LABORATORY CHARACTERIZATION OF HMA MIXES SUBJECTED TO INDIRECT TENSILE FATIGUE TEST

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DEDICATION

This thesis is dedicated to my parents who taught me that even the most difficult task can be accomplished if it is done one step at a time, my siblings for their constant moral support, and last but not the least all my teachers who have been encouraging, inspiring and mentoring me throughout my entire life.

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LIST OF ACRONYMS

AASHTO – American Association of State Highway and Transportation Officials

AC – Asphalt Concrete

ARL – Attock Refinery Limited

ASTM – American Society for Testing and Materials

BBR – Bending Beam Rheometer

HMA – Hot Mix Asphalt

ITFT – Indirect Tensile Fatigue Test

LVDT – Linear Variable Differential Transformer

MAPE – Mean Absolute Percentage Error

MEPDG – Mechanistic Empirical Pavement Design Guide

NCHRP – National Cooperative Highway Research Program

NHA – National Highway Authority

NRL – National Refinery Limited

OBC – Optimum Bitumen Content

PG – Performance Grading

RTFO – Rolling Thin Film Oven

RV – Rotational Viscometer

SGC – Superpave Gyratory Compactor

SHRP – Strategic Highway Research Program

UTM – Universal Testing Machine

VA – Air Voids

VFA – Voids Filled with Asphalt

VMA – Voids in Mineral Aggregate

ABSTRACT

Fatigue in the Hot Mix Asphalt (HMA) pavements is an important distress mainly caused due inadequate and deficient initial pavement structure and bituminous mixture design. This study investigates the fatigue characteristics of four selected wearing course gradations, including two gradations NHA A and NHA B adopted from local agencies and two gradations adopted from Superpave (SP-1) and Asphalt Institute manual series (MS-2), using the indirect tensile fatigue test under stress controlled mode subjected to the conditions prevailing in Pakistan. The material encompassed in the experimental design include aggregate from Margalla quarry and two bitumen grades of different stiffness, categorized according to penetration grade of 40/50 and 60/70. Marshall Mix design approach was used to define the optimum bitumen content to be used for each of the eight combinations of HMA mixtures which was further used to fabricate samples for the performance testing using Superpave gyratory compactor. The indirect tensile fatigue test was conducted on the prepared samples at 25 °C subjected to repeated haversine loading at a series of stress levels, ranging from 2000N to 5500N, in Universal Testing Machine (UTM-25). The results from the performance testing were screened and used to develop fatigue curves for each of the eight different HMA mixtures using the stress/strain approach, relationship between number of cycle to failure and initial strain. Further, the data for all the HMA mixtures was used collectively to develop a non-linear regression model including the bitumen viscosity, optimum bitumen content and the resilient modus as additional variables. In order to relatively characterize the different HMA mixtures, it was found that MS-2 gradation performed much better than any other gradation following the same trend by using either softer bitumen (60/70) or the stiffer bitumen (40/50). The results also revealed that using a stiffer bitumen (40/50) caused the number of cycles to failure for the HMA mixtures to increase by 2 to 3 times than using the softer bitumen (60/70) in the stress-controlled conditions.

Chapter 1

INTRODUCTION

1.1 BACKGROUND

The modern day pavements in Pakistan, and mostly all around the world, have been constructed to serve a particular need without considering about the future demands which may be placed upon them due to financial constraints. However, the early engineers and Romans (the pioneers in pavements construction) were able to build long lasting roads by going on the expensive side and increasing the cost of the structure. The engineers today face the challenge of building not only longer lasting stronger pavements but also in a restrained budget to full fill the demand of transporting people and goods from one place to another. Transportation has been playing a vital role in the advancement of the society, and the most widely used mode of transportation is the land mode and specifically highway mode. According to the economic survey of Pakistan in 2012-13 there are roughly a total of 250,000km long road network, out of which most of the pavements are comprised of hot mix asphalt (HMA) and its appraised asset value is worth over Rupees 2500 billion. Unfortunately, most of this valuable asset is being and has been lost due to the premature development of fatigue cracking and rutting in the asphalt bound layers progressing rapidly to levels of high severity in asphalt concrete pavements in Pakistan. The distresses mentioned earlier are caused mainly due to inadequate initial pavement structural design and deficient bituminous mixture designs.

