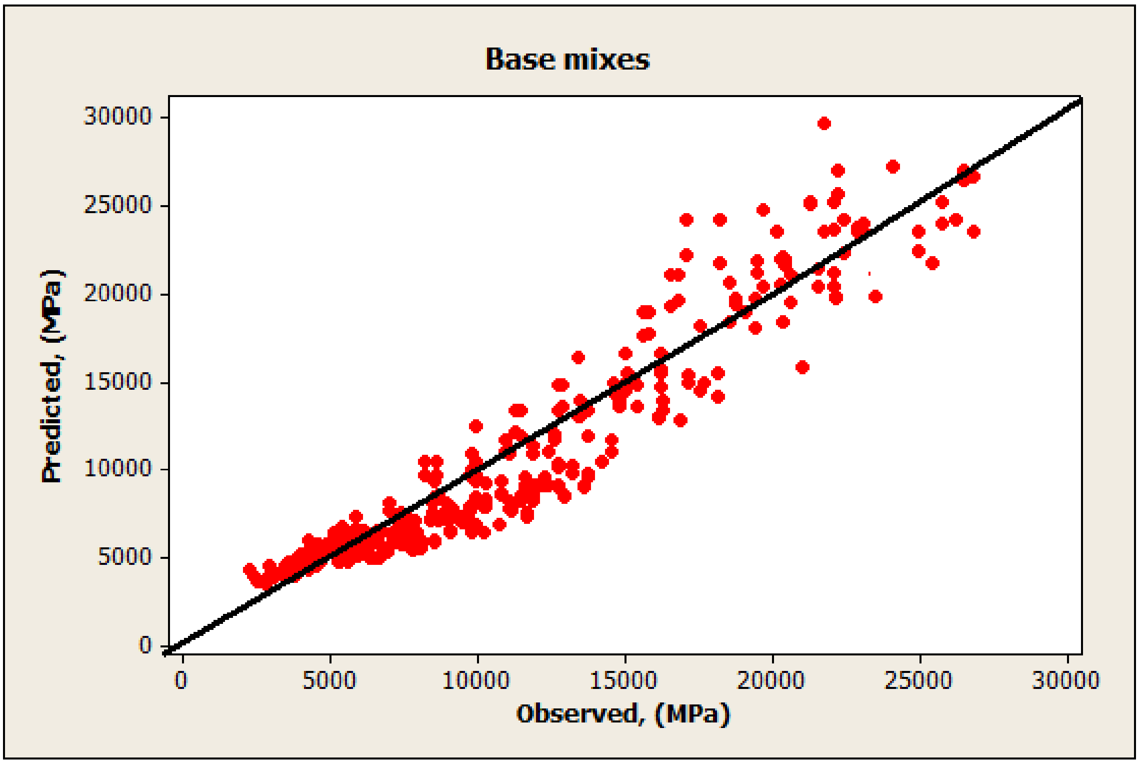


Figure 4.20 Validation plot for base course model

From the test results, it is clear that dynamic modulus has inverse relation with test temperature which means that by increasing the temperature the dynamic modulus ultimately decreases and vice versa and reverse phenomena is being observed in case of frequency; decrease in frequency results in reduction of dynamic modulus values. It has been observed that there is notable variation on dynamic modulus values which suggest that dynamic modulus test is very sensitive to higher temperatures and disposed to errors hence a great care is needed to perform test at higher temperatures and specimens should be left for equilibrium times to conditioned until required test temperatures is obtained. The test should be conducted after achieving the equilibrant time for desired temperature.

Graphically the average test results are expressed in form of isothermal and isochronal curves which conforms the above statement that dynamic modulus decrease to increase in temperature and decrease to decrease in frequency.

It is quite clear from figure 4.21 that dynamic modulus decrease with increase in temperature and increase when frequency is increased. As it is already said in chapter 2 that dynamic modulus is ratio of stress to peak recoverable strain so at lower/colder temperatures it has been observed that dynamic modulus values are significantly higher than other temperatures because strain is prone to temperatures and increased stiffness in colder/lower temperatures while increased flexibility under higher/warmer temperatures. This is reason at 4.4 °C temperature; dynamic modulus is high when as temperature is raised dynamic modulus tends to decrease significantly.

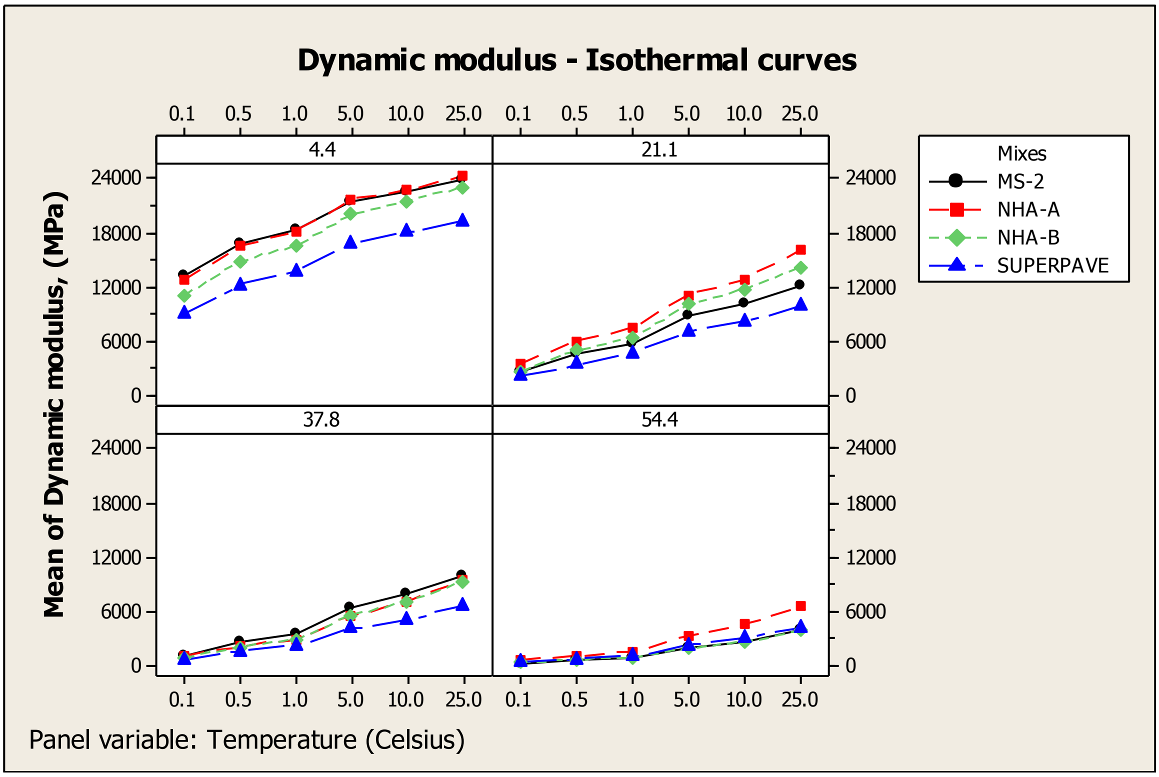


Figure 4.21 Dynamic modulus - Isothermal curves (Wearing course mixes)

It is also observed from above figure 4.22 that at higher frequency or with increase in frequency dynamic modulus increased because of fact that modulus is expressed by stress-strain relationship and higher the loading frequency, lower would be contact time/ pressure of tyre to pavement which ultimately increased dynamic modulus.

The mixes adopted for wearing course has same binder and aggregate source type, only factor varying is nominal maximum aggregate size. It is evident from the graph that NHA-A mix has higher dynamic modulus with equivalent value of modulus of MS-2 mix while rest mixes i-e NHA-B and Superpave mixes has lower dynamic modulus. The NHA-A exhibit higher dynamic modulus values because this mix is coarser in nature which make stronger stone-stone contact among larger aggregates and well coated by finer particles. MS-2 mix shows almost same dynamic modulus value when exposed to lower temperature but significantly drop is observed when temperature is raised which implies that even after NMAS is lesser but at lower temperature dynamic modulus is high which is also because of fact that higher portion of fines content in mix which solidifies the particle to particle bond which fills all the voids and offers high stress/resistance when load is applied.

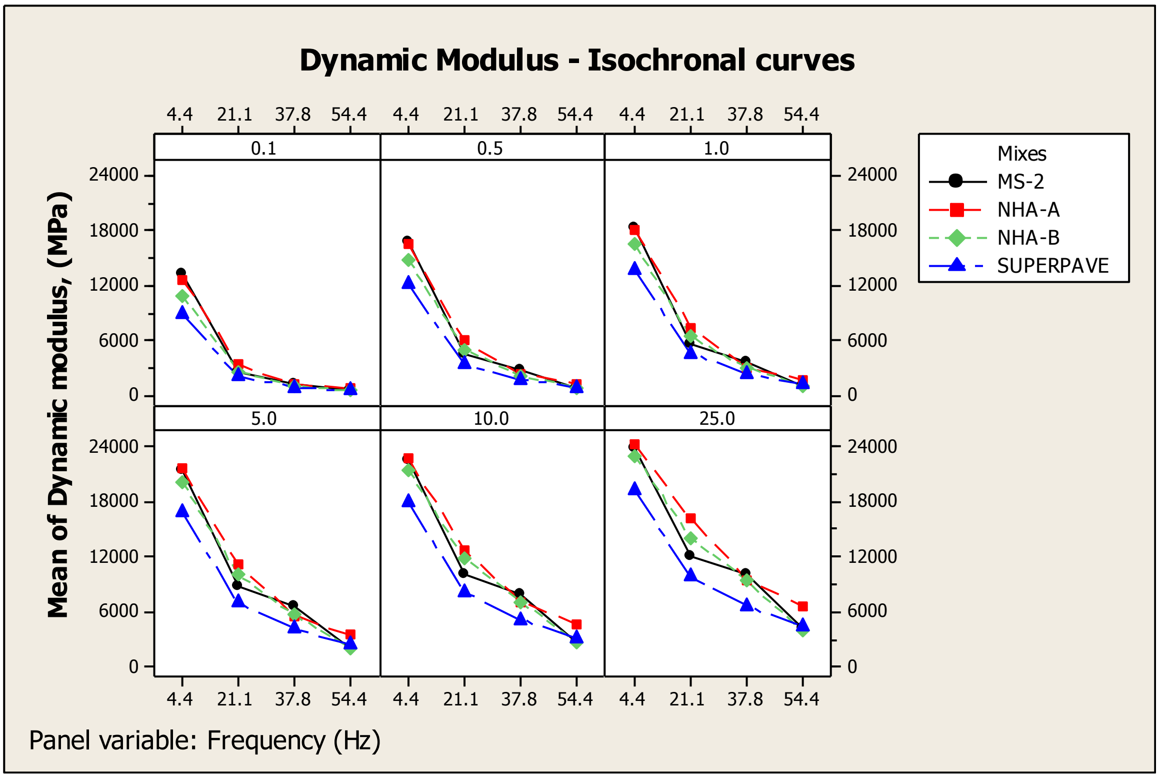


Figure 4.22 Dynamic modulus - Isochronal curves (Wearing course mixes)

It can be seen in figure 4.23 that same trend is exhibited by four different mixes of base course. With increase in temperature, dynamic modulus decreases and with decrease in frequency dynamic modulus also decreases unlike wearing course mixes. From graphs, it is also observed that dynamic modulus of base course is higher in comparison to wearing course mixes due to fact that base course contains higher portion of larger aggregate and offer more resistance to applied load which ultimately increase dynamic modulus. Analogous to wearing mixes, same trend is visualized when temperature is raised from 4.4 to 54.4 °C. At 4.4 °C dynamic modulus is higher compared to rest of test temperatures because strain is prone to lower/colder temperatures and increased stiffness which leads to higher dynamic modulus values and as temperature raises the dynamic modulus drops significantly and great deal of difference in values is observed when temperature is 54.4 °C because of same reason that higher temperatures are more sensitive to errors and strain which is prone to temperature and increased flexibility which causes reduction in dynamic modulus.

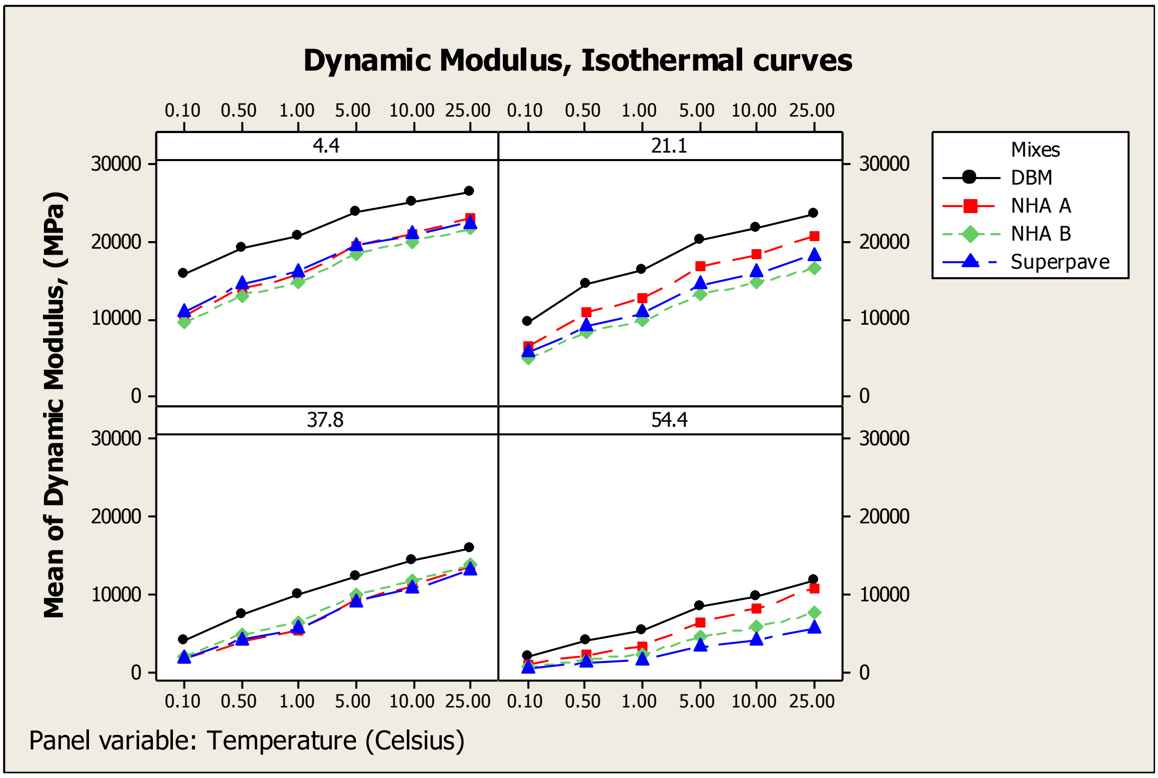


Figure 4.23 Dynamic modulus - Isothermal curves (Base course mixes)

It can be seen in figure 4.24 that same trend is observed analogous to wearing course that with decrease in frequency dynamic modulus decrease and vice versa. The mixes adopted for base course are almost same except MS-2, which is replaced by dense bituminous macadam (DBM). Although three mixes i-e NHA-A, NHA-B and superpave are same but gradation and percentage retained on each sieve is different when compared to wearing course gradations even NMAS change in base course and larger particles are incorporated more. From above both figures, it is clear that DBM mix exhibit higher dynamic modulus at all temperatures and all frequencies because of reason that this mix is in complete balance form in terms distribution of particles as almost 50% of fines are included to 50% of courser particles which form dense and compact mix that offers highest resistance and produces dynamic modulus greater than any other mix. The NHA-A mix which is next to DBM has higher dynamic modulus values and categorization of material in terms of fine and course is 30% and 70% respectively. The NHA-B is next after NHA-A mix then last superpave mix and all these have different proportion of percentage of fines and coarser particles.

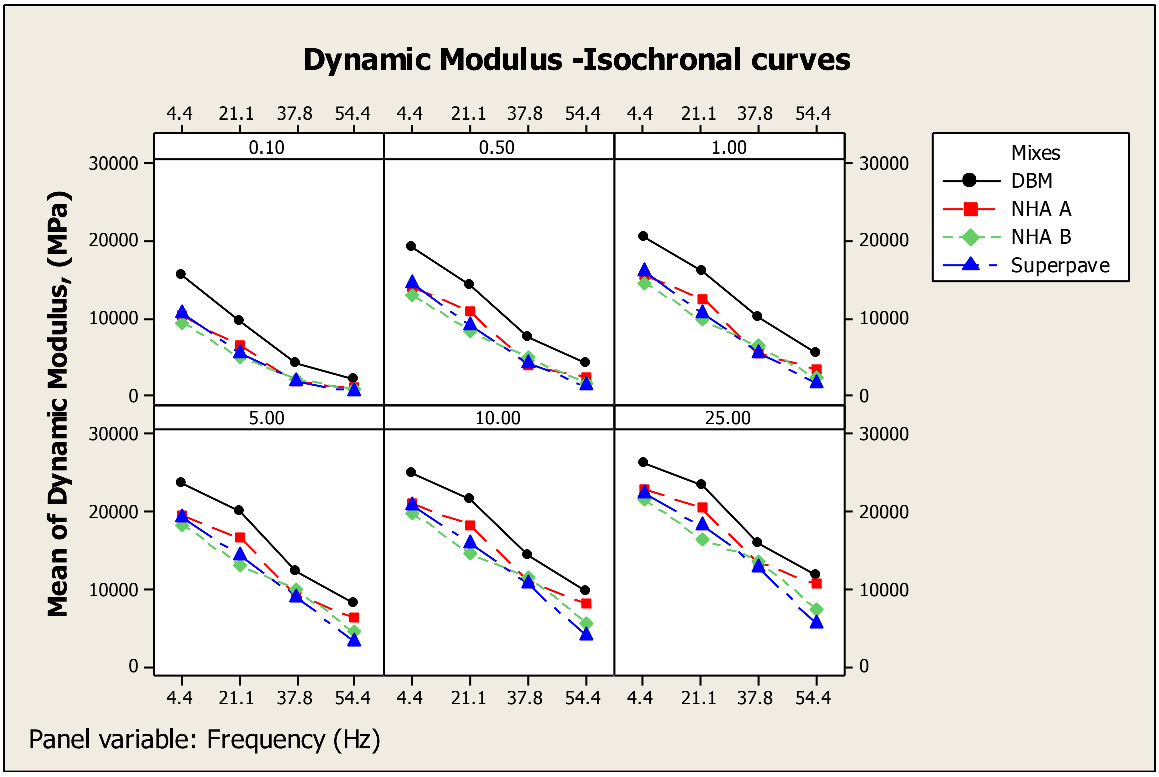


Figure 4.24 Dynamic modulus - Isochronal curves (Base course mixes)

The dynamic modulus variation at each temperature and frequency of four different mixes of wearing course can be best represented by bar chart as shown in figure 4.25. It is evident from figure that at frequency of 25 Hz and temperature of 4.4 °C, NHA-A mix bar is greater than other bars which suggests that it has greater dynamic modulus as compared to other mixes while MS-2 is almost equal to it and same trend can be visualized at frequency of 25 Hz and temperature of 21.1 °C but here MS-2 is below NHA-A and same trend can be seen at 54.4 °C and 25 Hz frequency while at 37.8 °C temperature, MS-2 has greater dynamic modulus than rest of other mixes. The same trend is envisaged at frequency of 10 Hz and at temperature of 4.4 °C as NHA-A mix has comparatively high dynamic modulus than other mixes at said temperature while MS-2 is just equal to NHA-A and at temperature of 21.1 °C, dynamic modulus is leading in comparison to other mixes and same is case at 54.4 °C temperature except 37.8 °C where MS-2 has higher dynamic modulus than NHA-A while other mixes are in follow up. Furthermore, the frequency of 5 Hz and temperature of 4.4 °C provides same picture that NHA-A mix has higher dynamic modulus than other mixes and MS-2 is just equal to it while at same frequency but temperature of 21.1 and 54.4 °C, NHA-A mix has higher dynamic modulus than other mixes including MS-2 while at 37.8 °C, MS-2 mix has higher dynamic modulus than other mixes. The same trend is followed in frequency of 1, 0.5 and 0.1

Hz as dynamic modulus of NHA-A is greater than other mixes at all temperatures except 37.8 °C where MS-2 has higher dynamic modulus than NHA-A and other mixes.

The dynamic modulus of NHA-A mix is significantly higher and can be concluded that NHA-A mix is better wearing course mix as compared to other mixes and reason can explained as this mix has good stone-stone matrix and space in between is filled by fine particles and resulting a compact mixtures which offer significant resistance to applied load resulting in higher dynamic modulus while MS-2 has more of finer particles but are so densely packed with each other surrounded by higher asphalt content with ultimately resulted that dynamic modulus equal to NHA-A mix but at higher temperatures, finer particles seems to be disintegrated as dynamic modulus drops significantly.