The hot mix asphalt (HMA) pavement structures, also known as flexible pavements, require a more economic and suitable design as compared to other engineering structures. A pavement that is not designed for a higher level of loading will fail earlier than the design life costing more money for repair. For decreasing the chance of early maintenance and repair problems, the most effective process is to appropriately choose the material for construction and use suitable values of design parameters for the flexible pavements design. (MS-4 Asphalt Handbook). Currently, in Pakistan, AASHTO Guide for Design of Pavement Structure along with the Marshall method are mostly used for structural and bituminous mixture design of asphalt concrete pavements respectively. These procedures are empirical which were developed as long as half a century ago for much lighter traffic and low tire pressures compared to the existing conditions in Pakistan. Therefore, the procedures being used are incapable of providing reliable designs for heavy axle loads and tire pressure existing in Pakistan today. It is appropriate to mention that the inadequate design is the most costly variable in the life-cycle cost analysis of highway pavements, since these are responsible for the premature and rapid deterioration in spite of the best possible quality control and construction practices. The use of AASHTO procedure for designing asphalt concrete pavements in Pakistan has been under discussion since the very start of asphaltic pavements. The mechanistic-empirical approach is promising but for it to produce satisfactory and cost-efficient asphalt mix design with appropriate equipment and local distress models and its field verification has become absolutely essential.

Fatigue cracking has been a problem in the performance and design of hot mix asphalt (HMA) pavements since the hot mix asphalt pavements are being used. The pavement structures that have lesser thickness fail under repeated loads. The type of structural failure resulting from repeated loading HMA mixtures results in the formation of fatigue cracking. The most important property, along with many numerous properties of the HMA mixtures, is adjusting the thickness of the HMA which in result effect the tensile strains at the bottom of the HMA layer. The tensile strain at the bottom of the HMA layer is the prime cause of the bottom-up fatigue cracking. Eventually, a method is required to define the tensile strains at the bottom of the HMA layer efficiently and subsequently determine the effect of the strains on the fatigue resistance of different mixtures. The laboratory tests used to determine the fatigue life of particular HMA mixes do not provide an accurate prediction of what is observed in the field but can give a relative comparison of different HMA mixes among each other. There is a need for a shift factor to be defined to correlate the results of the laboratory test and the field results as there are many reasons, including: aging, healing, densification due to traffic loading, rest periods, temperature variation throughout the entire design life.

The concept of constant stress and constant strain is also not the case in the field due to different loading conditions, along with that the environment changes the properties of the binder and the field compaction compared to the simulated laboratory compaction. The primary factor in the design of hot mix asphalt (HMA) pavements is to resist the rutting of subgrade and fatigue cracking, majorly bottom-up cracking. The hot mix asphalt (HMA) is characterised as viscoelastic material as it possesses both the characteristics of an elastic material and a viscous material, and this makes this a complex material. In conventional pavement design the thickness of the pavement increases as does the load applications on the pavement. Increasingly people believe that bottom-up fatigue cracking does not occur for thick pavements. There is a concept that below a particular level of strain there is no cumulative damage to the pavement over an infinite number of load cycles, and the concept is termed is termed as the endurance limit of HMA pavement. Hence the additional pavement thickness, more than the thickness required to maintain the required strains at the bottom below the endurance limit will just increase the cost of the structure but not increase the life of the pavement.(NCHRP 646)

A number of studies have been conducted concerned about the fatigue behaviour of asphalt mixtures all through the last two to three decades, and people have struggled to incorporate the conclusions of these studies into the pavement design process. The lengthy and time-consuming aspect of fatigue testing has led to the development of fatigue life predictive equations resulting from the initial strains and applied stresses to the HMA mixes. However, more and more research is required to develop and improve the equation and models.

Fatigue is a phenomenon in which an asphalt pavement is subjected to repeated stress levels less than the ultimate failure stress. Fatigue behaviour of asphalt mixtures is studied using two approaches, the traditional approach using the strain (or stress)-based models, and the dissipated energy approach were the dissipated energy is used and defined as damage indicator of the material. In addition, fatigue failure is defined using the stress-strain hysteresis loop in each loading cycle of the fatigue test.

The research was carried out to perform the indirect tensile fatigue test on laboratory compacted specimens to find the effect of varying the gradations and the type of bitumen. The specimens of each gradation were subjected to six different load levels to attain a fatigue curve for the plot of number of cycles to failure against the initial strain for each load level, and further modes were developed for the different gradations and different bitumen sources to compare which gradation and bitumen source works better.

1.2 PROBLEM STATEMENT

Pakistan is a developing country and the estimated length of road network currently present is approximately 260,000 km and this is a national asset. To maintain the asset annually huge amounts of budget are spent, and for a developing country it matters a lot. So to cater the efficient use of the allocated budget a system is to be developed so that the desired level of service is achieved during the construction, rehabilitation and maintenance of the HMA pavements. In Pakistan the empirical design approach is being used which does not include the effect of the distress on the design life of a pavement. Once the level of the severity of distresses is incorporated in the design, it will be helpful to minimize the distress by compensating the material and HMA mix properties. The mechanistic-empirical design can be used to cater the effect of climate, traffic loading and material properties in the pavement performance. In order to advance in direction where the large investments in motorways and expressways are at stake it is correct to rate the asphalt mix designs through performance based testing. This procedure will certainly help in saving the large investments and stop the brutal cycle where constructed pavements deteriorate at a much rapid pace than predicted.

The problems discussed earlier certify the requirement of a study to assist in the implementation of the mechanistic-empirical design approach in Pakistan. In this regard, the National Highway Authority (NHA) of Pakistan in collaboration with National University of Science and Technology, Islamabad and University of Engineering & Technology, Lahore and Taxila initialised a research project by the name of "Improvement of Asphalt Mix Design Technology for Pakistan" for the local materials, hot climate conditions, heavy axle loads and high tire pressure existing in Pakistan. This research is a part of a larger project which initially focuses on the laboratory experiments including the evaluation, modification and adoption of the bituminous mixture design methodology for designing rut and fatigue resistant pavements. The laboratory investigation of fatigue failure of compacted HMA mixtures using indirect tensile fatigue testing is a part of the overall study to characterize different HMA mixes.

1.3 RESEARCH OBJECTIVES

The implementation of the mechanistic-empirical design needs complete characterization of the laboratory prepared samples and the field data. The research objectives of the current study are as follows:

- To conduct indirect tensile fatigue test in order to characterise relatively the different HMA mixes used in the research.
- To develop laboratory based fatigue models for all the eight HMA mixes used in the research.

1.4 SCOPE OF THE THESIS

To accomplish the research objectives mentioned earlier in the thesis a methodology was planned and few of the major tasks have been highlighted. To get a detailed insight of the parameter affecting the fatigue life of HMA mixes subjected to indirect tensile fatigue testing including the effect of gradation and variation in bitumen source, literature review of the former research carried out which covers the testing and findings. The study comprises of four gradations for wearing courses, using two bitumen sources of NRL 40/50 and ARL 60/70 and the aggregate is procured from Margalla quarry. The initial stage of study includes the characterization of aggregate and bitumen, the fundamental ingredients of a HMA mix, in the laboratory followed by the determination of the optimum bitumen content (OBC) for all the different HMA mixes using Marshall Mix Design methodology. Based on the results of optimum bitumen contents 4 inch diameter cylindrical sample prepared by coring from 6 inch diameter cylindrical specimen compacted using Superpave Gyratory Compactor (SGC) to perform Indirect Tensile Fatigue Test using the jig assembly of indirect tension test in the Universal Testing Machine (UTM-25) according to EN 12697-24D and BS DD ABF. Once the performance testing is complete the statistical analysis is performed on the data, further developing fatigue curves and model for different HMA mixes.