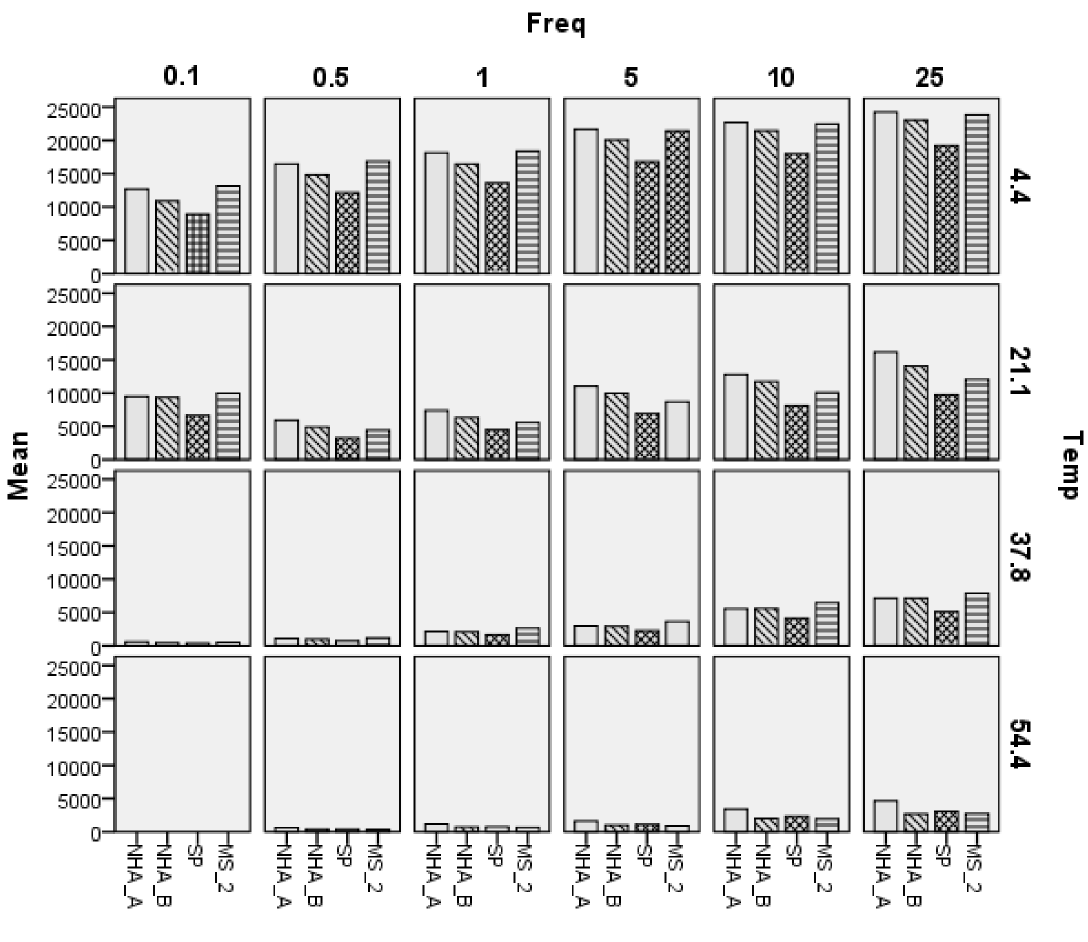


Figure 4.25 Comparison of dynamic modulus test results - Wearing course mixes

The figure 4.26 represents the bar chart for the comparison of the base course mixes at different temperatures and frequencies. It can be inferred from the figure that bar of DBM mix at 4.4 °C temperature and 25 Hz frequency is higher than other mixes bars which suggests that dynamic modulus of DBM mix is higher when it is compared to other mixes. At the same frequency but temperature of 21.1 °C, same trend is visualized as DBM leading while others are following it and similar sort of trend is obtained at same frequency and temperature of 37.8 °C and at higher temperature of 54.4 °C and same frequency DBM mix performs better than other mixes which can be clearly seen in figure given below. At lower frequency of 10 Hz and temperature of 4.4 °C, similar sort of trend is observed as DBM mix ahead of all other mixes and same is case at same frequency but at rest of the temperatures. As frequency is decreased, dynamic modulus is also decreased due to direct proportionality of the dynamic modulus with frequency. Hence at lower frequency like 5, 1, 0.5 and 0.1 Hz and all temperatures, DBM mix has higher dynamic modulus than all other mixes even at higher temperature of 37.8 °C and 54.4 °C, it solely ahead of all others mixes which is evident from the figure.

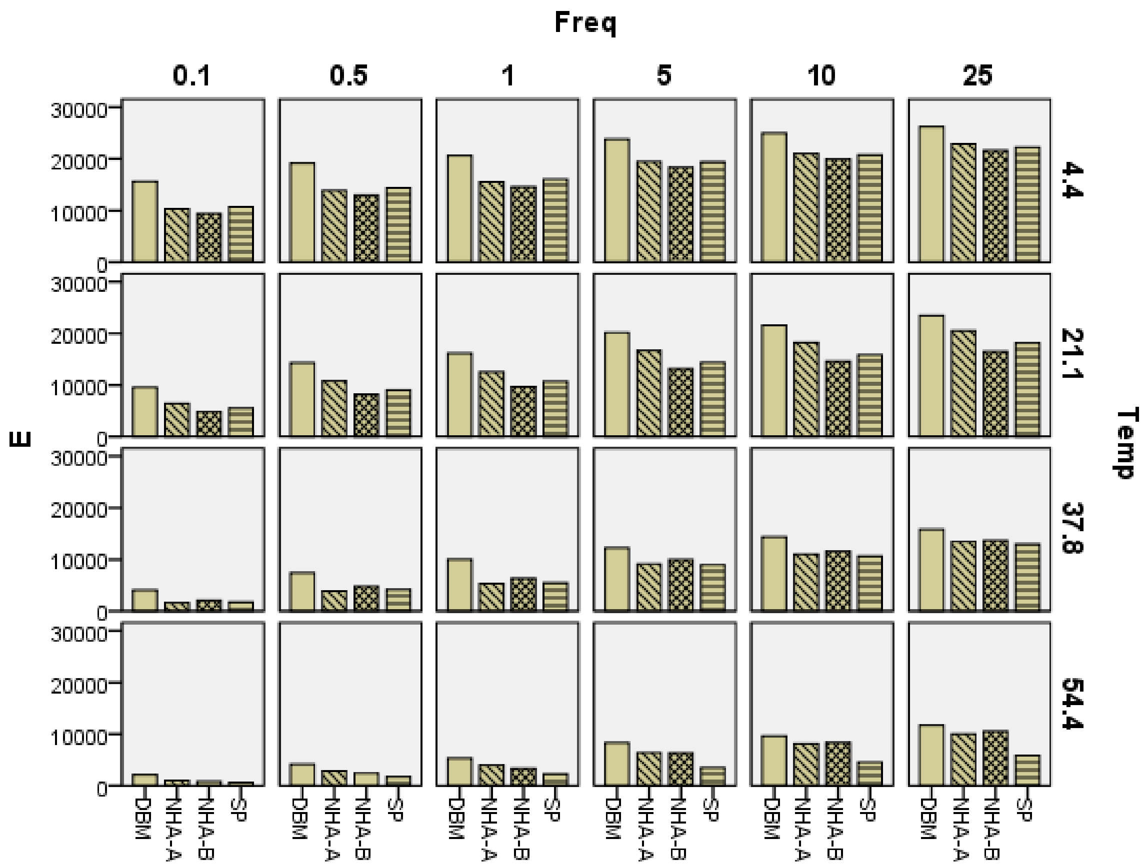


Figure 4.26 Comparison of dynamic modulus test results - Base course mixes

This suggested that DBM mix is lead candidate in dynamic modulus for base course mixes and its reason can be attributed to densely packed mixture in which larger aggregate has stone to stone contact and finer particles plays the role of filling intermediate voids which makes mix more viable and dense such that it offer maximum resistance and resulting higher dynamic modulus than all other base course mixes.

4.2.6 Estimation of Resistance to Fatigue from Dynamic Response

In general, fatigue is phenomena in which material start weakening caused by repeated loading. As material is subjected to repeated loading and unloading, if loading surpass certain threshold, crack initiation starts at surface and material loses strength and bond which ultimately propagate the crack. The dynamic modulus can be used to characterize the fatigue cracking by fatigue parameters ($|E^*| \times \text{Sin}\delta$). If the fatigue parameters ($|E^*| \times \text{Sin}\delta$) value is high, it represents the poor resistance to fatigue cracking and vice versa (Ye et al. 2009).

The figure 4.27 shows the fatigue parameter of wearing course mixes at 21 °C temperature. From figure 4.27, it is clear that NHA-A mix has high fatigue parameter value which means poor resistance to fatigue cracking. The best mix is superpave for wearing course mixes which has lowest fatigue parameter value and highest resistance to fatigue cracking.

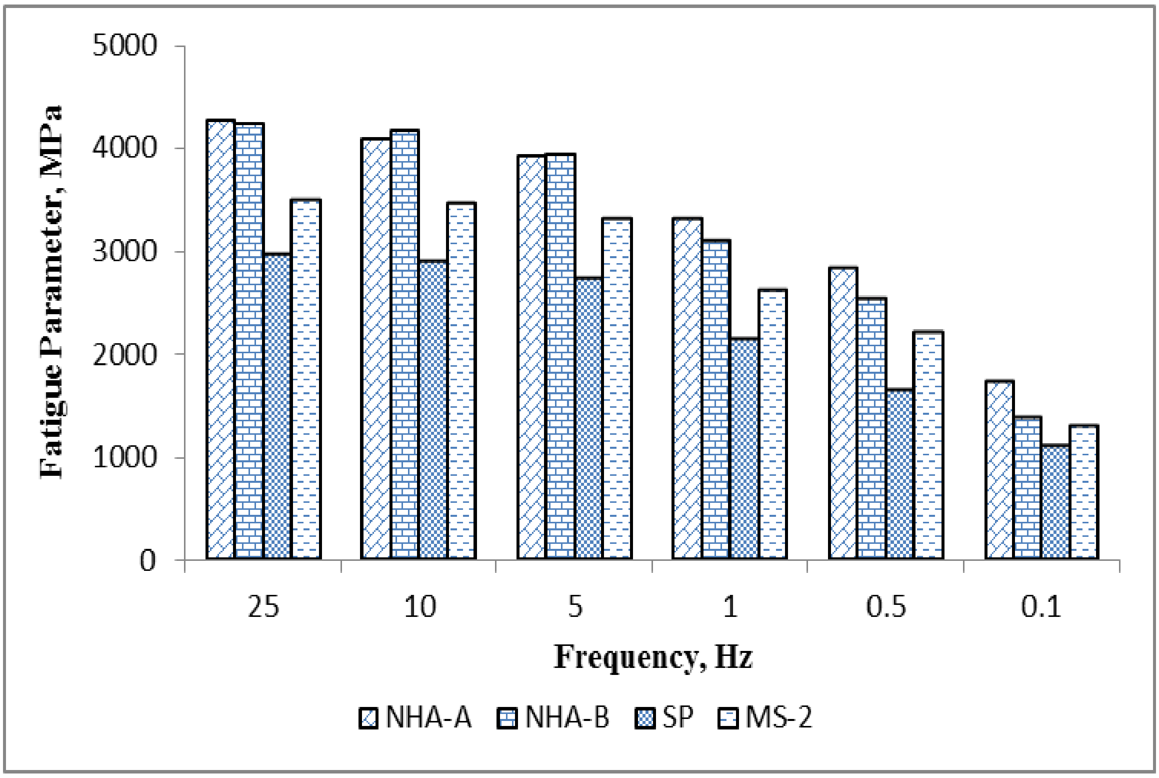


Figure 4.27 Fatigue parameter of asphalt mixture at 21°C - Wearing course mixes

Figure 4.27 illustrates the fatigue parameters of base course mixes at 21 °C temperature. It is evident from figure that DBM mix has highest fatigue parameter value in base course mix which leads to poor resistance to fatigue cracking while NHA-B mix has lowest fatigue parameter value which means NHA-B is less susceptible to fatigue cracking.

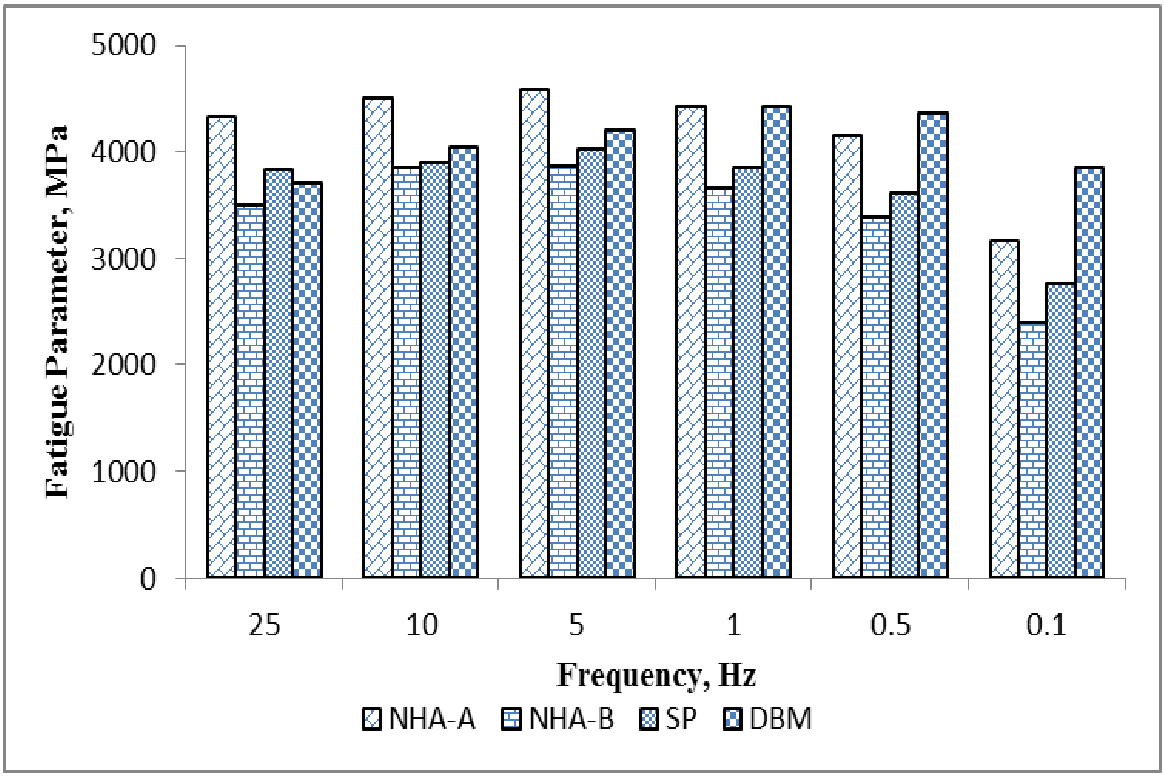


Figure 4.28 Fatigue parameter of asphalt mixture at 21°C - Base course mixes

4.3 Phase Angle Results

The phase angle can be defined as it is angle to which axial strain lags behind the compressive stress. The complete results of phase angle in tabular form are presented in appendix C for both wearing and base course mixes. From obtained results, it was observed that initially phase angle increase with increase in temperature and decreases with increases in frequency. However, this seems to be deemed fit until temperature crosses 37.8 °C as the phase angle tends to behave oppositely and tends to decreases with increase in temperature and decreases with decrease in frequency. This trend can be best represented in figure 4.29. It is clear from figure that phase angle initially increases with increase in temperature and after reaching maximum value, it tends to decrease. It is evident from that at lower temperatures, phase angle also increase with increasing dynamic modulus which suggests that most of energy is attributed to viscoelastic behavior of HMA. Viscoelastic behavior is mainly dependent on the elastic and viscous part i-e binder hence the initial relationship of increase in phase angle with increase in temperature at higher frequencies can be attributed to viscous part because it follows the trend of binder and dependent on the binder. However, it is observed that at higher temperature and low frequency phase angle tends to decrease because of aggregate influence. The phase angle at high temperature and low frequency is affected by aggregate and most of energy is attributed to viscoelasticity which tends to decrease the phase angle. Hence, this suggests that effect of aggregate is more pronounced at higher temperatures as compared to binder which completely describes its mechanical response.

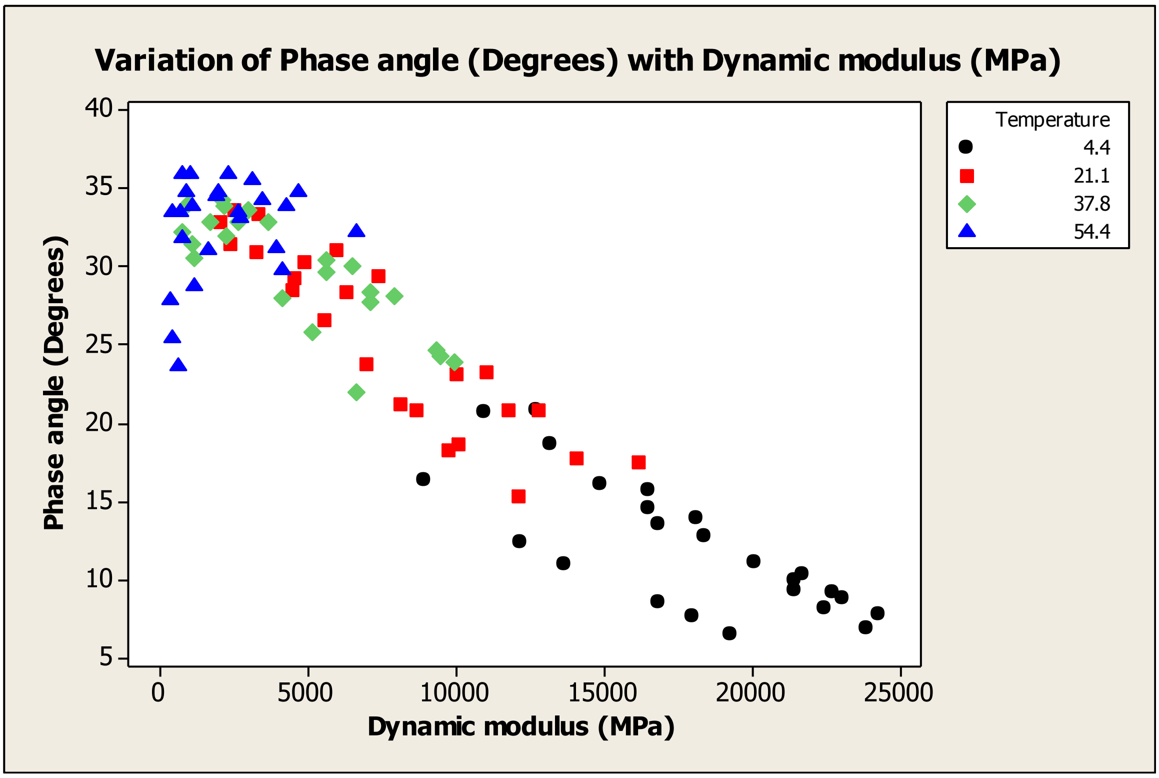


Figure 4.29 Variation of phase angle with dynamic modulus - Wearing course mixes

It can be inferred from figure 4.29 that the phase angle increases with dynamic modulus upto 37.8 °C which shows that wearing course mixes are enrich in binder content because of finer particles and large surface area which requires greater amount of bitumen content. Hence at higher temperature, more energy is dissipated and phase angle is decreased due to high binder content.

The figure 4.30 illustrates that initially phase angle for base course mixes increases with increase in dynamic modulus at lower temperatures and this can be best explained by viscoelastic behavior of HMA. It can also inferred from same figure that at higher temperatures phase angle drastically drops down which is explained by the influence of large aggregate and lower binder content because base course mixes generally have less binder content in comparison of wearing course mixes. This is in agreement with the findings of past researches that concluded that the elastic behavior of the aggregate dictates the response of the HMA at high temperatures and low frequencies (Pellinen, & Witczak 2002; Clyne et al. 2003; Flinstch et al. 2007).

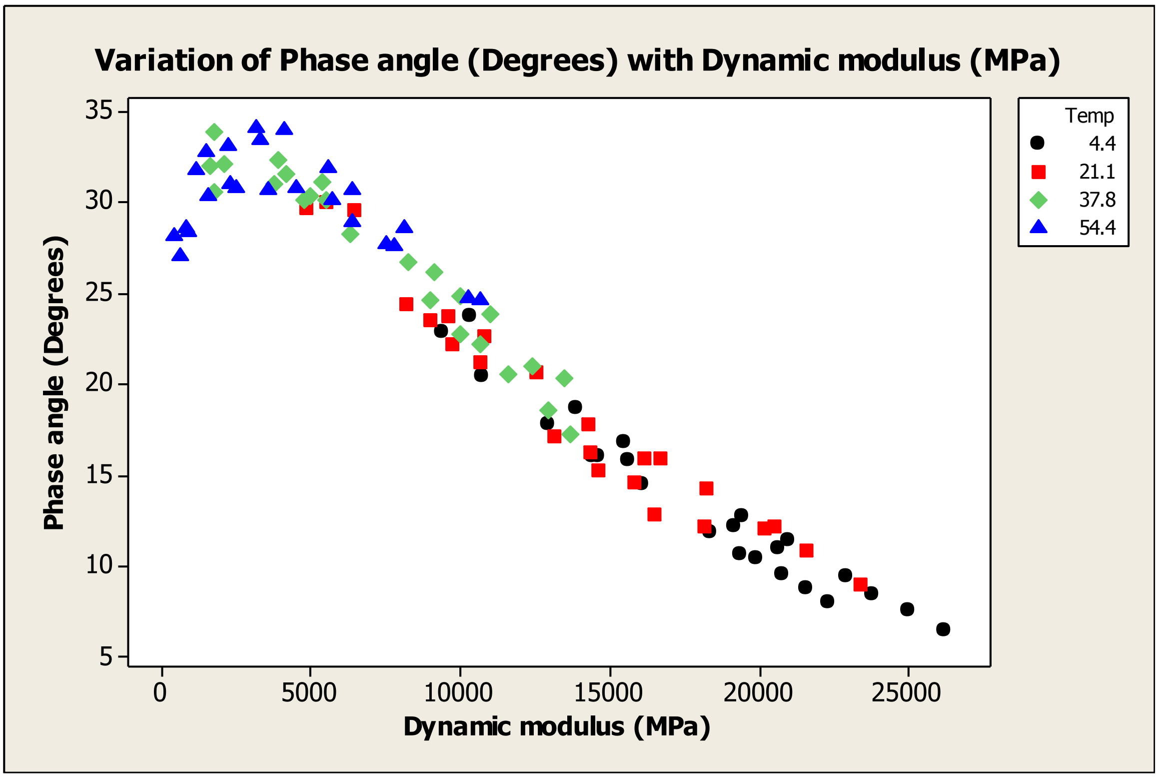


Figure 4.30 Variation of phase angle with dynamic modulus - Base course mixes

4.3.1 Two level Factorial Design for Phase Angle

The same procedure is adopted for factorial design of phase angle which is earlier adopted for dynamic modulus. The response variable is phase angle and factors used for said analysis is same as illustrated in table 4.2. The estimates of main effects and interaction effects for wearing course mixes are presented in table 4.9.

Table 4.9 Effect Estimates for Phase Angle - Wearing Course Mixes

One factor			Two Factors			Three factors		
Main factors	**Effects**	**p-value**	**Interaction**	**Effects**	**p-value**	**Interaction**	**Effects**	**p-value**
Temp	22.057	0	Temp*Freq	4.436	0.022	Temp*Freq *NMAS	-0.713	0.708
Freq	-7.959	0	Tem*NMAS	0.195	0.903			
NMAS	-1052	0.377	Freq*NMAS	-0.349	0.806			

It can be observed from table 4.9 that temperature has direct relation with phase angle for wearing course mixes as it is described by positive arithmetic sign while frequency is inversely related to phase angle. The NMAS is insignificant parameter as its p-value is greater than α = 0.05 which is assumed for this experiment hence it lies in fail to reject zone and proved to be insignificant. The 2-way interactions of temperature, frequency is significant while other two way interactions are insignificant as it can be seen by their higher p-value than α = 0.05. The 3-way interaction is also insignificant as its p-value is also on the higher side.

The table 4.10 describes the two level factorial design for base course mixes. A similar kind of trend is observed like wearing course mixes. The temperature has direct relation to the phase angle while frequency has negative relation which is illustrated by its arithmetic sign. These both are significant parameters as its value is less than α = 0.05 which implies that it falls in rejection zone and variable is significant at given degree of confidence while NMAS is again proved to be insignificant indicated by its higher p-value. The all 2-way interactions of temperature, frequency and NMAS are insignificant and same is case for 3-way interaction as its p-value is greater than α = 0.05 which falls in the fail to reject zone and proved to be insignificant.

Table 4.10 Effect Estimates for Phase Angle of Base Course Mixes

One factor			**Two Factors**			**Three factors**		
Main factors	**Effects**	**p-value**	**Interaction**	**Effects**	**p-value**	**Interaction**	**Effects**	**p-value**
Temp	17.894	0	Temp*Freq	2.478	0.122	Temp*Freq	0.703	0.659
Freq	-9.820	0	Tem*NMAS	-1.642	0.220	*NMAS		
NMAS	0.784	0.431	Freq*NMAS	-0.885	0.457			

The table 4.11 illustrates the analysis of variance for phase of wearing course mixes from observed data. The higher value of *F* represents the significance of factors. It is evident from table that main effect is significant as its p-value is less than α = 0.05 and value *F* is greater than 10 while 2-way and 3-way interaction proved to insignificant as represented by low value of *F* and high p-value. The degree of freedom for main effect is three (03) which shows that three factors are explaining the variation in response variable i-e temperature, frequency and NMAS.

The table 4.12 illustrates that analysis of variance (ANOVA) for base course mixes. It is evident from the table that main effect is significant as represented by higher value of *F* and low p-value while 2-way and 3-way interactions are insignificant as their p-value is less than α = 0.05 which suggests that it falls in fail to reject zone and proven to be insignificant. The degree of freedom for main effect is three (03) which is already described that three factors are explaining the response.

Table 4.11 ANOVA for Phase Angle - Wearing Course Mixes

Sources	DF	Sum Of Sq	Mean Sum of Sq	*F*	P
Main Effects	3	4027.61	1342.54	74.82	0
2-Way Interaction	3	104.04	34.68	1.93	0.130
3-Way Interaction	1	2.54	2.54	0.14	0.708
Residual Errors	88	1578.94	17.94		
Pure Error	48	155.67	3.24		
Total	95	7702.99			

Table 4.12 ANOVA for Phase Angle - Base Course Mixes

Sources	DF	Sum Of Sq	Mean Sum of Sq	*F*	P
Main Effects	3	3259.89	1086.63	86.53	0
2-Way Interaction	3	74.66	24.89	1.98	0.123
3-Way Interaction	1	2.46	2.46	0.20	0.659
Residual Errors	88	1105.15	12.56		
Pure Error	48	277.81	5.79		
Total	95	6316.77			

The figure 4.31 represents the cumulative probability plot for wearing course mixes which describes the significance of various factors incorporated in the study at 95% confidence interval. From figure, it can be inferred that standardized main effect of temperature and frequency is significant factor and all 2-way interactions are insignificant. The NMAS is insignificant which does have any significant effect on the phase angle. However, the 3-way interaction of temperature, frequency and NMAS is also insignificant and same is illustrated by the low value of *F* and high p-value presented in table 4.8 and 4.10.

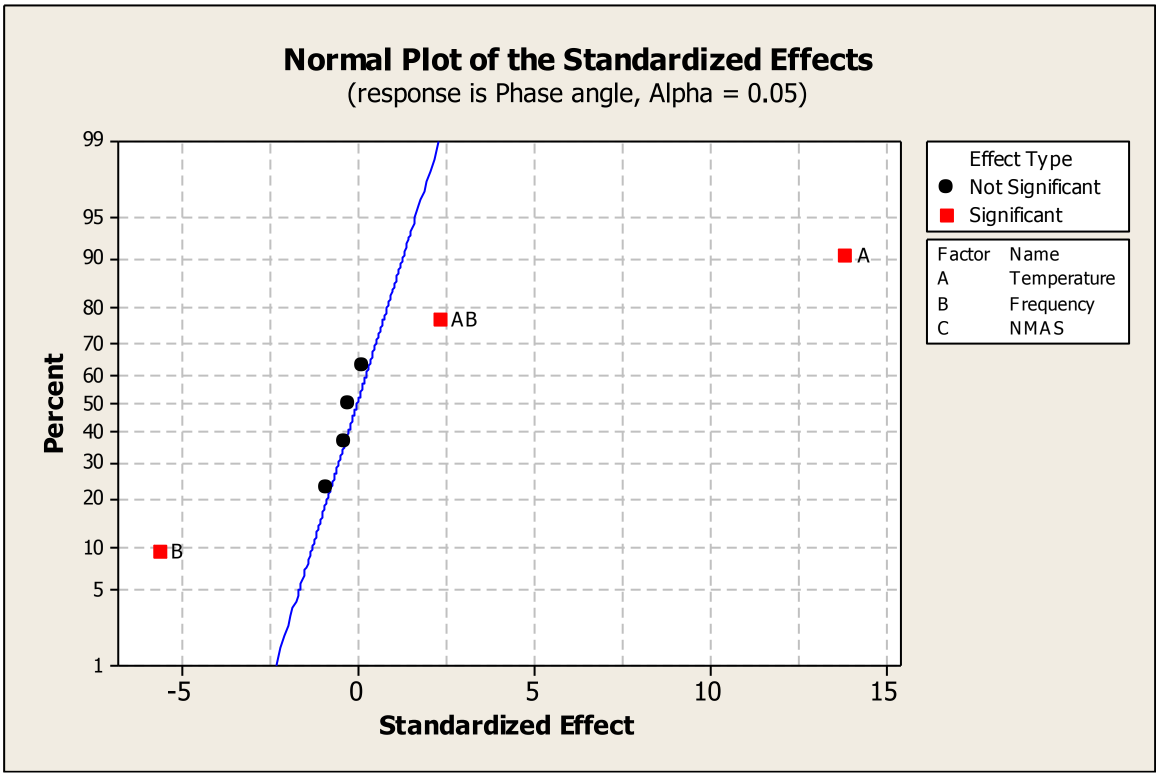


Figure 4.31 Cumulative normal plot for phase angle - Wearing course mixes

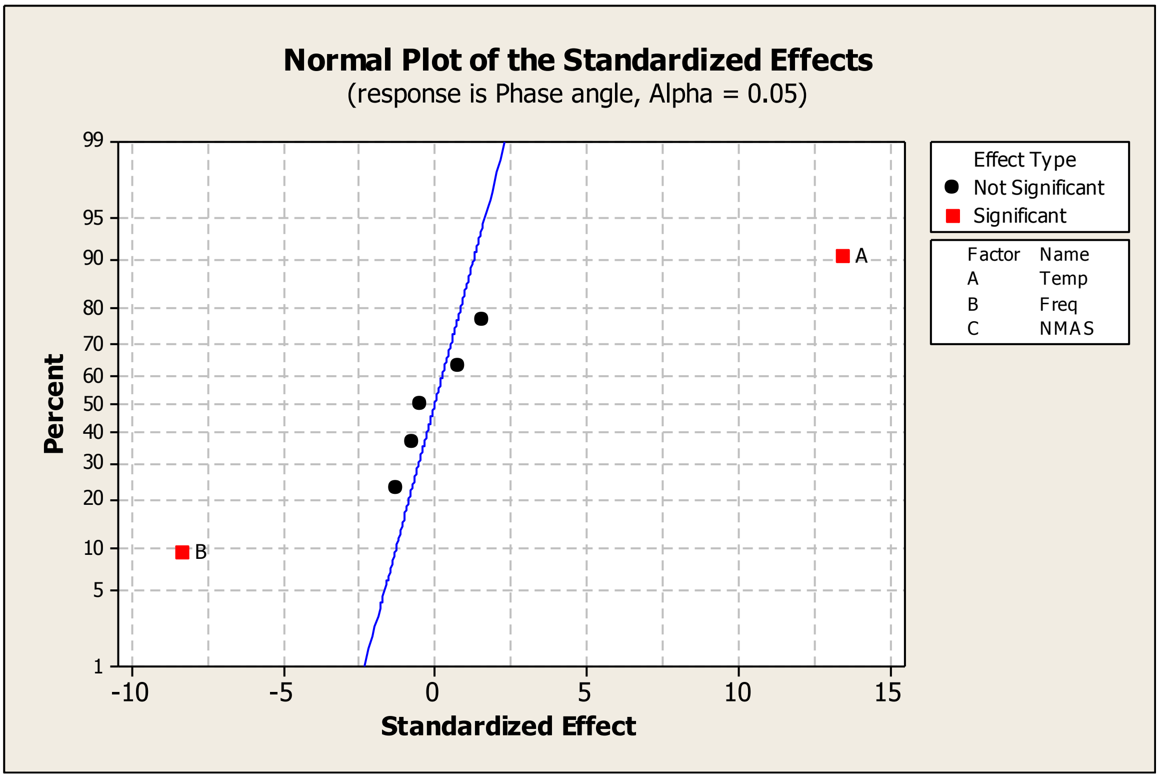


Figure 4.32 Cumulative normal plot for phase angle - Base course mixes

The figure 4.32 shows the cumulative probability plot for standardized main and interactions effects for base course mixes. It is evident from figure that main effect temperature, frequency is significant as denoted by red dot while NMAS is insignificant factor represented by black dot. The 2-way interactions are also insignificant as suggested by figure and same is case for 3-way interactions which conforms the by higher p-value and low *F* value already illustrated in table 4.9 and 4.11.

The figure 4.33 symbolizes the main effect plot for wearing course mixes which illustrates the significance of factor influencing the phase angle. The slope of line shows the strength of relationship/effect of factors i-e temperature, frequency and NMAS on the dependent variable i-e phase angle. The dependency of factor on the response can be estimated by sharpness of the slope of line. From figure it is clear that temperature has highest effect on the phase and frequency also effect the phase angle while NMAS has little or no significant influence on the phase angle as the line has almost no slope.

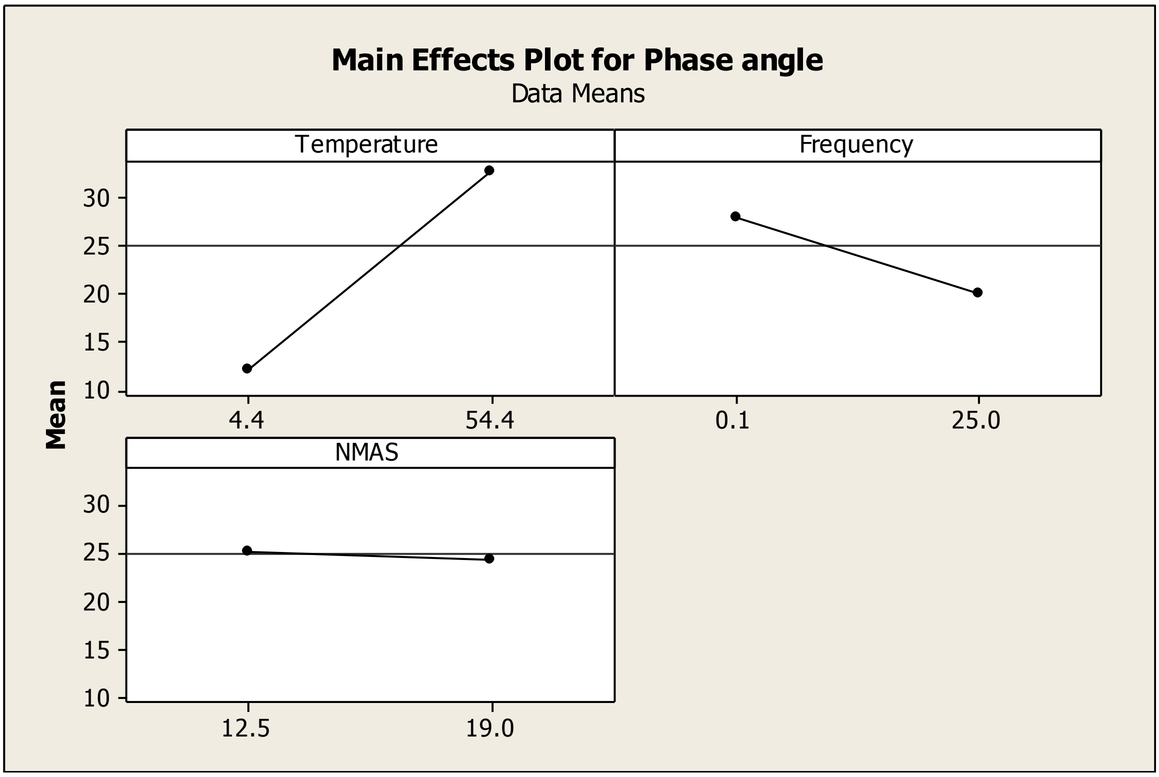


Figure 4.33 Main effect plot for phase angle - Wearing course mixes

The figure 4.34 shows the main effect plot for base course mixes which clearly defines the significance of various factors affecting the phase angle. As it is already described the slope of line indicates the influence of factors i-e temperature, frequency and NMAS on the response variable i-e phase angle. The figure provides clear evident that the temperature has sharpest slope line which means it is most significant factor and affects the phase angle. However, the frequency is also significant factor having influence on phase angle as suggested by the slope of line represented in figure while NMAS seems to be insignificant have less or no effect as its slope of line is almost zero and denoted by straight line.

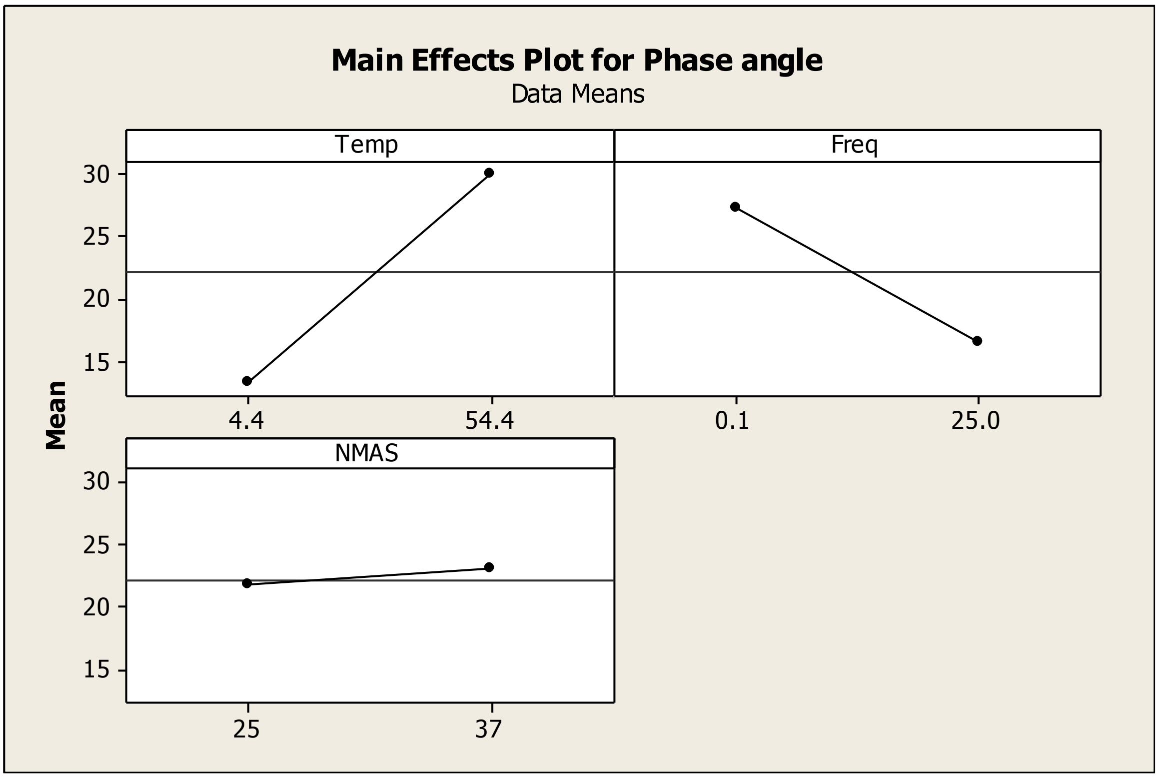


Figure 4.34 Main effect plot for phase angle - Base course mixes

The figure 4.33, 4.34 presents the main effect plot which clearly defines the influence of various individual effects on the phase angle. However, to know the interaction effect on these factors on phase angle, it is necessary to understand which is subsequently displayed in figures 4.35 and 4.36.

From interaction plot of wearing course mixes illustrated by figure 4.35, it is clear that temperature and frequency has significant influence on the phase angle as it can be observed from non-parallel lines while rest of the interactions i-e temperature & NMAS and frequency & NMAS are insignificant as it is represented by the parallel line which shows that it has no effect on the phase angle.

The figure 4.36 represents the interaction of factors that influence the phase angle of base course mixes. The figure indicates that there is no any significant influence of interaction of factors on the phase angle as the lines do not show any non-parallel trend which suggest that all interaction effects are insignificant.