1.5 ORGANIZATION OF THESIS

The research is organised into five chapters. Chapter one gives a brief introduction to the HMA mix performance test carried out in the research, also the problem statement, objectives and the scope of the research. The second chapter includes the detailed explanation of phenomenon of fatigue along with the different tests with their significance and procedure, the study of previous research studies related to the fatigue test and the factors affecting the fatigue life of different HMA mixes. Further in the third chapter the complete characterization of the basic ingredients of the HMA mixes which are the aggregate and binder, the detailed laboratory tests are defined and procedure is explained. The chapter three also illustrates the research methodology including the HMA mix preparation, optimum bitumen content determination and the performance test. The chapter four elaborates the results and analysis performed on the results, the fatigue curves and the models generated from the data of number of cycles to failure. The last and final chapter five clarifies the conclusions drawn from the research carried and further the recommendations and future work needed to be carried out. The organization of the thesis can also be illustrated by Figure 1.1.

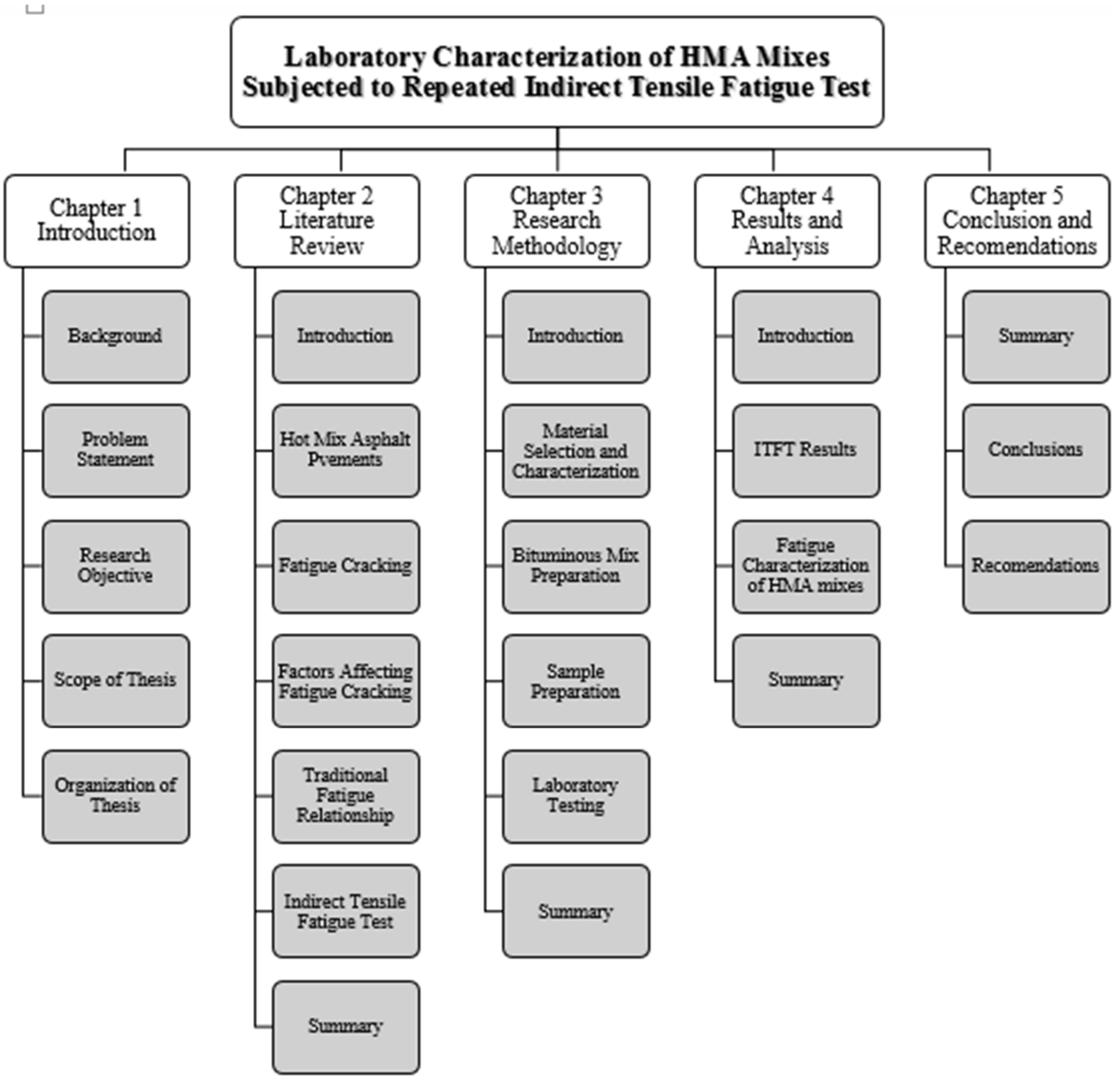

Figure 1. 1 Organization of Thesis

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter gives a review of the related literature and the concept behind the fatigue cracking in hot mix asphalt pavements. A brief review of the asphalt concrete pavements is given followed by viscoelastic properties and the distresses caused in the pavement due to loading and other factors discussed further in the chapter. Further the study of fatigue cracking along with the factors affecting fatigue in pavements and also the traditional approach used to study these distresses is discussed. The performance test used in the research, the Indirect Tensile Fatigue Test, has also been studied and some recent researches carried out using the particular performance test are also summarised.

The primary objective of the design of a hot mix asphalt (HMA) pavement is to resist the rutting of the subgrade and the bottom-up fatigue cracking. In a traditional approach while designing a pavement the thickness of the pavement must increase with an increase in the design load, and this traditional approach is based on the concept that in the case of thicker pavements bottom-up cracking does not occur. The concept of endurance limit for the HMA pavement is taken into account which states that there is a strain level below which no damage is accumulated for infinite number of loading cycles. Therefore, by increasing the pavement thickness greater than that required to keep strain levels at the bottom of HMA layer below the endurance limit will not provide more life to the pavement but instead over budget the project (NCHRP 646). This concept has been taken in to account in this research to take step in finding the endurance limit for the HMA mixes used in Pakistan.