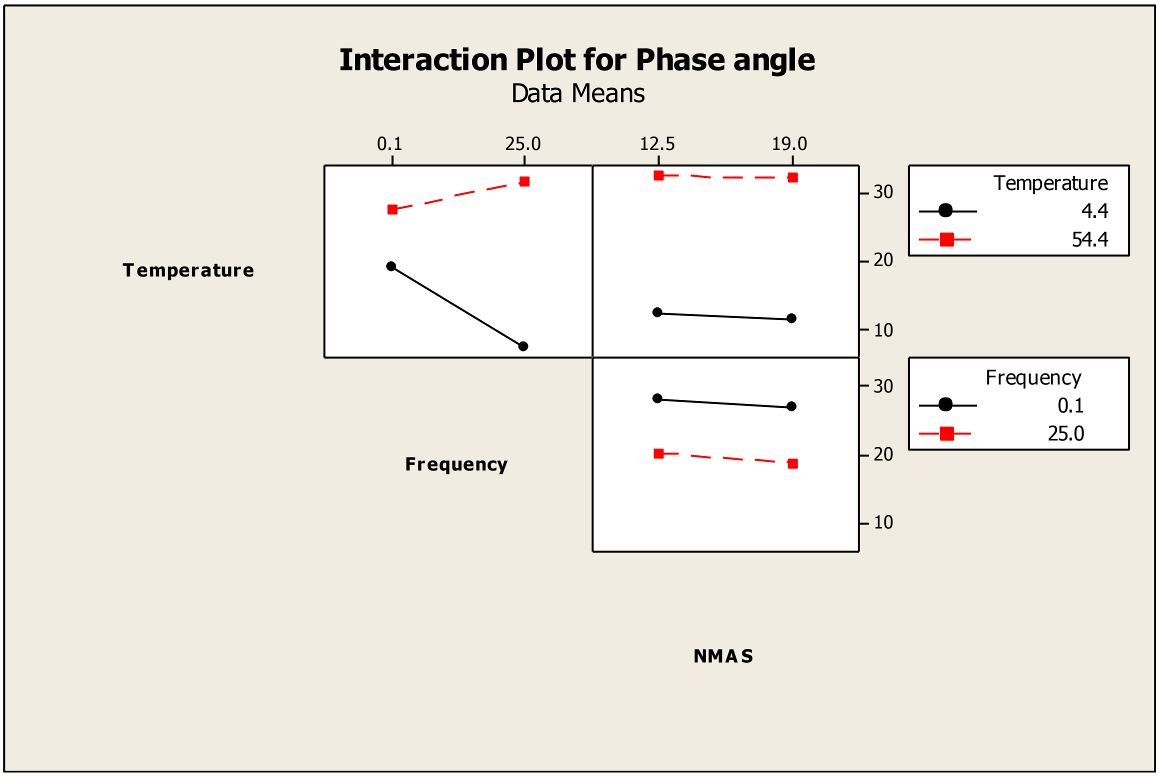


Figure 4.35 Interaction effect plot for phase angle - Wearing course mixes

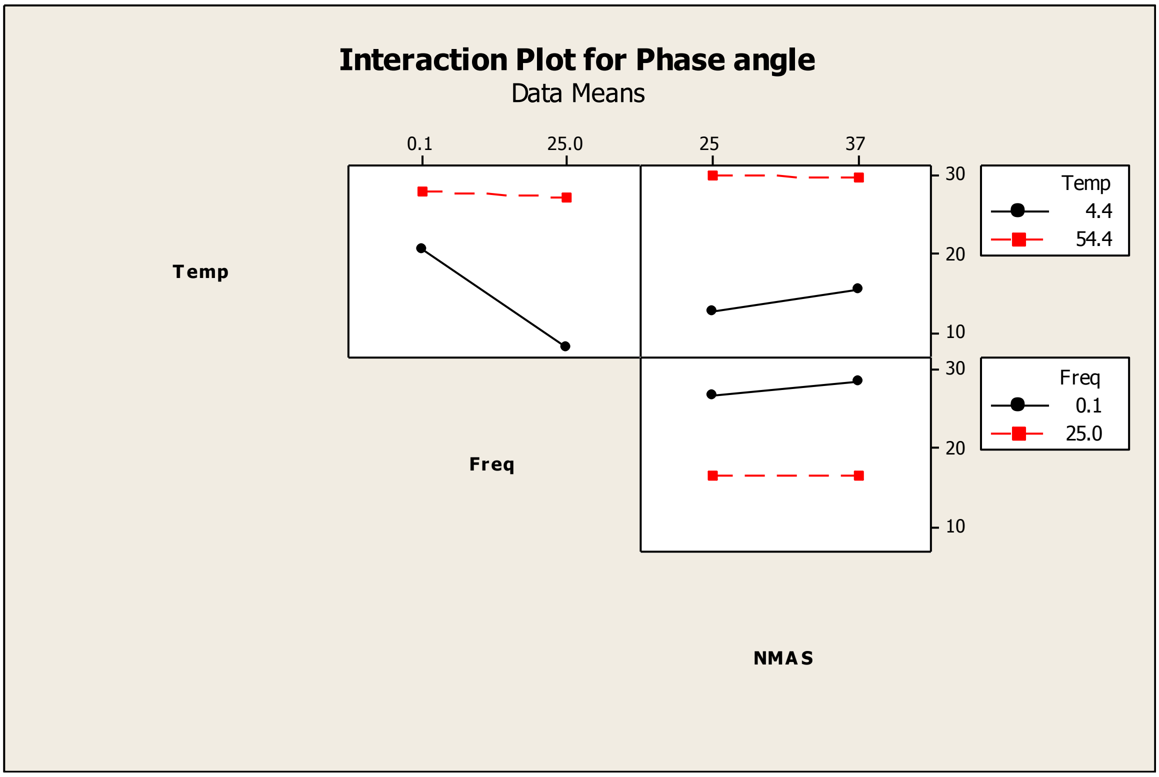


Figure 4.36 Interaction effect plot for phase angle - Base course mixes

As it is clear from the cumulative normal plot and main & interaction plot that which factors are affecting the phase angle. So for better understanding, the pareto chart is presented which describes the significant variable by bar crossing the 95% confidence interval reference line.

The figure 4.37 illustrates the pareto chart for wearing course mixes which indicates the significance of variables i-e temperature, frequency, NMAS and interaction effects also. This figure indicates that temperature barscrosses the reference line and denotes that temperature is significant factor affecting the phase angle while frequency also affects as its bar also crossing the reference line and NMAS is insignificant factor which does not cross the reference line and conforms the main effect plot. The 2-way interaction of temperature and frequency is also significant as bar is crossing the reference line while all other 2-way and 3-way interactions are insignificant as their bars are well behind the reference which also conforms the interaction plot estimates.

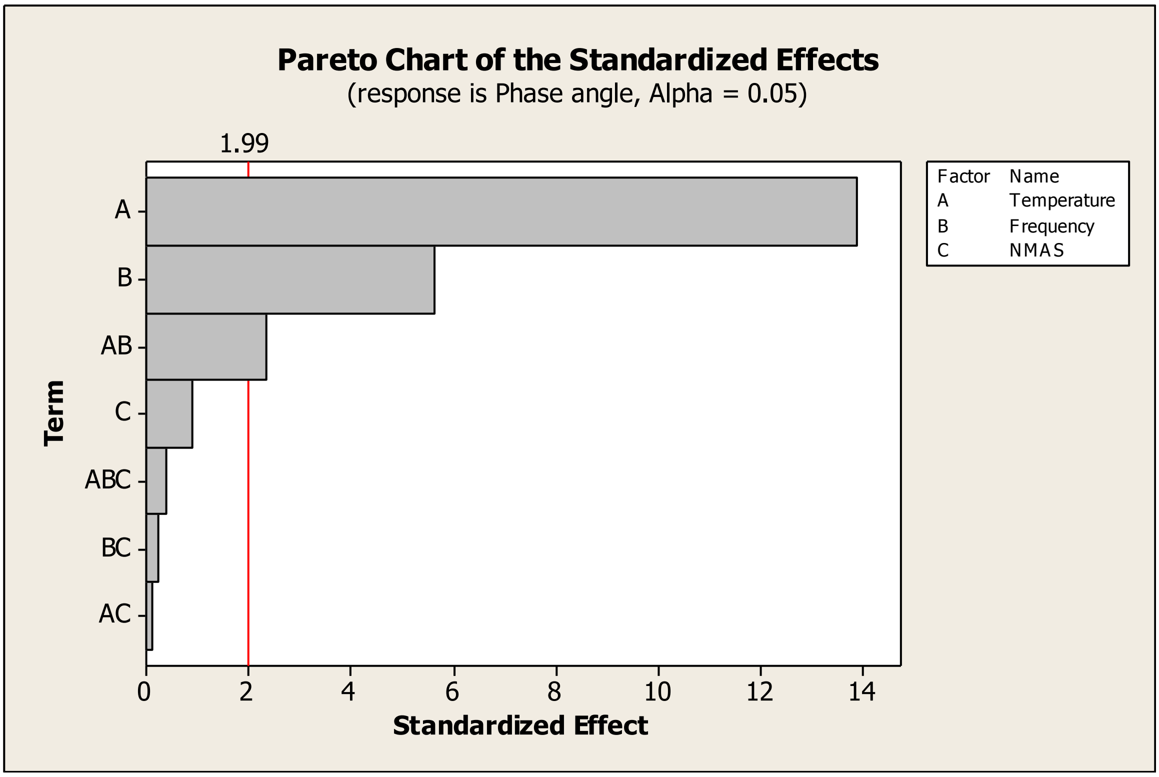


Figure 4.37 Pareto chart for phase angle - Wearing course mixes

The figure 4.38 represents the pareto chart for phase angle of base course mixes which gives clear picture of significant variables which have influence on phase angle. The confidence level is kept same i-e 95% and reference line is demarcation line between significant and insignificant variable. This figure indicates that temperature has highest effect on phase angle as it crosses the reference line far ahead of it while frequency is also significant factor less than temperature as its bar crosses the reference line also while NMAS is behind line which means it has no effect on phase angle and same is true for all 2-way interactions and 3-way interaction as none of any bar make it to other side of the reference line which indicates their insignificance.

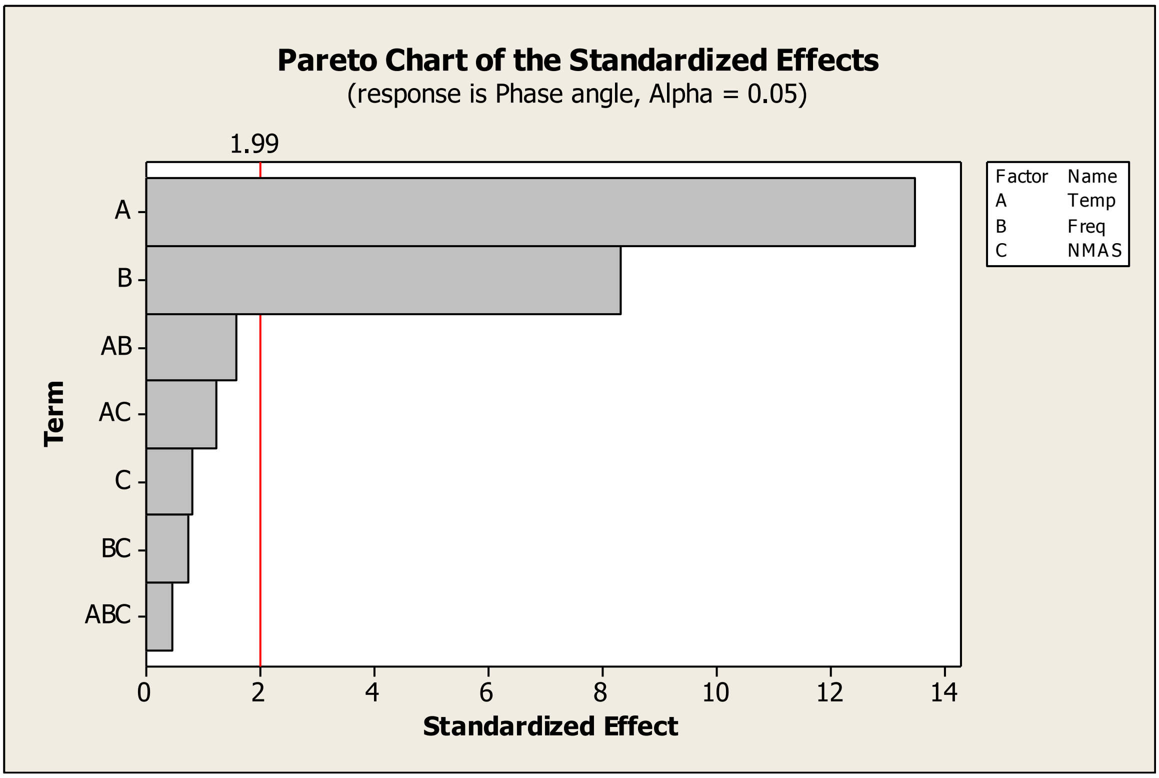


Figure 4.38 Pareto chart for phase angle - Base course mixes

The cube plot is very helpful while determining the highest value of phase angle to the respective temperature and frequency. The figure 4.39 shows cube plot of 3-way interaction for wearing course mixes which indicates that lowest phase can be obtained at 4.4 °C with NMAS of 19 mm and loading frequency of 25 Hz i-e 6.83^o while the highest phase angle would be at temperature of 54.4 °C with NMAS of 12.5 mm and loading frequency of 25 Hz i-e 32.49^o.

The figure 4.40 illustrates the same trend of cube plot of base course mixes analogous to wearing course mixes. In this case, lowest value of phase angle 7.74^o in correspondence to 4.4 °C temperature, 25 Hz frequency and NMAS of 25mm while highest phase angle is noted as 28.62^o against the temperature 54.4 °C, frequency of 0.1 Hz and NMAS of 37.5 mm.

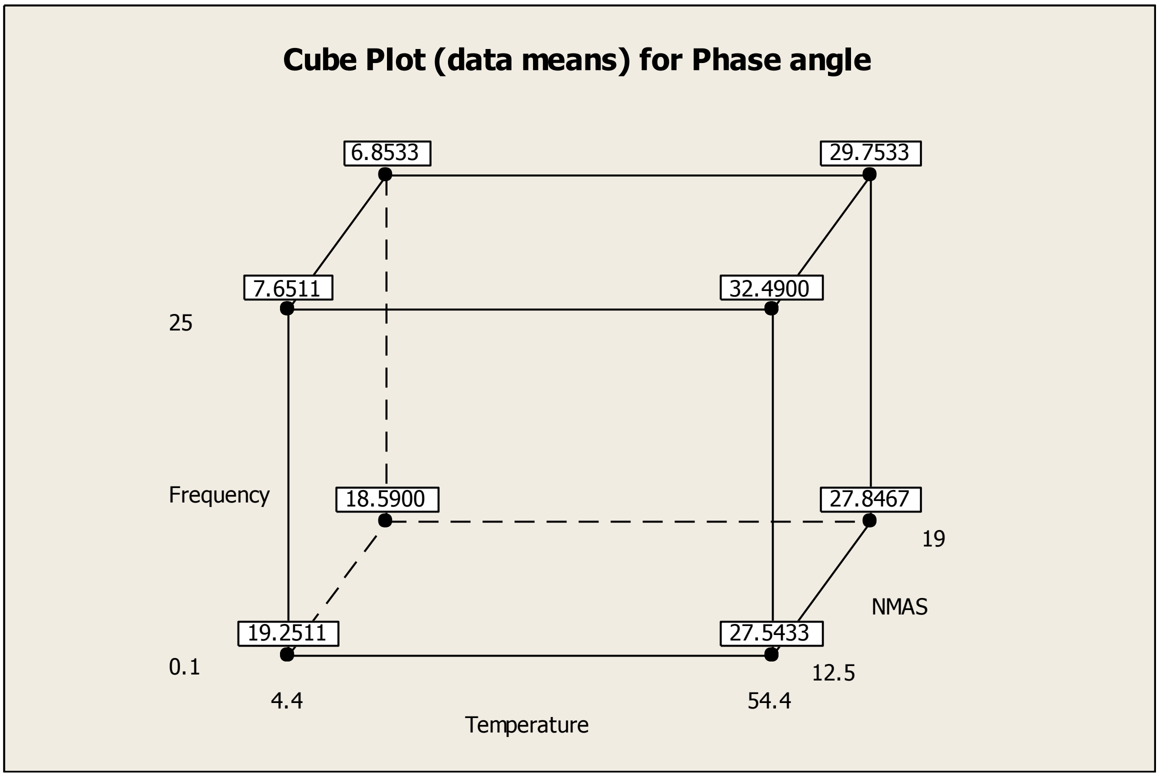


Figure 4.39 Cube plot of 3-way interaction for phase angle - Wearing course mixes

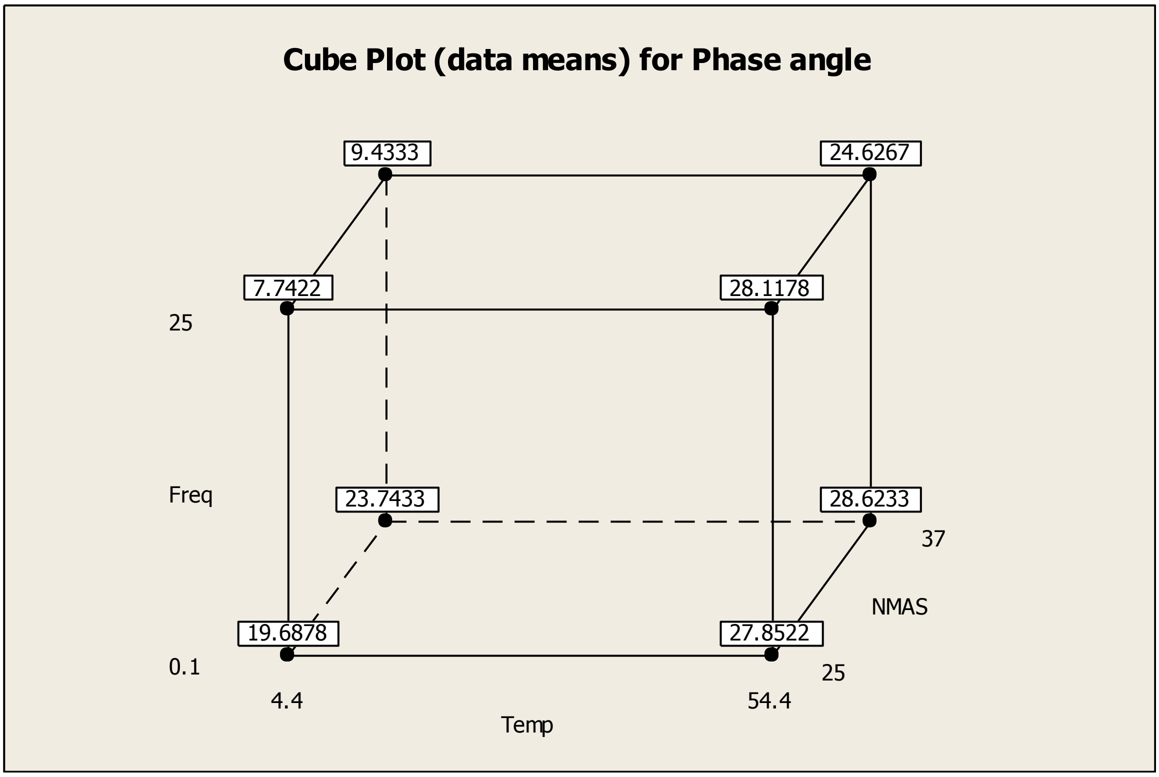


Figure 4.40 Cube plot of 3-way interaction for phase angle - Base course mixes

The trend of phase angle with frequency and temperature can be best represented by the isochronal and isothermal curves respectively. The phase angle increases with decrease in frequency at temperature of 4.4 and 21.1 °C while at 37.8 °C temperature, phase angle tends to reduce and same is case at 54.4 °C where significant drop is observed and it can also be inferred that at lower temperatures, phase angle of mixes lean towards elastic part while at higher temperatures it tends to be on viscous part. From figure 4.41, it is clear that superpave mix has higher phase angle at lower temperatures and tends to elastic in nature while at higher temperature it tends towards viscous part which is attributed to binder and superpave mix has higher asphalt content as compared to other mixes which is reason superpave has higher phase angle and tends to drop less at higher temperatures as compared to other mixes. It is also evident from figure that at lower temperature, phase angle of superpave mix is higher than other mixes and MS-2 is following it and likely so because it has also asphalt content close to superpave mix.

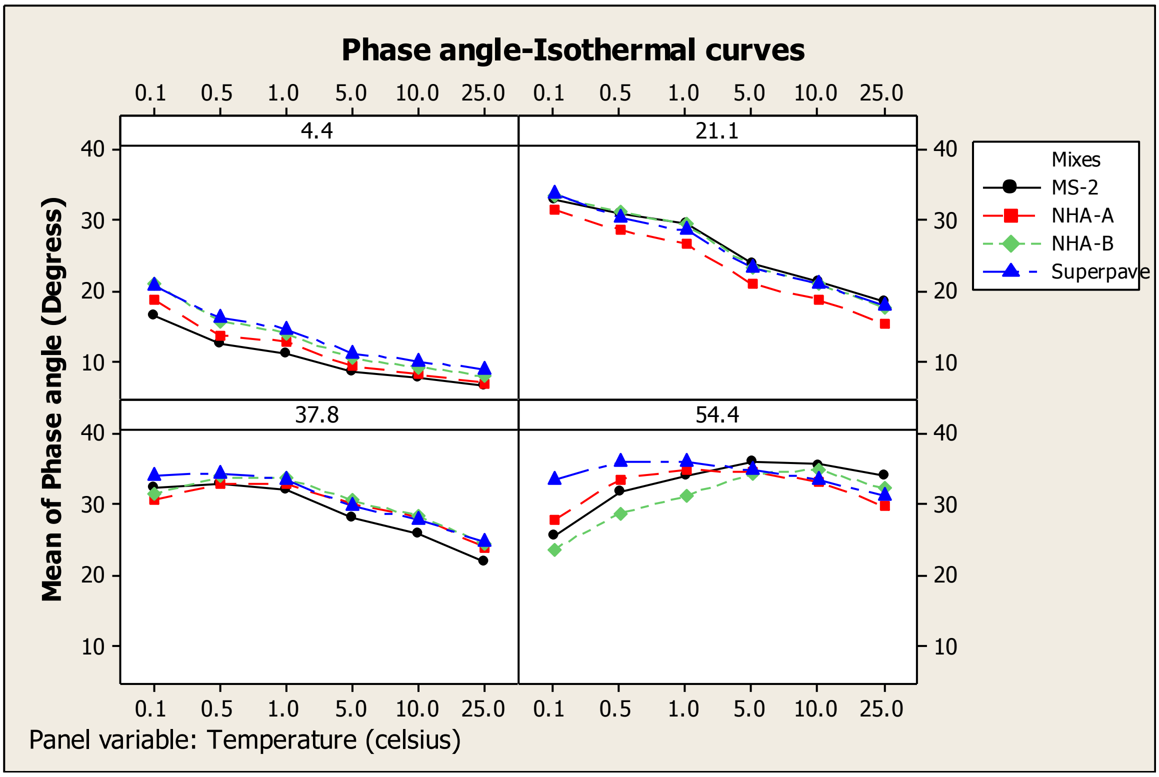


Figure 4.41 Phase angle-Isothermal Curves (Wearing course mixes)

The figure 4.42 shows the isochronal curves which illustrates the variation of different temperatures at single frequency. This figure helps to conform the above said statement that at lower frequencies and higher temperatures, superpave mix tends to behave viscous while phase angle of other mixes drops significantly. This trend can be seen in 0.5 and 0.1 Hz frequency panel where Superpave mix curve is significantly higher than other mixes. It can also be inferred from same figure that drop in phase angle at higher temperatures is prominent at 0.5 and 0.1 Hz frequency which can be seen from respective panels as well.

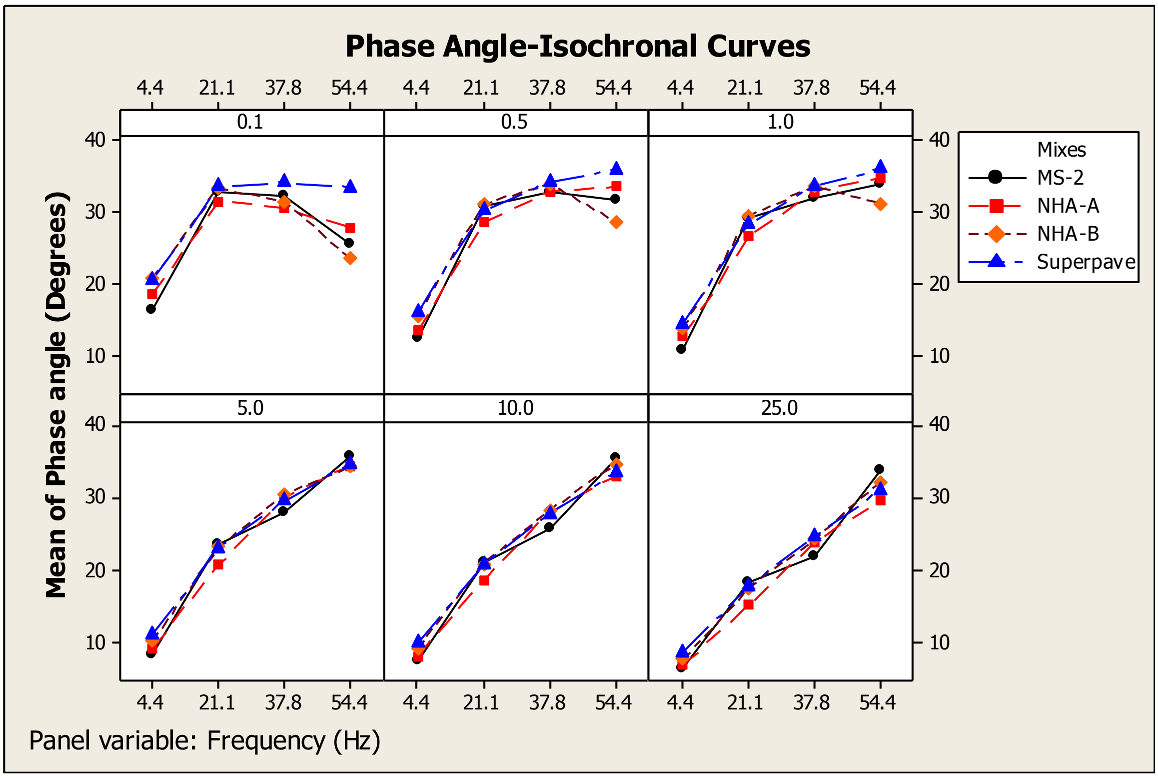


Figure 4.42 Phase angle-Isochronal Curves (Wearing course mixes)

The figure 4.43 illustrates isothermal curves for base course mixes which gives clear picture of phase angle at each temperature variation and all frequencies. It can be inferred from figure that at lower temperature and higher frequency of 25 or 10 Hz, all mixes are on elastic side while at lower frequency of 0.1 Hz, they all tend to viscous portion. Initially DBM mix has lower phase angle which can be seen in 4.4 °C panel but at higher temperature it is on viscous side. At 37.8 °C temperature, higher phase angle is observed, however a significantly drop is also notified at lower frequency while superpave mix does not drop much and on higher side. At 54.4 °C, though superpave mix has higher phase angle at high frequency but prominent drop is observed while DBM mix has lower phase angle at higher frequency and no any significantly drop is observed at lower frequencies. As the asphalt content of both DBM and superpave mixes are nearly equal and bit higher than other mixes which causes the mixes to lean toward viscous part.

The variation of phase angle for base course mixes at each frequency and all temperatures can be represented by isochronal curves as shown in figure 4.44. This figure suggests that at higher frequency of 25 Hz, DBM mix has very low phase angle and on the elastic side while other mixes have higher phase angle especially superpave mix. However, at lower temperature no significant drop is observed but at higher temperatures, phase angle of

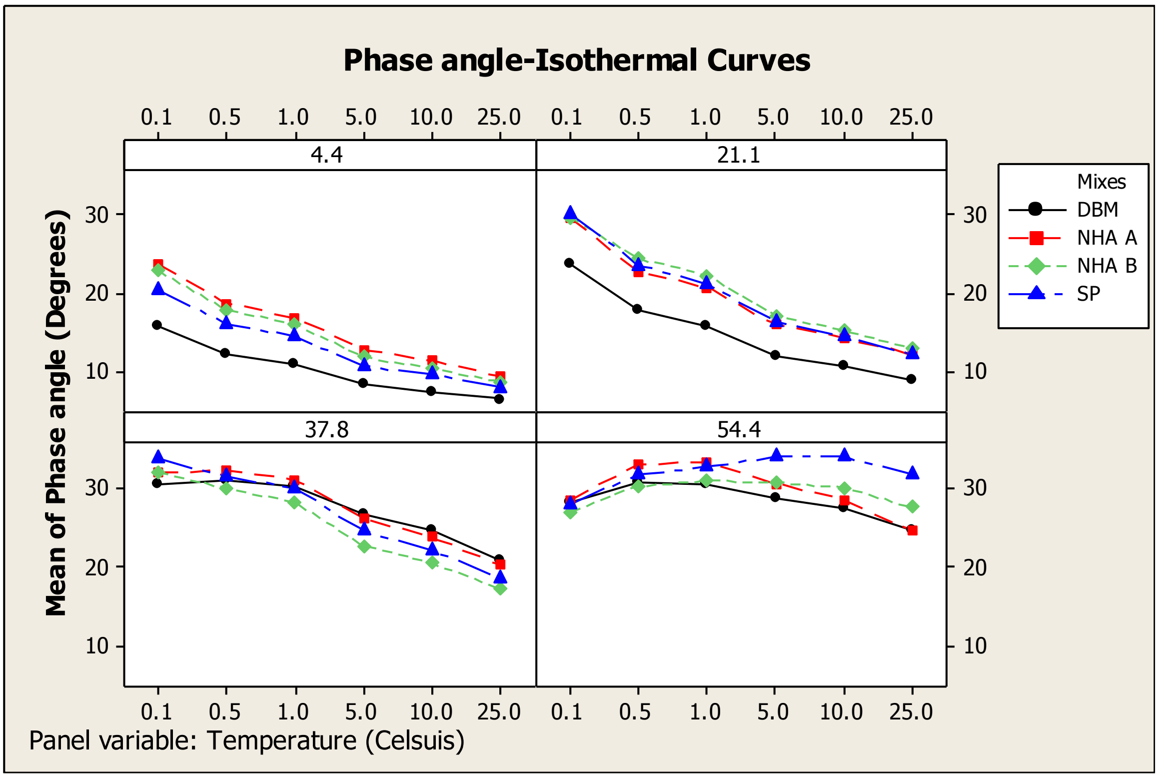


Figure 4.43 Phase angle-Isothermal Curves (Base course mixes)

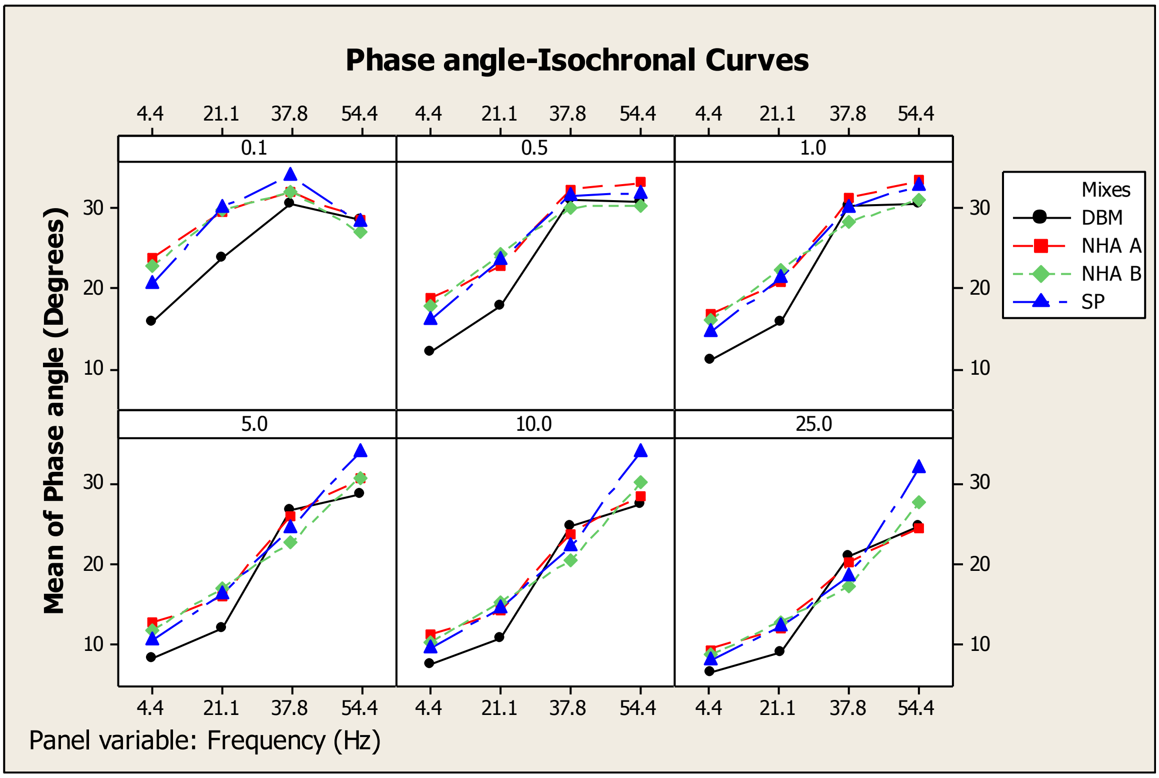


Figure 4.44 Phase angle-Isochronal Curves (Base course mixes)

DBM mix considerably drops and no prominent change can be visualized in Superpave mix at said temperature. An anomaly is seen in panel of 0.5 and 0.1 Hz that after lower phase angle of DBM at lower temperatures, it significantly increase and has almost higher phase angle at 54.4 °C temperature accompanied by superpave mix.

4.4 Summary

The laboratory test results obtained for dynamic modulus and phase angle were analyzed and different plot are presented herein. The obtained test result at different temperatures and frequencies were employed for the development of |E*| master curves for which mean value of dynamic modulus is required. The reference temperature is 21.1°C where each temperature is to be shifted by its corresponding reduced frequency at that point. This was accomplished by the time temperature superposition principle in which temperature change is attributed to change in frequency. Master curves are developed for both wearing and base course mixes which serves as basis for input to M-EPDG design procedure.

Two level factorial design has been carried out to determine the effect and interaction of different parameters which affect the dynamic modulus. Temperature, NMAS and loading frequency are the factors considered for the design of experiment in both wearing and base course mixes. For wearing course, temperature, NMAS and frequency were found to be statistically significant main effect while two way and three way interaction found to be insignificant. In case of base course mixes, temperature and frequency emerges as significant parameters while NMAS found to be insignificant alongwith two and three way interaction. The factorial plots which includes cumulative standardized, Pareto chart, cube plot also developed for both wearing and base course mixes.

The dynamic modulus predictive models are also developed separately for wearing and base course mixes. Their statistics is also presented in tabular form and model predictive ability is verified by calculating the mean absolute percentage error (MAPE) and plotting the observed data to fitted data.

The resistance to fatigue is also estimated using fatigue parameter and results shows that Superpave wearing course mix has good resistance to fatigue cracking while NHA-B base course mix has also good resistance to fatigue cracking.

Sensitivity analysis is also carried out for dynamic modulus test results. The plot with panel variable as temperature with all frequencies in single panel is called Isothermal curve while if panel variable is frequency with all temperatures in single panel can be categorized as isochronal curves. Based on these plots, it can be inferred that temperature has inverse effect on dynamic modulus while frequency has direct relation with dynamic modulus. It is also observed that that dynamic modulus is higher at lower temperature because of fact that asphalt mixture tends to be stiffer as binder plays important role at lower temperature while at higher temperatures, the interaction and interlocking of aggregate is main reason for low dynamic modulus values. The isothermal and isochronal curves alongwith bar chart diagram gives clear picture that NHA-A mix has higher dynamic modulus than other wearing course mixes while DBM mix is leading in base course mixes. On contrary to this, phase angle of superpave wearing course mix found to be more on viscous side due to high bitumen content relatively to other mixes while in case of base course mixes, superpave and DBM mixes have higher phase angle.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The dynamic modulus test was performed on four wearing course mixes and four base course mixes. The superpave gyratory specimens were prepared and after extraction, 100 mm diameter and 150 mm height was obtained using core cutter and saw cutting.

The dynamic modulus test was conducted on three replicate specimens at four test temperatures of 4.4, 21.1, 37.8 and 54.4^{o}C and six loading frequencies 25, 10, 5, 1, 0.5 and 0.1 Hz. Laboratory obtained dynamic modulus test results were employed to statistical analysis which includes two level factorial design in which temperature, frequency and NMAS factors were considered. The main and interaction effects were further elaborated by main and interaction plot alongwith pareto chart and cube plot for both wearing and base course mixes. The master curves were developed at reference temperature of 21 °C for both wearing and base course mixes using principle of time temperature superposition. By using this principle, the temperature is shifted to reference temperature with respect to loading frequency until smooth curve is obtained. This was accomplished by master solver excel sheet. As per AASHTO TP 62-07, for the dynamic modulus test and development of master curves, it requires performing test at -10 °C temperature but this test cannot be performed due to inability of AMPT. Master curves development needs an additional frequency of 0.01 Hz at 37.8 °C as input in excel sheet. The development of master curves for both wearing and base course mixes helps in implementation of relatively new design procedure in Pakistan. A catalog of dynamic modulus values for commonly mixtures used in Pakistan is developed and presented in appendix which will be helpful and shall provide basis for implementation of mechanistic-empirical pavement design guide structural approach.

On the basis of sensitivity analysis, NHA-A mix is leading in wearing course mixes while MS-2 is following and after that NHA-B and in last superpave. However for base course mixes, DBM mix is ahead of all other mixtures while NHA-A is after that and then comes NHA-B and in last stands Superpave mix. These ranking is on the basis of the laboratory test results of dynamic modulus obtained using simple performance tester (SPT). The higher value of phase angle represents the viscous portion while lower phase angle shows elastic behavior of asphalt mixtures. The phase angle of superpave mix is higher in wearing course mix and tends to be viscous at higher temperatures while in case of base course mixes, DBM and superpave mixes has higher phase angle and tends to viscous at higher temperatures meanwhile DBM mix also behave elastic at lower temperatures.

5.2 Conclusions

This study presents the dynamic modulus testing of different asphalt concrete mixtures at various temperatures (4.4 to 54.4°C) and frequencies (0.1 to 25 Hz). Laboratory obtained results were employed to two-level factorial design analysis to determine the factors affecting the dynamic modulus and phase angle and results showed that test temperature and loading frequency have significant impact on |E*| and phase angle whereas NMAS is significant in wearing course and insignificant in base course mixes. The other factors like binder content, gradation and aggregate source have no influence on the measured dynamic modulus. Sensitivity of dynamic modulus values to the input parameters revealed that for a given loading frequency, an increase in temperature (from 21.1 to 37.8 °C), translated into 45% and 43% drop in |E*| values on average for wearing and base course mixes, respectively. Similarly, for a given temperature, an increase in loading frequency (from 0.1 to 25Hz), 80% and 67% of variation in |E*| values on average was attributed for wearing and base course mixes, respectively. The Given the tested gradations/ mixes using Margalla aggregate and 60/70 penetration grade bitumen, NHA-A wearing course mix and DBM base course mix are relatively more stiff exhibiting higher values of dynamic modulus.. However, on evaluating the resistance to fatigue cracking, Superpave wearing course mix and NHA-B base course mix have shown relatively better resistance to fatigue cracking. Statistical models were developed for both wearing and base course mixes using Cobb-Douglas formulation incorporating test temperature, loading frequency and mix volumetric parameter as independent variables. The R^2 for wearing and base course model is 89.7% and 77%, respectively. It is also observed that phase angle initially increase as temperature increases and drop immensely after reaching peak value. This trend is observed generally in all mixes as phase angle decreases after 37.8 °C temperatures and at lower frequencies. Isothermal and Isochronal plots revealed that Superpave wearing mix has higher phase angle and less drop is observed hence it shows viscous behavior of mix. The DBM and superpave mixes of base course have higher phase angle and behaves as viscous at higher temperature while DBM mix is more of elastic in nature at lower temperatures. The laboratory determination of dynamic modulus values would facilitate the implementation of performance based mechanistic-empirical structural design and analysis approach in Pakistan.

5.3 Contributions to State-of-the-Practice

This research study is also one part of the ongoing of research carried out by National highway Authority (NHA) of Pakistan in collaboration with NUST titled as "Improvement of asphalt mix design technology of Pakistan". This study provides a basis for implementation of performance based design system. The default values of dynamic modulus found in this study established by developing by master curves which will ultimately provide base for the adopting the mechanistic-empirical design and analysis approach which in turns suit the Pakistan region where premature failure is frequently is visualized. The dynamic modulus catalog at different temperatures and frequencies is presented which will also be helpful for improvement of current mix design which is empirical in nature.

5.4 Recommendations

The study only focuses on the determination of dynamic modulus where as other performance tests like Hamburg wheel tracker, indirect tensile strength and flow number & flow time etc tests should be carried out to completely characterize the mixtures used in this study. In order to determine resistance to fatigue cracking, indirect tension fatigue test should be carried out. However, the effect of other binder source and aggregate source be also investigated and come up with most suitable combination of binder and aggregates. After completion of these tests, the need of hour is to take challenge at national level and implement these performance based design and analysis system incorporating the clients, contractors and consultancy firm by playing their roles in adopting relatively new design approach for Pakistan.

REFERENCES

AASHTO, TP 62-07. (2007). *Standard Test Method for Determining the Dynamic Modulus of Hot Mix Asphalt (HMA)*. American Association of State Highway and Transportation Officials.

Apeagyei, A., K. (2011), *"Rutting as a Function of Dynamic Modulus and Gradation*", Journal of Materials in Civil Engineering, Vol. 23, No. 9, 1302-1310.

ASTM. (2003). *Standard Test Method for Dynamic Modulus of Asphalt Mixtures.* ASTM International : West Conshohocken, PA., 2003. www.astm.org.

Bari, J., & Witczak, M. W. (2006). *"Development of a New Revised Version of the Witczak E* Predictive Model for Hot Mix Asphalt Mixtures*". Journal of the Association of Asphalt Paving Technologists from the Proceedings of the Technical Sessions, *75*, 381-423, Savannah, Ga.

Bayat, A. R., & Knight, M. (2010). "*Investigation of Hot-Mix Asphalt Dynamic Modulus by Means of Field-Measured Pavement Response"*. Journal of the Transportation Research Board,, *2154*, 138-145.

Bennert, T., & Aboobaker, N. (2009). "*Dynamic Modulus of Hot Mix Asphalt"*. U.S Department of Transportation, Washington,D.C: Report FHWA-NJ-2009-011.

Bonaquist, R. F. (2008). "*Refining the Simple Performance Tester for Use in Routine Practice"*. National Cooperative Highway Research Program (NCHRP) Report 614: Transportation Research Board, National Research Council, Washington D.C.

Bonaquist, R. F. (2010). "*Wisconsin Mixture Characterization Using the Asphalt Mixture Performance Tester (AMPT) on Historical Aggregate Structures"*. Wisconsin Department of Transportation: Final Report No. WHRP 09-03, 2010.

Bonnaure, F. G., Gravois, A., & Uge, P. (1977). *"A New Method for Predicting the Stiffness of Asphalt Paving Mixtures"*. Proceedings, Association of Asphalt Paving Technologists: Vol. 46, pp. 64-100.

Cao, W., Liu, S., & Feng, Z. (2013). "*Comparison of performance of stone matrix asphalt mixtures using basalt and limestone aggregates"*. Construction and Building Materials, *41*, 474-479.

Cho, Y.H., Park, D.W., & Hwang, S.-D. (2010). "*A predictive equation for dynamic modulus of asphalt mixtures used in Korea"*. Construction and Building Materials, *24*(1), 513-519.

Clyne, T. R., Li, X., & Marasteanu, M. O. (2003). "*Dynamic modulus and Resilient Modulus of Mn/Dot Asphalt Mixtures"*. Minnesota Department of Transportation, Research Services: Report: MN/RC – 2003-09.

Colbert, B., & You, Z. (2012). "*The determination of mechanical performance of laboratory produced hot mix asphalt mixtures using controlled RAP and virgin aggregate size fractions"*. Construction and Building Materials, *26*(1), 655-662.

Contreras, J. N., Fresno, D. C., & Zamanillo, A. V. (2010). "*Dynamic modulus of asphalt mixture by ultrasonic direct test"*. *NDT&E International*, *43*(1), 629-634.

Cross, S. A., & Jakatimath, Y. (2007). "*Determination of Dynamic Modulus Master Curves for Oklahoma HMA Mixtures"*. Oklahoma Department of Transportation: Final report.

Dougan, C. E., Stephens, J. E., & Mahoney, J. (2003). *"Dyanmic Modulus: Test protocols-Problems and Solutions"*. Connecticut Department of Transportation, USA: Report: CT-SPR-0003084-F-03-3 .

Ekingen , E. R. (2004). *"Determining Gradation and Creep Effects in Mixtures Using the Complex Modulus Test"*. ME Thesis: University of Florida, USA.

Flintsch, G. W., Loulizi, A., & Diefenderfer, B. K. (2007). *"Asphalt Material Characterization in Support of Implementation of Mechanistic Emperical Pavement Design Guide"*. Virginia Transportation Research Council: Final Report.

Ghosh, A., Padmarekha, A., and Krishnan, J., M. (2013), "*Implementation and Proof-Checking of Mechanistic-Empirical Pavement Design for Indian Highways Using AASHTOWARE Pavement ME Design Softwar*e", Procedia - Social and Behavioral Sciences 104, 119 – 128

Hassan, H. F., & Al-Jabri, K. (2011). *"Laboratory Evaluation of Hot-Mix Asphalt Concrete Containing Copper Slag Aggregate"*. Journal of Material in Civil Engineering, *23*(6), 879-885.

Huang, Y. H. (2004). *"Pavement Analysis and Design"* (2nd ed.). Pearson Prentice Hall.

Kallas, B. F. (1970). "Dynamic Modulus of Asphalt Concrete in Tension and Tension-Compression". Proceedings, Association of Asphalt Paving Technologists: Vol. 39, pp. 1-20.

Khattab, A., M. El-Badawy, S., M. Al Hazmi, A., Elmwafi, M, (2014), *"Evaluation of Witczak E* predictive models for the implementation of AASHTOWare-Pavement ME Design in the Kingdom of Saudi Arabia"*, Construction and Building Materials, 64, 360–369

Kumar, S. A., & Veeraragavan, A. (2011). "Dynamic mechanical characterization of asphalt concrete mixes with modified asphalt binders". Materials Science and Engineering A, *528*(21), 6445-6554.

Lee, K., Kim, H., & Kim , N. (2002). *"Dynamic Modulus of Asphalt Mixtures for Development of Korean Pavement Design Guide". ASTM Journal of Testing and Evaluation*, 28-59.

Mohammad, L. N., Saadeh, S., & Cooper, S. (2007). "Characterization of Louisiana Asphalt Mixtures Using Simple Performance Tests". In Proceedings of the 86th Annual Meeting of the Transportation Research Board: National Research Council, Washington .

Mun, S., & Lee, S. (2010). "Determination of the fatigue-cracking resistance of asphalt concrete mixtures at low temperatures". *Cold Regions Science and Technology, 61*(2), 116-124.

Mun, L. and Lee, S. (2012), *"Fatigue resistance potential for hot mix asphalt using viscoelastic continuum damage analysis"* Fatigue & Fracture of Engineering Materials & Structures., 35(3) 205-218.

Papazian, H. S. (1962). *"The response of linear viscoelastic materials in the frequency domain with emphasis on asphaltic concrete"*. 1st International Conference on the structural Design of Asphalt Pavements.: pp. 454-463.

Pellinen, T. K., & Witczak, M. W. (2002). "Stress Dependent Master Curve Construction forDynamic (Complex) Modulus". Annual Meeting Association of Asphalt Paving: Colorado Springs, Colorado, USA.

Rafique, H. (2013). *"Moisture Susceptibility of Apshalt Cocnrete mixture used in Pakistan"*. MS Thesis: National Univeristy of Science and Technology (NUST) Islamabad Pakistan.

Robbins, M. M. (2009). *"An Investigation into Dynamic Modulus of Hot-Mix Asphalt and its contributing factors"*. MS Thesis: Auburn University, Alabama USA.

Shu, X., & Huang, B. (2008). "Micromechanics-based dynamic modulus prediction of polymeric asphalt concrete mixtures". Composites: Part B, 39(2), 704-713.

Waraich, A. S. (2012). *"Mechanistics Characterization of HMa for pavements using SPT protocols"*. MS Thesis: National University of Science and Technology (NUST) Islamabad Pakistan.

Witczak, M. (2005). *"Simple Performance Tests: Summary of Recommended Methods and Database"*. NCHRP Report 547: Transportation Researach Board, Washigton D.C.

Witczak, M. W., & Root, R. E. (1974). "Summary of Complex Modulus Laboratory Test Procedures and Results". American Society for Testing and Materials: pp. 67-94.

Witczak, M. W., Kaloush, K., Pellnen, T., & Basyouny, M. E. (2002). *"Simple Performance Test for Superpave Mix Design"*. Washington D.C: National Cooperative Highway Research Program (NCHRP) report 465.

Yao, B., Cheng, G., Wang, X., & Cheng, C. (2013). "Characterization of the stiffness of asphalt surfacing materials on orthotropic steel bridge decks using dynamic modulus test and flexural beam test". Construction and Building Materials, 44, 200-206.

Ye, Q., Wu, S., & Li, N. (2009). "Investigation of the dynamic and fatigue properties of fiber-modified asphalt mixtures". International Journal of Fatigue, 31(10), 1598-1602.

Yu, H., & Shen, S. (2011). "Impact of aggregate packing on dynamic modulus of hot mix asphalt mixtures using three-dimensional discrete element method". Construction and Building Materials, 26(3), 302-309.

Zhang, J., Alvarez, A. E., Lee, S. I., Torres, A., & Walubita, L. F. (2013). *"Comparison of flow number, dynamic modulus, and repeated load tests for evaluation of HMA permanent deformation*". Construction and Building Materials, 44, 391-398.

Zhao, Y., Tang, J., & Liu, H. (2012). *"Construction of triaxial dynamic modulus master curve for asphalt mixtures"*. Construction and Building Materials, 37(2), 21-26.

Zhu, H., Sun, L., Yang, J., Chen, Z., and Gu, W., (2011),*"Developing Master Curves and Predicting Dynamic Modulus of Polymer-Modified Asphalt Mixtures*", Journal of Materials in Civil Engineering, 23(2), 131-137

APPENDICES

APPENDIX A

DYNAMIC MODULUS |E*| TEST RESULTS

Table A-1 Dynamic Modulus Test Results for NHA-A Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa) Specimen 1	Specimen 2	Specimen 3	Average	S.D	CV (%)
4.4	25	24101	26489	22187	**24259**	2155	8.88
	10	23086	24922	20126	**22711**	242	10.65
	5	22050	23485	19488	**21674**	2025	9.34
	1	18821	19418	16175	**18138**	1726	9.52
	0.5	17665	17138	14604	**16469**	1636	9.94
	0.1	14540	12571	10927	**12679**	1809	14.27
21.1	25	19251	15051	14191	**16164**	2707	16.75
	10	13600	12752	11945	**12766**	1909	13.87
	5	11836	11091	10236	**11054**	801	7.24
	1	7955	7459	6719	**7378**	622	8.43
	0.5	6405	6062	5324	**5930**	552	9.31
	0.1	3635	3422	2865	**3307**	398	12.02
37.8	25	9430	7396	11657	**9494**	2131	22.45
	10	7143	5126	9066	**7112**	1970	27.7
	5	5627	3768	7366	**5587**	1799	32.21
	1	2936	1783	4213	**2977**	1216	40.83
	0.5	2151	1311	3067	**2176**	878	40.36
	0.1	1107	751.7	1356	**1072**	304	28.34
	0.01	566	329.9	800.1	**565**	235	41.59
54.4	25	6100	5592	8099	**6597**	1325	20.09
	10	4128	3964	5910	**4667**	1079	23.12
	5	2959	2821	4495	**3425**	929	27.13
	1	1388	1311	2170	**1623**	475	29.28
	0.5	1033	967	1467	**1156**	272	23.5
	0.1	705.2	562.5	597.9	**622**	74.3	11.93

Table A-2 Dynamic Modulus Test Results for NHA-B Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa) Specimen 1	Specimen 2	Specimen 3	Average	S.D	CV (%)
4.4	25	25782	22102	21251	**23045**	2408	10.45
	10	23680	20303	20403	**21462**	1921	8.95
	5	22114	18739	19383	**20079**	1792	8.95
	1	18109	15080	16216	**16468**	1530	9.29
	0.5	16247	13485	14801	**14844**	1382	9.31
	0.1	11889	9807	11067	**10921**	1049	9.6
21.1	25	15213	13764	13193	**14057**	1041	7.41
	10	12943	11477	10774	**11731**	1107	9.43
	5	11129	9726	9137	**9997**	1023	10.24
	1	7144	6205	5594	**6314**	781	12.36
	0.5	5554	4847	4280	**4894**	638	13.04
	0.1	2887	2526	2141	**2518**	373	14.82
37.8	25	7442	10728	9904	**9358**	1710	18.27
	10	5232	8513	7604	**7116**	1694	23.8
	5	3856	6929	6031	**5605**	1580	28.19
	1	1823	3854	3110	**2929**	1028	35.08
	0.5	1312	2773	2172	**2086**	734	35.21
	0.1	723.1	1182	950.8	**952**	229	24.1
	0.01	321.2	542.6	455.9	**440**	111.6	25.36
54.4	25	2790	3079	5815	**3895**	1669	42.86
	10	2110	2292	3574	**2659**	798	30.1
	5	1808	1913	2249	**1990**	230	11.58
	1	1475	1494	1517	**1495**	21	1.41
	0.5	409.4	385.3	996	**597**	346	57.96
	0.1	321.7	266.9	592.6	**394**	174	44.29

Table A-3 Dynamic Modulus Test Results for Superpave-1 Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa)					
		Specimen 1	Specimen 2	Specimen 3	Average	S.D	CV (%)
4.4	25	17076	18207	22437	**19240**	2826	14.69
	10	16568	16834	20627	**18010**	2271	16.61
	5	15768	15630	19056	**16818**	1939	11.53
	1	12853	12712	15378	**13648**	1500	10.99
	0.5	11479	11246	13742	**12156**	1379	11.34
	0.1	8600	8189	9948	**8912**	920	10.32
21.1	25	10807	8508	9954	**9756**	1162	11.91
	10	8943	6975	8445	**8121**	1023	10.6
	5	7616	5875	7329	**6940**	933	13.45
	1	4941	3672	4880	**4498**	716	15.91
	0.5	2954	2903	3980	**3279**	608	18.53
	0.1	2182	1558	2257	**1999**	384	19.2
37.8	25	6148	6611	7167	**6642**	510	7.68
	10	4607	5116	5681	**5135**	537	10.46
	5	3602	4125	4648	**4125**	523	12.68
	1	1866	2273	2654	**2264**	394	17.4
	0.5	1355	1653	1973	**1660**	309	18.61
	0.1	624.4	703.4	876.9	**735**	129.2	17.58
	0.01	333.4	364.1	421.8	**373**	44.9	12.03
54.4	25	5229	2305	5342	**4292**	1722	40.11
	10	3795	1500	3971	**3089**	1379	44.69
	5	2883	1054	3038	**2325**	1103	47.46
	1	1383	459.8	1468	**1104**	559	50.67
	0.5	951.6	314.1	1007	**758**	385	50.83
	0.1	541.6	136.4	448	**375**	212	56.52

Table A-4 Dynamic Modulus Test Results for MS-2 Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa)					
		Specimen 1	Specimen 2	Specimen 3	Average	S.D	CV (%)
4.4	25	22902	26846	21776	**23841**	2662	11.17
	10	21523	26221	19662	**22469**	3380	15.04
	5	20357	25386	18530	**21424**	3350	16.57
	1	17569	22600	14998	**18389**	3867	21.03
	0.5	16107	21003	13427	**16846**	3842	22.8
	0.1	12716	16903	9901	**13173**	3523	26.75
21.1	25	11569	12244	12394	**12069**	683	5.57
	10	9725	10229	10261	**10072**	301	2.99
	5	8388	8637	9016	**8680**	316	3.64
	1	5357	5540	5797	**5565**	221	3.97
	0.5	4227	4452	4623	**4434**	199	4.48
	0.1	2236	2365	2541	**2381**	153.1	6.43
37.8	25	9780	10178	9941	**9966**	200	2.01
	10	7751	8075	7873	**7900**	163.6	2.07
	5	6290	6646	6451	**6462**	178	2.76
	1	3464	3791	3652	**3636**	164.1	4.51
	0.5	2505	2768	2675	**2649**	113.4	5.03
	0.1	1093	1185	1196	**1158**	56.6	4.88
	0.01	658.3	661.2	676	**665**	9.49	1.43
54.4	25	5639	3611	3029	**4093**	1370	33.48
	10	3893	2293	1937	**2708**	1042	38.48
	5	2826	1578	1362	**1922**	790	41.12
	1	1287	703.5	671.1	**887**	347	39.03
	0.5	896	514.6	519.5	**643**	219	34.01
	0.1	437.6	283.7	334.8	**352**	78.4	22.27

Table A-5 Dynamic Modulus Test Results for NHA-A Base Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	25299	20627	22883	**22936**	2337	10.2
	10	23160	18691	21165	**21005**	2239	10.66
	5	21548	17107	19649	**19435**	2228	11.47
	1	17541	13484	15534	**15520**	2029	13.07
	0.5	15958	12019	13710	**13896**	1976	14.22
	0.1	12200	8789	9959	**10316**	1733	16.8
21.1	25	20898	19526	21134	**20519**	1023	5.01
	10	18469	17315	19019	**18268**	870	4.76
	5	16962	15629	17422	**16671**	1100	6.64
	1	12922	11427	13280	**12543**	983	7.84
	0.5	11271	9665	11425	**10787**	975	9.04
	0.1	6743	5876	6631	**6417**	472	7.35
37.8	25	10265	15062	15100	**13476**	2781	20.63
	10	7651	12774	12564	**10996**	2899	26.36
	5	5766	11138	10545	**9150**	2945	32.19
	1	2827	7219	6003	**5350**	2268	42.39
	0.5	1995	5402	4277	**3891**	1736	44.61
	0.1	944.3	2208	1754	**1635**	640	39.14
	0.01	386.1	501.6	459.2	**449**	58.4	13.01
54.4	25	10536	8123	11358	**10006**	1681	16.8
	10	7839	6009	10502	**8117**	2259	27.84
	5	6016	4781	8330	**6376**	1802	28.26
	1	2958	3211	5668	**3946**	1497	37.94
	0.5	2012	2848	3788	**2883**	889	30.82
	0.1	835.4	917.6	1305	**1019**	251	24.6

Table A-6 Dynamic Modulus Test Results for NHA-B Base Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	19944	24461	20425	**21610**	2481	11.48
	10	18273	22592	18822	**19896**	2351	11.82
	5	16707	21043	17378	**18376**	2334	12.7
	1	12946	16951	13931	**14609**	2087	14.28
	0.5	11213	15370	12333	**12972**	2151	16.58
	0.1	7801	11399	9068	**9423**	1825	19.37
21.1	25	16406	17387	15745	**16513**	826	5.00
	10	14465	15400	13915	**14593**	751	5.14
	5	13021	14002	12511	**13178**	758	5.75
	1	9569	10377	9164	**9703**	618	6.36
	0.5	8156	8779	7714	**8216**	535	6.51
	0.1	4886	5230	4466	**4861**	383	7.87
37.8	25	12842	15754	12512	**13703**	1784	13.02
	10	10926	13553	10305	**11595**	1724	14.87
	5	9482	11861	8578	**9974**	1696	17.00
	1	5976	7940	5058	**6325**	1472	23.28
	0.5	4486	6193	3692	**4790**	1278	26.68
	0.1	1893	2777	1558	**2076**	630	30.34
	0.01	448	501.9	342.7	**431**	81	18.79
54.4	25	10456	10175	10859	**10497**	344	3.28
	10	8669	7805	8498	**8324**	458	5.50
	5	6196	6084	6763	**6348**	364	5.73
	1	3462	3088	3427	**3326**	207	6.21
	0.5	2893	2114	2274	**2427**	411	16.95
	0.1	911.3	830.6	801.7	**848**	56.8	6.70

Table A-7 Dynamic Modulus Test Results for Superpave-2 Base Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	23082	23495	20312	**22296**	1898	8.46
	10	21629	21981	18725	**20778**	1787	8.6
	5	20076	20706	17400	**19394**	1755	9.05
	1	17247	16934	14064	**16082**	1754	10.91
	0.5	15310	15175	12711	**14399**	1463	10.16
	0.1	11144	11610	9357	**10704**	1189	11.11
21.1	25	17285	18677	18513	**18158**	761	4.19
	10	15187	16874	15479	**15847**	902	5.69
	5	13599	15507	13989	**14365**	1008	7.02
	1	10061	11951	9994	**10669**	1130	10.61
	0.5	8231	10369	8459	**9020**	1174	13.02
	0.1	4697	6699	5150	**5515**	1050	19.03
37.8	25	15632	11525	11666	**12941**	2332	18.02
	10	13386	9081	9461	**10643**	2383	22.39
	5	11618	7453	7865	**8979**	2295	25.56
	1	7716	4223	4561	**5500**	1927	35.03
	0.5	5985	3094	3341	**4140**	1603	38.71
	0.1	2657	1299	1371	**1776**	764	43.03
	0.01	801.6	696.6	785.2	**761**	56.5	7.42
54.4	25	4768	5799	6990	**5852**	1112	19
	10	3018	4914	5746	**4559**	1398	30.67
	5	2072	3974	4424	**3490**	1248	35.77
	1	861.7	2237	3798	**2299**	1469	63.91
	0.5	576.3	1894	2710	**1727**	1077	62.35
	0.1	256.2	789.7	877.9	**641**	336	52.46

Table A-8 Dynamic Modulus Test Results for DBM Base Course Mix

Temperature (Celsius)	Frequency (Hz)	Dynamic modulus (MPa) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	24430	25244	28943	**26206**	2405	9.18
	10	22870	24169	28032	**25024**	2685	10.73
	5	21304	23064	26984	**23784**	2858	12.03
	1	17338	20410	24151	**20633**	3412	16.54
	0.5	15667	19260	22587	**19171**	3461	18.05
	0.1	12362	15766	18666	**15598**	3155	20.23
21.1	25	20053	24924	25304	**23427**	2928	12.5
	10	17723	23049	23941	**21571**	3362	15.59
	5	15786	22069	22631	**20162**	3800	18.85
	1	12167	17110	19214	**16164**	3618	22.38
	0.5	10220	15318	17381	**14306**	3686	25.77
	0.1	6315	9970	12422	**9569**	3073	32.12
37.8	25	15701	14261	17621	**15861**	1686	10.63
	10	14102	12989	16111	**14401**	1582	10.99
	5	12200	10290	14333	**12274**	2023	16.48
	1	9323	8488	12330	**10047**	2021	20.11
	0.5	5942	6706	9678	**7442**	1974	26.52
	0.1	2304	3132	6787	**4074**	2385	58.55
	0.01	1212	1412	3427	**2017**	1225	60.74
54.4	25	11787	13626	9777	**11730**	1925	16.41
	10	9263	12284	7394	**9647**	2468	25.58
	5	7474	11503	5894	**8290**	2855	34.32
	1	4107	8488	3400	**5332**	2756	51.7
	0.5	2942	6706	2678	**4109**	2253	54.84
	0.1	1304	3132	1787	**2074**	947	45.67

APPENDIX B

DEFAULT |E*| VALUES CATALOG -

(INPUT FOR M-EPDG INCLUDING |E*| SHIFT FACTORS AND REDUCED FREQUENCIES)

Table B-1 MEPDG Input for NHA-A Wearing Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	2.808968	16103.06	3276.7	22599.2
-10.0	14	10	2.808968	6441.224	3239.8	22344.7
-10.0	14	5	2.808968	3220.612	3201.8	22082.7
-10.0	14	1	2.808968	644.1224	3064.3	21134.8
-10.0	14	0.5	2.808968	322.0612	2976.0	20525.3
-10.0	14	0.1	2.808968	64.41224	2674.9	18448.9
4.4	40	25	1.426075	666.8304	3068.2	21161.6
4.4	40	10	1.426075	266.7322	2948.1	20333.1
4.4	40	5	1.426075	133.3661	2829.6	19515.7
4.4	40	1	1.426075	26.67322	2441.6	16839.5
4.4	40	0.5	1.426075	13.33661	2222.2	15326.2
4.4	40	0.1	1.426075	2.667322	1617.8	11157.6
21.1	70	25	-0.0009	24.94839	2421.8	16702.9
21.1	70	10	-0.0009	9.979356	2121.6	14633.0
21.1	70	5	-0.0009	4.989678	1864.3	12857.9
21.1	70	1	-0.0009	0.997936	1229.0	8476.6
21.1	70	0.5	-0.0009	0.498968	974.2	6719.2
21.1	70	0.1	-0.0009	0.099794	514.4	3548.0
37.8	100	25	-1.27491	1.327471	1340.0	9242.2
37.8	100	10	-1.27491	0.530989	996.0	6869.3
37.8	100	5	-1.27491	0.265494	769.0	5303.7
37.8	100	1	-1.27491	0.053099	392.4	2706.3
37.8	100	0.5	-1.27491	0.026549	291.9	2013.4
37.8	100	0.1	-1.27491	0.00531	156.7	1081.1
54.4	130	25	-2.41932	0.095197	504.2	3477.5
54.4	130	10	-2.41932	0.038079	340.2	2346.2
54.4	130	5	-2.41932	0.019039	254.3	1753.8
54.4	130	1	-2.41932	0.003808	140.4	968.0
54.4	130	0.5	-2.41932	0.001904	114.2	787.3
54.4	130	0.1	-2.41932	0.000381	79.8	550.1

Table B-2 MEPDG Input for NHA-B Wearing Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	2.471362	7401.203	3255.8	22455.1
-10.0	14	10	2.471362	2960.481	3206.1	22112.5
-10.0	14	5	2.471362	1480.241	3154.1	21753.8
-10.0	14	1	2.471362	296.0481	2962.7	20433.6
-10.0	14	0.5	2.471362	148.0241	2838.8	19579.3
-10.0	14	0.1	2.471362	29.60481	2423.0	16711.6
4.4	40	25	1.254677	449.3837	3023.9	20855.8
4.4	40	10	1.254677	179.7535	2876.5	19839.4
4.4	40	5	1.254677	89.87674	2730.2	18830.4
4.4	40	1	1.254677	17.97535	2254.8	15551.7
4.4	40	0.5	1.254677	8.987674	1993.4	13748.7
4.4	40	0.1	1.254677	1.797535	1320.3	9105.8
21.1	70	25	-0.00079	24.95459	2367.5	16328.5
21.1	70	10	-0.00079	9.981835	2034.8	14034.1
21.1	70	5	-0.00079	4.990918	1752.4	12086.4
21.1	70	1	-0.00079	0.998184	1082.5	7465.7
21.1	70	0.5	-0.00079	0.499092	830.5	5728.0
21.1	70	0.1	-0.00079	0.099818	412.1	2842.1
37.8	100	25	-1.12168	1.889102	1341.0	9248.9
37.8	100	10	-1.12168	0.755641	976.9	6737.4
37.8	100	5	-1.12168	0.37782	740.6	5108.2
37.8	100	1	-1.12168	0.075564	363.6	2507.7
37.8	100	0.5	-1.12168	0.037782	268.1	1849.0
37.8	100	0.1	-1.12168	0.007556	144.9	999.6
54.4	130	25	-2.12854	0.18595	544.8	3757.8
54.4	130	10	-2.12854	0.07438	361.0	2490.0
54.4	130	5	-2.12854	0.03719	266.3	1836.5
54.4	130	1	-2.12854	0.007438	144.2	994.4
54.4	130	0.5	-2.12854	0.003719	117.1	807.6
54.4	130	0.1	-2.12854	0.000744	82.5	569.3

Table B-3 MEPDG Input for Superpave-1 Wearing Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	2.151426	3542.961	3220.5	22211.5
-10.0	14	10	2.151426	1417.184	3165.3	21831.3
-10.0	14	5	2.151426	708.5921	3110.4	21452.3
-10.0	14	1	2.151426	141.7184	2922.2	20154.4
-10.0	14	0.5	2.151426	70.85921	2807.5	19363.3
-10.0	14	0.1	2.151426	14.17184	2441.9	16841.5
4.4	40	25	1.09225	309.1649	3025.5	20866.8
4.4	40	10	1.09225	123.6659	2901.5	20011.4
4.4	40	5	1.09225	61.83297	2782.1	19188.3
4.4	40	1	1.09225	12.36659	2404.0	16580.5
4.4	40	0.5	1.09225	6.183297	2195.2	15140.2
4.4	40	0.1	1.09225	1.236659	1625.5	11211.0
21.1	70	25	-0.00069	24.96046	2587.4	17845.0
21.1	70	10	-0.00069	9.984185	2342.4	16155.8
21.1	70	5	-0.00069	4.992092	2125.5	14659.4
21.1	70	1	-0.00069	0.998418	1544.7	10653.7
21.1	70	0.5	-0.00069	0.499209	1283.8	8854.5
21.1	70	0.1	-0.00069	0.099842	742.2	5118.7
37.8	100	25	-0.97647	2.63916	1905.3	13140.6
37.8	100	10	-0.97647	1.055664	1565.8	10799.1
37.8	100	5	-0.97647	0.527832	1304.6	8997.5
37.8	100	1	-0.97647	0.105566	758.4	5230.5
37.8	100	0.5	-0.97647	0.052783	573.3	3954.4
37.8	100	0.1	-0.97647	0.010557	281.9	1944.3
54.4	130	25	-1.85299	0.350713	1154.5	7962.7
54.4	130	10	-1.85299	0.140285	844.4	5823.8
54.4	130	5	-1.85299	0.070143	644.9	4447.6
54.4	130	1	-1.85299	0.014029	320.4	2209.9
54.4	130	0.5	-1.85299	0.007014	234.8	1619.1
54.4	130	0.1	-1.85299	0.001403	119.8	826.2

Table B-4 MEPDG Input for MS-2 Wearing Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	2.445798	6978.11	3235.0	22312.0
-10.0	14	10	2.445798	2791.244	3179.9	21931.6
-10.0	14	5	2.445798	1395.622	3123.4	21542.0
-10.0	14	1	2.445798	279.1244	2922.4	20155.9
-10.0	14	0.5	2.445798	139.5622	2796.2	19285.5
-10.0	14	0.1	2.445798	27.91244	2385.6	16453.2
4.4	40	25	1.241699	436.1527	2989.8	20620.8
4.4	40	10	1.241699	174.4611	2839.9	19586.8
4.4	40	5	1.241699	87.23054	2694.1	18581.2
4.4	40	1	1.241699	17.44611	2233.0	15400.9
4.4	40	0.5	1.241699	8.723054	1984.1	13684.1
4.4	40	0.1	1.241699	1.744611	1346.0	9283.6
21.1	70	25	-0.00078	24.95506	2350.5	16211.3
21.1	70	10	-0.00078	9.982023	2034.4	14031.5
21.1	70	5	-0.00078	4.991011	1767.7	12191.5
21.1	70	1	-0.00078	0.998202	1129.6	7790.5
21.1	70	0.5	-0.00078	0.499101	883.3	6091.9
21.1	70	0.1	-0.00078	0.09982	456.3	3146.8
37.8	100	25	-1.11008	1.940254	1388.4	9575.6
37.8	100	10	-1.11008	0.776101	1036.6	7149.8
37.8	100	5	-1.11008	0.388051	802.2	5532.7
37.8	100	1	-1.11008	0.07761	409.2	2821.9
37.8	100	0.5	-1.11008	0.038805	303.6	2094.0
37.8	100	0.1	-1.11008	0.007761	161.6	1114.8
54.4	130	25	-2.10653	0.195621	607.9	4192.8
54.4	130	10	-2.10653	0.078248	410.6	2832.0
54.4	130	5	-2.10653	0.039124	304.7	2101.3
54.4	130	1	-2.10653	0.007825	162.1	1118.0
54.4	130	0.5	-2.10653	0.003912	129.3	891.7
54.4	130	0.1	-2.10653	0.000782	86.7	597.7

Table B-5 MEPDG Input for NHA-A Base Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	2.209906	4053.65	3230.8	22283.1
-10.0	14	10	2.209906	1621.46	3181.8	21945.1
-10.0	14	5	2.209906	810.73	3133.3	21610.5
-10.0	14	1	2.209906	162.146	2968.2	20472.0
-10.0	14	0.5	2.209906	81.073	2867.7	19778.6
-10.0	14	0.1	2.209906	16.2146	2543.9	17545.6
4.4	40	25	1.12194	331.0393	3051.9	21048.9
4.4	40	10	1.12194	132.4157	2941.0	20283.9
4.4	40	5	1.12194	66.20787	2834.3	19548.0
4.4	40	1	1.12194	13.24157	2493.1	17195.0
4.4	40	0.5	1.12194	6.620787	2301.1	15871.0
4.4	40	0.1	1.12194	1.324157	1757.3	12119.9
21.1	70	25	-0.00071	24.95939	2644.4	18238.3
21.1	70	10	-0.00071	9.983755	2418.3	16678.7
21.1	70	5	-0.00071	4.991878	2215.0	15277.2
21.1	70	1	-0.00071	0.998376	1651.2	11388.6
21.1	70	0.5	-0.00071	0.499188	1385.6	9556.3
21.1	70	0.1	-0.00071	0.099838	800.3	5519.7
37.8	100	25	-1.00302	2.482695	1983.9	13683.1
37.8	100	10	-1.00302	0.993078	1649.2	11374.7
37.8	100	5	-1.00302	0.496539	1383.5	9542.2
37.8	100	1	-1.00302	0.099308	798.6	5507.7
37.8	100	0.5	-1.00302	0.049654	590.0	4069.5
37.8	100	0.1	-1.00302	0.009931	254.0	1752.1
54.4	130	25	-1.90336	0.312309	1206.3	8320.0
54.4	130	10	-1.90336	0.124923	874.9	6034.5
54.4	130	5	-1.90336	0.062462	655.1	4518.2
54.4	130	1	-1.90336	0.012492	289.4	1995.7
54.4	130	0.5	-1.90336	0.006246	193.9	1337.1
54.4	130	0.1	-1.90336	0.001249	73.8	508.7

Table B-6 MEPDG Input for NHA-B Base Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	1.641934	1096.161	3047.9	21021.0
-10.0	14	10	1.641934	438.4643	2951.4	20355.5
-10.0	14	5	1.641934	219.2322	2861.0	19732.2
-10.0	14	1	1.641934	43.84643	2580.4	17796.7
-10.0	14	0.5	1.641934	21.92322	2424.6	16722.3
-10.0	14	0.1	1.641934	4.384643	1977.3	13637.8
4.4	40	25	0.833588	170.4229	2823.9	19476.7
4.4	40	10	0.833588	68.16915	2668.1	18402.0
4.4	40	5	0.833588	34.08458	2526.3	17424.1
4.4	40	1	0.833588	6.816915	2111.4	14562.4
4.4	40	0.5	0.833588	3.408458	1897.4	13086.4
4.4	40	0.1	0.833588	0.681692	1346.4	9286.4
21.1	70	25	-0.00052	24.96982	2455.5	16935.8
21.1	70	10	-0.00052	9.987928	2220.7	15316.2
21.1	70	5	-0.00052	4.993964	2017.7	13916.1
21.1	70	1	-0.00052	0.998793	1481.0	10214.5
21.1	70	0.5	-0.00052	0.499396	1236.9	8530.7
21.1	70	0.1	-0.00052	0.099879	707.4	4879.2
37.8	100	25	-0.74523	4.494801	1985.1	13691.2
37.8	100	10	-0.74523	1.79792	1684.9	11620.8
37.8	100	5	-0.74523	0.89896	1444.0	9959.1
37.8	100	1	-0.74523	0.179792	889.5	6134.8
37.8	100	0.5	-0.74523	0.089896	676.8	4667.8
37.8	100	0.1	-0.74523	0.017979	301.6	2079.9
54.4	130	25	-1.41417	0.963316	1468.3	10126.9
54.4	130	10	-1.41417	0.385327	1146.3	7906.2
54.4	130	5	-1.41417	0.192663	912.0	6289.8
54.4	130	1	-1.41417	0.038533	456.3	3147.1
54.4	130	0.5	-1.41417	0.019266	313.8	2164.6
54.4	130	0.1	-1.41417	0.003853	110.5	762.2

Table B-7 MEPDG Input for Superpave-2 Base Course Mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	2.753189	14162.13	3123.7	21544.3
-10.0	14	10	2.753189	5664.852	3039.5	20963.5
-10.0	14	5	2.753189	2832.426	2958.3	20403.4
-10.0	14	1	2.753189	566.4852	2696.0	18594.5
-10.0	14	0.5	2.753189	283.2426	2545.9	17558.9
-10.0	14	0.1	2.753189	56.64852	2105.4	14521.2
4.4	40	25	1.397757	624.7363	2715.3	18727.6
4.4	40	10	1.397757	249.8945	2516.2	17354.0
4.4	40	5	1.397757	124.9473	2337.5	16121.5
4.4	40	1	1.397757	24.98945	1839.4	12686.5
4.4	40	0.5	1.397757	12.49473	1601.3	11043.8
4.4	40	0.1	1.397757	2.498945	1056.6	7287.1
21.1	70	25	-0.00088	24.94941	1838.9	12682.7
21.1	70	10	-0.00088	9.979766	1523.0	10504.5
21.1	70	5	-0.00088	4.989883	1284.0	8855.5
21.1	70	1	-0.00088	0.997977	787.4	5430.7
21.1	70	0.5	-0.00088	0.498988	616.8	4254.4
21.1	70	0.1	-0.00088	0.099798	337.2	2325.4
37.8	100	25	-1.2496	1.407156	882.9	6089.1
37.8	100	10	-1.2496	0.562862	644.3	4443.6
37.8	100	5	-1.2496	0.281431	499.2	3442.8
37.8	100	1	-1.2496	0.056286	272.2	1877.4
37.8	100	0.5	-1.2496	0.028143	212.2	1463.7
37.8	100	0.1	-1.2496	0.005629	128.0	883.1
54.4	130	25	-2.37128	0.106332	345.3	2381.8
54.4	130	10	-2.37128	0.042533	245.7	1694.8
54.4	130	5	-2.37128	0.021266	192.8	1329.6
54.4	130	1	-2.37128	0.004253	118.8	819.1
54.4	130	0.5	-2.37128	0.002127	100.3	692.0
54.4	130	0.1	-2.37128	0.000425	74.3	512.5

Table B-8 MEPDG Input for DBM Base Course mix

Temp °C	Temp °F	Frequency Hz	Shift Factor	Reduced Frequency	|E*| ksi	|E*| MPa
-10.0	14	25	3.875844	187838.1	3349.3	23099.9
-10.0	14	10	3.875844	75135.22	3344.3	23065.5
-10.0	14	5	3.875844	37567.61	3339.1	23029.6
-10.0	14	1	3.875844	7513.522	3319.6	22895.0
-10.0	14	0.5	3.875844	3756.761	3306.4	22804.2
-10.0	14	0.1	3.875844	751.3522	3257.4	22466.6
4.4	40	25	1.967714	2320.885	3294.8	22724.6
4.4	40	10	1.967714	928.3538	3265.8	22524.1
4.4	40	5	1.967714	464.1769	3235.7	22316.7
4.4	40	1	1.967714	92.83538	3125.9	21559.7
4.4	40	0.5	1.967714	46.41769	3054.5	21066.9
4.4	40	0.1	1.967714	9.283538	2805.8	19351.4
21.1	70	25	-0.00124	24.92882	2973.8	20510.2
21.1	70	10	-0.00124	9.971527	2819.8	19448.0
21.1	70	5	-0.00124	4.985763	2670.7	18420.1
21.1	70	1	-0.00124	0.997153	2203.2	15195.3
21.1	70	0.5	-0.00124	0.498576	1952.8	13468.3
21.1	70	0.1	-0.00124	0.099715	1316.4	9078.9
37.8	100	25	-1.75914	0.435311	1901.1	13111.9
37.8	100	10	-1.75914	0.174124	1538.7	10612.7
37.8	100	5	-1.75914	0.087062	1263.2	8712.2
37.8	100	1	-1.75914	0.017412	707.6	4880.0
37.8	100	0.5	-1.75914	0.008706	529.2	3650.0
37.8	100	0.1	-1.75914	0.001741	263.0	1813.8
54.4	130	25	-3.3382	0.011475	595.3	4105.9
54.4	130	10	-3.3382	0.00459	400.4	2761.8
54.4	130	5	-3.3382	0.002295	295.9	2041.0
54.4	130	1	-3.3382	0.000459	155.5	1072.7
54.4	130	0.5	-3.3382	0.000229	123.3	850.5
54.4	130	0.1	-3.3382	4.59E-05	81.5	562.4

APPENDIX C

PHASE ANGLE RESULTS

Table C-1 Phase Angle Results for NHA-A Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	5.43	7.62	7.51	**6.85**	1.234	18
	10	6.67	8.88	8.84	**8.13**	1.265	15.55
	5	7.91	9.73	10.03	**9.22**	1.147	12.44
	1	11.64	12.78	13.68	**12.70**	1.022	8.05
	0.5	10.97	14.20	15.37	**13.51**	2.28	16.86
	0.1	17.49	17.95	20.33	**18.59**	1.524	8.2
21.1	25	12.23	16.64	17.02	**15.30**	2.66	17.41
	10	18.07	18.62	19.36	**18.68**	0.647	3.46
	5	20.15	20.51	21.74	**20.80**	0.817	3.93
	1	25.95	26.04	28.00	**26.66**	1.158	4.34
	0.5	27.99	27.68	29.94	**28.54**	1.225	4.29
	0.1	30.89	30.31	33.25	**31.48**	1.557	4.95
37.8	25	24.17	27.22	20.51	**23.97**	3.36	14.02
	10	28.87	31.27	24.18	**28.11**	3.61	12.83
	5	30.88	32.90	26.52	**30.10**	3.26	10.83
	1	33.72	33.89	31.08	**32.90**	1.576	4.79
	0.5	33.46	32.82	32.28	**32.85**	0.591	1.8
	0.1	31.02	27.99	32.92	**30.64**	2.49	8.11
	0.01	26.89	24.33	25.33	**25.52**	2.33	9.1
54.4	25	32.68	30.71	25.87	**29.75**	3.5	11.78
	10	36.16	33.49	29.91	**33.19**	3.14	9.45
	5	37.50	34.53	31.58	**34.54**	2.96	8.57
	1	36.53	33.70	34.34	**34.86**	1.484	4.26
	0.5	34.71	31.65	34.39	**33.58**	1.682	5.01
	0.1	26.77	25.55	31.22	**27.85**	2.98	10.72

Table C-2 Phase Angle Results for NHA-B Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees)					
		Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	7.61	8.68	6.84	**7.71**	0.92	11.99
	10	9.00	10.11	8.25	**9.12**	0.94	10.26
	5	10.07	11.32	9.41	**10.27**	0.97	9.45
	1	13.68	15.13	12.86	**13.89**	1.15	8.28
	0.5	15.32	16.92	14.70	**15.65**	1.15	7.32
	0.1	20.31	22.22	19.78	**20.77**	1.28	6.18
21.1	25	16.81	17.41	18.42	**17.55**	0.81	4.64
	10	19.81	20.74	22.08	**20.88**	1.14	5.47
	5	22.02	23.15	24.63	**23.27**	1.31	5.63
	1	28.51	28.86	30.73	**29.37**	1.19	4.06
	0.5	30.48	30.59	32.32	**31.13**	1.03	3.32
	0.1	33.30	32.76	34.08	**33.38**	0.68	2.03
37.8	25	28.32	21.51	23.18	**24.34**	3.55	14.58
	10	32.39	25.18	27.49	**28.35**	3.68	12.99
	5	34.04	27.62	29.89	**30.52**	3.26	10.67
	1	34.89	31.88	34.27	**33.68**	1.59	4.72
	0.5	33.59	32.97	35.17	**33.91**	1.13	3.35
	0.1	28.45	32.61	33.40	**31.49**	2.70	8.55
	0.01	24.22	26.55	29.63	**26.80**	3.93	14.40
54.4	25	33.57	37.00	26.32	**32.30**	5.45	16.88
	10	36.92	36.73	30.85	**34.83**	3.45	9.91
	5	34.68	35.55	32.84	**34.36**	1.38	4.03
	1	27.85	30.45	35.18	**31.16**	3.72	11.93
	0.5	24.45	27.27	34.54	**28.75**	5.21	18.11
	0.1	18.98	21.89	30.21	**23.69**	5.83	24.60

Table C-3 Phase Angle Results for Superpave-1 Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees)					
		Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	9.27	8.65	8.31	**8.74**	0.49	5.57
	10	9.93	10.00	9.80	**9.91**	0.10	1.02
	5	11.06	11.18	10.92	**11.05**	0.13	1.18
	1	14.45	14.76	14.30	**14.50**	0.24	1.62
	0.5	16.01	16.41	15.96	**16.13**	0.25	1.53
	0.1	20.25	20.92	20.76	**20.64**	0.35	1.70
21.1	25	17.37	19.16	16.73	**17.75**	1.26	7.09
	10	20.42	22.37	19.85	**20.88**	1.32	6.33
	5	22.72	24.65	22.22	**23.20**	1.28	5.53
	1	27.81	29.90	27.62	**28.44**	1.27	4.45
	0.5	29.52	31.78	29.50	**30.27**	1.31	4.33
	0.1	32.60	35.11	33.09	**33.60**	1.33	3.96
37.8	25	26.96	23.79	23.36	**24.70**	1.97	7.96
	10	29.98	26.92	26.56	**27.82**	1.88	6.76
	5	31.65	28.94	28.46	**29.68**	1.72	5.79
	1	34.62	33.43	32.65	**33.57**	0.99	2.96
	0.5	34.67	34.67	33.40	**34.25**	0.73	2.14
	0.1	33.24	35.33	33.76	**34.11**	1.09	3.19
	0.01	31.30	32.20	30.40	**31.30**	2.10	6.70
54.4	25	29.12	35.89	28.68	**31.23**	1.09	3.19
	10	31.73	38.29	30.59	**33.54**	4.04	12.94
	5	33.22	39.04	32.12	**34.79**	4.16	12.39
	1	35.19	38.44	34.46	**36.03**	2.12	5.88
	0.5	34.67	37.17	35.94	**35.93**	1.25	3.48
	0.1	35.42	32.24	32.76	**33.47**	1.71	5.10

Table C-4 Phase Angle Results for MS-2 Wearing Course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	6.20	4.72	8.58	**6.50**	1.95	29.96
	10	7.06	5.64	9.97	**7.56**	2.21	29.21
	5	8.03	6.25	11.13	**8.47**	2.47	29.16
	1	10.36	8.01	14.43	**10.93**	3.25	29.71
	0.5	11.88	9.39	15.94	**12.40**	3.31	26.66
	0.1	15.86	12.82	20.34	**16.34**	3.78	23.15
21.1	25	18.22	18.34	18.12	**18.23**	0.11	0.60
	10	21.70	21.41	20.38	**21.16**	0.69	3.28
	5	24.22	24.10	22.90	**23.74**	0.73	3.07
	1	29.78	29.95	28.24	**29.32**	0.94	3.21
	0.5	31.27	31.45	30.03	**30.92**	0.77	2.50
	0.1	32.94	33.63	32.10	**32.89**	0.77	2.34
37.8	25	22.14	21.95	21.79	**21.96**	0.18	0.80
	10	26.11	25.74	25.53	**25.79**	0.29	1.14
	5	28.37	28.01	27.68	**28.02**	0.35	1.23
	1	32.43	32.25	31.46	**32.05**	0.52	1.61
	0.5	33.27	33.28	32.19	**32.91**	0.63	1.90
	0.1	32.22	33.21	31.36	**32.26**	0.93	2.87
	0.01	34.41	34.98	33.36	**34.25**	0.82	2.40
54.4	25	30.91	35.48	35.44	**33.94**	2.63	7.74
	10	33.45	37.34	35.92	**35.57**	1.97	5.53
	5	34.60	37.89	35.32	**35.94**	1.73	4.81
	1	34.87	35.62	31.45	**33.98**	2.22	6.54
	0.5	33.49	33.16	28.77	**31.81**	2.64	8.28
	0.1	27.48	26.47	22.44	**25.46**	2.67	10.47

Table C-5 Phase Angle Results for NHA-A Base course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	6.91	12.15	9.24	**9.43**	2.63	27.83
	10	9.30	13.75	11.07	**11.37**	2.24	19.70
	5	10.38	15.35	12.52	**12.75**	2.49	19.55
	1	14.16	19.08	17.26	**16.83**	2.49	14.78
	0.5	16.24	20.60	19.25	**18.70**	2.23	11.94
	0.1	20.78	25.59	24.86	**23.74**	2.59	10.92
21.1	25	12.03	12.78	11.69	**12.17**	0.56	4.58
	10	14.14	14.79	13.82	**14.25**	0.49	3.47
	5	15.70	16.47	15.69	**15.95**	0.45	2.80
	1	20.37	20.97	20.68	**20.67**	0.30	1.45
	0.5	22.33	22.87	22.84	**22.68**	0.30	1.34
	0.1	29.00	29.39	30.40	**29.60**	0.72	2.44
37.8	25	24.38	16.97	19.47	**20.27**	3.77	18.59
	10	28.92	19.73	22.94	**23.86**	4.64	19.42
	5	31.54	21.65	25.21	**26.13**	5.01	19.17
	1	34.38	27.53	31.53	**31.15**	3.44	11.05
	0.5	33.94	29.81	33.16	**32.30**	2.19	6.79
	0.1	30.24	33.08	32.66	**31.99**	1.53	4.79
	0.01	20.90	21.01	20.50	**20.80**	0.27	1.29
54.4	25	23.67	31.34	18.87	**24.63**	6.29	25.54
	10	28.22	34.80	22.76	**28.59**	6.03	21.08
	5	30.43	36.28	25.32	**30.68**	5.48	17.88
	1	32.90	36.24	31.00	**33.38**	2.65	7.95
	0.5	32.69	34.67	32.07	**33.14**	1.36	4.10
	0.1	28.68	28.33	28.86	**28.62**	0.27	0.94

Table C-6 Phase Angle Results for NHA-B Base course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	9.55	8.22	8.47	**8.75**	0.71	8.08
	10	11.38	9.68	9.98	**10.35**	0.91	8.77
	5	13.11	10.96	11.44	**11.84**	1.13	9.53
	1	17.82	14.81	15.45	**16.03**	1.59	9.89
	0.5	19.86	16.35	17.27	**17.83**	1.82	10.21
	0.1	25.34	20.76	22.35	**22.82**	2.33	10.19
21.1	25	12.51	12.69	13.42	**12.87**	0.48	3.74
	10	14.80	15.03	16.06	**15.30**	0.67	4.39
	5	16.48	16.87	17.90	**17.08**	0.73	4.29
	1	21.27	22.14	23.19	**22.20**	0.96	4.33
	0.5	23.37	24.35	25.33	**24.35**	0.98	4.02
	0.1	28.85	30.01	30.05	**29.64**	0.68	2.30
37.8	25	17.51	15.56	18.59	**17.22**	1.54	8.92
	10	20.84	18.41	22.32	**20.52**	1.97	9.62
	5	22.85	20.37	25.13	**22.78**	2.38	10.45
	1	28.42	26.12	30.29	**28.28**	1.99	7.07
	0.5	30.11	28.23	31.89	**30.08**	1.83	6.09
	0.1	32.00	31.35	32.84	**32.06**	0.75	2.33
	0.01	21.99	22.46	23.39	**22.61**	0.71	3.15
54.4	25	39.11	22.98	20.86	**27.65**	9.98	36.10
	10	37.68	27.69	25.05	**30.14**	6.66	22.10
	5	34.93	29.78	27.77	**30.83**	3.69	11.98
	1	27.96	32.52	32.58	**31.02**	2.65	8.54
	0.5	24.84	32.56	33.69	**30.36**	4.82	15.86
	0.1	19.69	29.30	32.09	**27.03**	6.51	24.07

Table C-7 Phase Angle Results for Superpave-2 Base course mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	7.63	7.52	8.86	**8.00**	0.74	9.30
	10	9.70	8.67	10.34	**9.57**	0.84	8.80
	5	10.64	9.73	11.64	**10.67**	0.96	8.95
	1	15.23	12.69	15.63	**14.52**	1.60	10.98
	0.5	16.22	14.15	17.60	**15.99**	1.74	10.86
	0.1	20.27	18.05	23.08	**20.47**	2.52	12.32
21.1	25	13.38	10.79	12.43	**12.20**	1.31	10.74
	10	15.77	12.35	15.66	**14.59**	1.94	13.32
	5	17.65	13.90	17.28	**16.28**	2.07	12.70
	1	23.02	18.30	22.27	**21.20**	2.54	11.97
	0.5	25.64	20.43	24.57	**23.55**	2.75	11.69
	0.1	31.90	27.53	30.71	**30.05**	2.26	7.52
37.8	25	15.32	19.90	20.33	**18.52**	2.78	15.00
	10	18.16	24.49	23.89	**22.18**	3.45	15.59
	5	20.39	26.96	26.47	**24.61**	3.66	14.87
	1	26.45	31.79	32.01	**30.08**	3.15	10.47
	0.5	28.82	32.31	33.57	**31.57**	2.46	7.80
	0.1	33.17	33.52	35.07	**33.92**	1.01	2.98
	0.01	45.95	46.22	50.33	**47.50**	2.45	5.17
54.4	25	33.53	41.18	21.10	**31.94**	10.13	31.73
	10	36.88	39.96	25.17	**34.00**	7.80	22.95
	5	38.13	36.60	27.53	**34.09**	5.73	16.81
	1	37.93	28.28	32.21	**32.81**	4.85	14.79
	0.5	36.83	24.99	33.65	**31.82**	6.13	19.26
	0.1	30.38	20.19	33.85	**28.14**	7.10	25.23

Table C-8 Phase Angle Results for DBM Base course Mix

Temperature (Celsius)	Frequency (Hz)	Phase Angle (Degrees) Specimen 1	Specimen 2	Specimen 3	Average	S.D	C.V (%)
4.4	25	8.38	6.41	4.64	**6.48**	1.96	30.55
	10	9.81	7.37	5.30	**7.49**	30.13	2.26
	5	10.89	8.22	6.02	**8.38**	2.44	29.11
	1	14.49	10.55	7.87	**10.97**	3.33	30.35
	0.5	16.16	11.67	8.58	**12.14**	3.81	31.40
	0.1	21.25	14.84	11.25	**15.78**	5.07	32.10
21.1	25	12.06	8.21	6.73	**9.00**	2.75	30.57
	10	14.65	10.06	7.67	**10.79**	3.55	32.87
	5	16.00	11.53	8.60	**12.04**	4.20	35.89
	1	20.17	16.07	11.38	**15.87**	4.40	27.71
	0.5	23.07	17.21	13.03	**17.77**	5.04	28.38
	0.1	29.40	23.20	18.50	**23.70**	5.47	23.07
37.8	25	21.41	15.44	26.07	**20.97**	5.33	25.41
	10	25.39	18.20	30.83	**24.81**	6.34	25.54
	5	27.77	20.11	32.38	**26.75**	6.20	23.17
	1	31.30	25.47	34.23	**30.33**	4.46	14.70
	0.5	31.65	27.66	33.68	**31.00**	3.06	9.88
	0.1	30.44	30.89	30.49	**30.61**	0.25	0.81
	0.01	22.41	22.87	22.78	**22.69**	0.24	1.07
54.4	25	19.01	34.95	20.34	**24.77**	8.84	35.71
	10	22.28	35.70	24.74	**27.57**	7.14	25.91
	5	24.25	35.36	26.96	**28.86**	5.79	20.07
	1	28.94	31.57	31.37	**30.63**	1.46	4.78
	0.5	30.11	29.18	33.05	**30.78**	2.02	6.56
	0.1	30.07	23.49	31.61	**28.39**	4.31	15.19

APPENDIX D

|E*| MODEL OUTPUTS

Nonlinear Regression Analysis for Wearing Course Mixes

Iteration History (b)

Iteration Number	Residual SS	Parameter a	b	c	d
1.0	3.253E10	.010	.010	.010	.010
1.1	2.057E153	.588	13.175	19.817	22.033
1.2	1.369E14	.068	1.327	1.991	2.213
1.3	3.253E10	.016	.142	.208	.230
2.0	3.253E10	.016	.142	.208	.230
2.1	3.253E10	.019	.186	.275	.307
3.0	3.253E10	.019	.186	.275	.307
3.1	3.253E10	.023	.231	.341	.385
4.0	3.253E10	.023	.231	.341	.385
4.1	3.253E10	.027	.276	.406	.462
5.0	3.253E10	.027	.276	.406	.462
5.1	3.253E10	.033	.320	.470	.539
6.0	3.253E10	.033	.320	.470	.539
6.1	3.253E10	.040	.363	.532	.614
7.0	3.253E10	.040	.363	.532	.614
7.1	3.252E10	.047	.406	.592	.689
8.0	3.252E10	.047	.406	.592	.689
8.1	3.251E10	.057	.449	.652	.764
9.0	3.251E10	.057	.449	.652	.764
9.1	3.249E10	.068	.492	.712	.837
10.0	3.249E10	.068	.492	.712	.837

10.1	3.244E10	.081	.534	.770	.911
11.0	3.244E10	.081	.534	.770	.911
11.1	3.236E10	.096	.577	.828	.983
12.0	3.236E10	.096	.577	.828	.983
12.1	3.221E10	.115	.619	.885	1.055
13.0	3.221E10	.115	.619	.885	1.055
13.1	3.193E10	.136	.660	.941	1.126
14.0	3.193E10	.136	.660	.941	1.126
14.1	3.144E10	.161	.700	.995	1.195
15.0	3.144E10	.161	.700	.995	1.195
15.1	3.065E10	.189	.737	1.047	1.261
16.0	3.065E10	.189	.737	1.047	1.261
16.1	2.940E10	.225	.776	1.101	1.331
17.0	2.940E10	.225	.776	1.101	1.331
17.1	2.815E10	.273	.804	1.154	1.410
18.0	2.815E10	.273	.804	1.154	1.410
18.1	2.771E10	.332	.732	1.152	1.482
19.0	2.771E10	.332	.732	1.152	1.482
19.1	2.688E10	.437	.585	1.140	1.605
20.0	2.688E10	.437	.585	1.140	1.605
20.1	2.448E10	.640	.271	1.139	1.911
21.0	2.448E10	.640	.271	1.139	1.911
21.1	1.747E10	1.004	-.306	1.103	2.595
22.0	1.747E10	1.004	-.306	1.103	2.595
22.1	7.892E9	1.897	-.468	.270	3.438
23.0	7.892E9	1.897	-.468	.270	3.438

23.1	1.427E10	5.794	-.604	.127	3.001
23.2	5.592E9	2.700	-.595	.133	3.604
24.0	5.592E9	2.700	-.595	.133	3.604
24.1	5.735E9	4.399	-.599	.163	3.352
24.2	5.418E9	3.354	-.599	.163	3.497
25.0	5.418E9	3.354	-.599	.163	3.497
25.1	5.325E9	4.705	-.591	.163	3.349
26.0	5.325E9	4.705	-.591	.163	3.349
26.1	5.105E9	6.081	-.591	.163	3.265
27.0	5.105E9	6.081	-.591	.163	3.265
27.1	5.040E9	8.838	-.591	.163	3.108
28.0	5.040E9	8.838	-.591	.163	3.108
28.1	4.796E9	10.226	-.590	.163	3.081
29.0	4.796E9	10.226	-.590	.163	3.081
29.1	4.698E9	12.762	-.591	.163	2.990
30.0	4.698E9	12.762	-.591	.163	2.990
30.1	4.587E9	15.537	-.591	.162	2.919
31.0	4.587E9	15.537	-.591	.162	2.919
31.1	4.494E9	21.089	-.591	.162	2.793
32.0	4.494E9	21.089	-.591	.162	2.793
32.1	4.322E9	26.645	-.591	.162	2.715
33.0	4.322E9	26.645	-.591	.162	2.715
33.1	4.255E9	37.758	-.591	.161	2.569
34.0	4.255E9	37.758	-.591	.161	2.569
34.1	4.031E9	48.874	-.591	.161	2.486
35.0	4.031E9	48.874	-.591	.161	2.486

35.1	3.994E9	71.106 -.592	.161	2.328
36.0	3.994E9	71.106 -.592	.161	2.328
36.1	3.751E9	82.223 -.592	.160	2.301
37.0	3.751E9	82.223 -.592	.160	2.301
37.1	3.668E9	102.482-.592	.160	2.212
38.0	3.668E9	102.482-.592	.160	2.212
38.1	3.570E9	124.717-.592	.160	2.140
39.0	3.570E9	124.717-.592	.160	2.140
39.1	3.498E9	169.186-.593	.160	2.014
40.0	3.498E9	169.186-.593	.160	2.014
40.1	3.342E9	213.655-.593	.159	1.935
41.0	3.342E9	213.655-.593	.159	1.935
41.1	3.302E9	302.594-.593	.159	1.789
42.0	3.302E9	302.594-.593	.159	1.789
42.1	3.114E9	347.063-.593	.159	1.761
43.0	3.114E9	347.063-.593	.159	1.761
43.1	3.044E9	427.509-.594	.158	1.677
44.0	3.044E9	427.509-.594	.158	1.677
44.1	2.962E9	516.448-.594	.158	1.607
45.0	2.962E9	516.448-.594	.158	1.607
45.1	2.905E9	694.327-.594	.158	1.484
46.0	2.905E9	694.327-.594	.158	1.484
46.1	2.771E9	872.206-.594	.158	1.407
47.0	2.771E9	872.206-.594	.158	1.407
47.1	2.748E9	1227.963-.595	.157	1.263
48.0	2.748E9	1227.963-.595	.157	1.263

48.1 2.577E9 1405.842-.595 .157 1.235

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 183 model evaluations and 88 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.00E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	714298.941	29590.361	656301.000	772294.000
b	-.603	.016	-.634	-.571
c	.152	.008	.137	.168
d	-1.133	.160	-1.447	-.819

Correlations of Parameter Estimates

	a	b	c	d
a	1.000	-.042	-.006	-.996
b	-.042	1.000	-.002	-.031
c	-.006	-.002	1.000	-.025
d	-.996	-.031	-.025	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3.111E10	4	7.776E9
Residual	1.429E9	284	5032464.462
Uncorrected Total	3.253E10	288	
Corrected Total	1.393E10	287	

Dependent variable: E_

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .897.

Nonlinear Regression Analysis for Base Course Mixes

Iteration History (b)

Iteration Number	Residual SS	a	b	c	d
1.0	5.037E10	.010	.010	.010	.010
1.1	9.423E153	.576	14.631	18.819	22.786
1.2	1.662E14	.067	1.472	1.891	2.288
1.3	5.037E10	.016	.156	.198	.238
2.0	5.037E10	.016	.156	.198	.238
2.1	5.037E10	.019	.204	.262	.317
3.0	5.037E10	.019	.204	.262	.317
3.1	5.037E10	.023	.253	.326	.398
4.0	5.037E10	.023	.253	.326	.398
4.1	5.036E10	.027	.301	.389	.478
5.0	5.036E10	.027	.301	.389	.478
5.1	5.036E10	.032	.349	.450	.558
6.0	5.036E10	.032	.349	.450	.558
6.1	5.036E10	.039	.395	.511	.637
7.0	5.036E10	.039	.395	.511	.637
7.1	5.035E10	.046	.441	.570	.715
8.0	5.035E10	.046	.441	.570	.715
8.1	5.033E10	.055	.487	.628	.793
9.0	5.033E10	.055	.487	.628	.793
9.1	5.029E10	.066	.532	.686	.870
10.0	5.029E10	.066	.532	.686	.870
10.1	5.023E10	.078	.577	.743	.946

11.0	5.023E10	.078	.577	.743	.946
11.1	5.010E10	.093	.622	.799	1.022
12.0	5.010E10	.093	.622	.799	1.022
12.1	4.985E10	.111	.666	.855	1.098
13.0	4.985E10	.111	.666	.855	1.098
13.1	4.938E10	.132	.710	.910	1.173
14.0	4.938E10	.132	.710	.910	1.173
14.1	4.853E10	.156	.753	.965	1.246
15.0	4.853E10	.156	.753	.965	1.246
15.1	4.706E10	.184	.794	1.017	1.317
16.0	4.706E10	.184	.794	1.017	1.317
16.1	4.452E10	.218	.836	1.070	1.392
17.0	4.452E10	.218	.836	1.070	1.392
17.1	4.096E10	.260	.878	1.123	1.469
18.0	4.096E10	.260	.878	1.123	1.469
18.1	3.890E10	.327	.882	1.147	1.569
19.0	3.890E10	.327	.882	1.147	1.569
19.1	3.809E10	.393	.809	1.098	1.642
20.0	3.809E10	.393	.809	1.098	1.642
20.1	3.645E10	.522	.680	1.022	1.818
21.0	3.645E10	.522	.680	1.022	1.818
21.1	3.218E10	.754	.418	.886	2.239
22.0	3.218E10	.754	.418	.886	2.239
22.1	1.784E10	1.136	-.085	.580	3.213
23.0	1.784E10	1.136	-.085	.580	3.213
23.1	1.647E10	3.160	-.374	-.112	3.702

24.0	1.647E10	3.160	-.374	-.112	3.702
24.1	6.712E9	4.258	-.362	.162	3.537
25.0	6.712E9	4.258	-.362	.162	3.537
25.1	6.648E9	6.561	-.325	.170	3.254
26.0	6.648E9	6.561	-.325	.170	3.254
26.1	6.120E9	7.739	-.324	.172	3.225
27.0	6.120E9	7.739	-.324	.172	3.225
27.1	6.057E9	9.895	-.324	.172	3.117
28.0	6.057E9	9.895	-.324	.172	3.117
28.1	5.941E9	12.249	-.324	.172	3.036
29.0	5.941E9	12.249	-.324	.172	3.036
29.1	5.926E9	16.960	-.325	.171	2.893
30.0	5.926E9	16.960	-.325	.171	2.893
30.1	5.721E9	19.318	-.324	.171	2.862
31.0	5.721E9	19.318	-.324	.171	2.862
31.1	5.656E9	23.613	-.325	.171	2.776
32.0	5.656E9	23.613	-.325	.171	2.776
32.1	5.573E9	28.329	-.325	.171	2.706
33.0	5.573E9	28.329	-.325	.171	2.706
33.1	5.533E9	37.761	-.325	.171	2.580
34.0	5.533E9	37.761	-.325	.171	2.580
34.1	5.381E9	47.195	-.325	.170	2.499
35.0	5.381E9	47.195	-.325	.170	2.499
35.1	5.392E9	66.064	-.326	.170	2.350
35.2	5.293E9	56.173	-.325	.170	2.434
36.0	5.293E9	56.173	-.325	.170	2.434

36.1	5.253E9	74.128 -.326	.170	2.313
37.0	5.253E9	74.128 -.326	.170	2.313
37.1	5.117E9	92.083 -.326	.170	2.234
38.0	5.117E9	92.083 -.326	.170	2.234
38.1	5.126E9	127.994-.326	.170	2.088
38.2	5.035E9	109.245-.326	.170	2.170
39.0	5.035E9	109.245-.326	.170	2.170
39.1	4.998E9	143.570-.326	.170	2.050
40.0	4.998E9	143.570-.326	.170	2.050
40.1	4.870E9	177.895-.326	.169	1.972
41.0	4.870E9	177.895-.326	.169	1.972
41.1	4.883E9	246.545-.327	.169	1.828
41.2	4.794E9	210.082-.326	.169	1.910
42.0	4.794E9	210.082-.326	.169	1.910
42.1	4.759E9	274.455-.327	.169	1.793
43.0	4.759E9	274.455-.327	.169	1.793
43.1	4.641E9	338.828-.327	.169	1.715
44.0	4.641E9	338.828-.327	.169	1.715
44.1	4.656E9	467.575-.327	.169	1.573
44.2	4.570E9	398.346-.327	.169	1.655
45.0	4.570E9	398.346-.327	.169	1.655
45.1	4.538E9	517.381-.327	.169	1.541
46.0	4.538E9	517.381-.327	.169	1.541
46.1	4.430E9	636.416-.327	.168	1.464
47.0	4.430E9	636.416-.327	.168	1.464
47.1	4.446E9	874.486-.327	.168	1.324

Derivatives are calculated numerically.

a. Major iteration number is displayed to the left of the decimal, and minor iteration number is to the right of the decimal.

b. Run stopped after 225 model evaluations and 102 derivative evaluations because the relative reduction between successive residual sums of squares is at most SSCON = 1.00E-008.

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	1609273.900	105562.482	1402371.000	1816175.000
b	-.333	.015	-.362	-.304
c	.164	.009	.145	.182
d	-1.670	.265	-2.192	-1.148

Correlations of Parameter Estimates

	a	b	c	d
a	1.000	-.076	.006	-.998
b	-.076	1.000	.005	.023
c	.006	.005	1.000	-.031
d	-.998	.023	-.031	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	4.731E10	4	1.183E10
Residual	3.052E9	284	1.075E7
Uncorrected Total	5.037E10	288	
Corrected Total	1.324E10	287	

Dependent variable: E

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .769.