2.2 HOT MIX ASPHALT PAVEMENTS

Hot mix asphalt pavements are one of the many types of flexible pavements. The design of flexible pavements has progressively evolved from an art to a complicated science, but still the empirical approach in the design still has an important role in the pavement design. In earlier days up to 1920s, the thickness of the pavement was determined on the basis of experience or certain thumb rules and the same thickness of the pavement was used for a particular section of the pavement irrespective of the varying underlying soil conditions. As time passed and more and more experience was gained different agencies started to develop various methods to determine the thickness required for a particular pavement.

The flexible pavement under loading responds elastically and the strength of the pavement is achieved from the load distribution property of the layered system (Lenz 2011). The load applied on top of the flexible pavement causes different stresses and strains throughout the layers from top to the bottom decreasing in magnitude. The typical cross section of the layered system in a flexible pavement is shown in Figure 2.1.

The design of flexible pavements is classified into five different categories including the empirical method with or without the soil strength, the limiting shear failure method, limiting deflection method, regression method based on the road test or pavement performance and mechanistic-empirical method (Huang). The mechanistic-empirical method is based on the mechanical properties of the materials which give a relation between the input, in the form of loading, and the output, in the form of stresses and strains in the pavement. The stress strain values, response values, are used to determine the distress from laboratory and field data. This approach is much better as the performance cannot be determined by theory alone. In 1960 (Saal and Pell) for the very first time recommended the use of horizontal tensile strains at the bottom of the asphaltic layer to minimise the effect of fatigue cracking, resulting in bottom-up cracking. The flexible pavements are designed primarily to resist fatigue cracking at the bottom of HMA layer and rutting due to the compressive load on the top of subgrade. The most important and significant distress in the flexible pavement are the cracking, which occurs at low temperature and also due to repeated loading, and rutting, that is caused mainly due to high temperature.

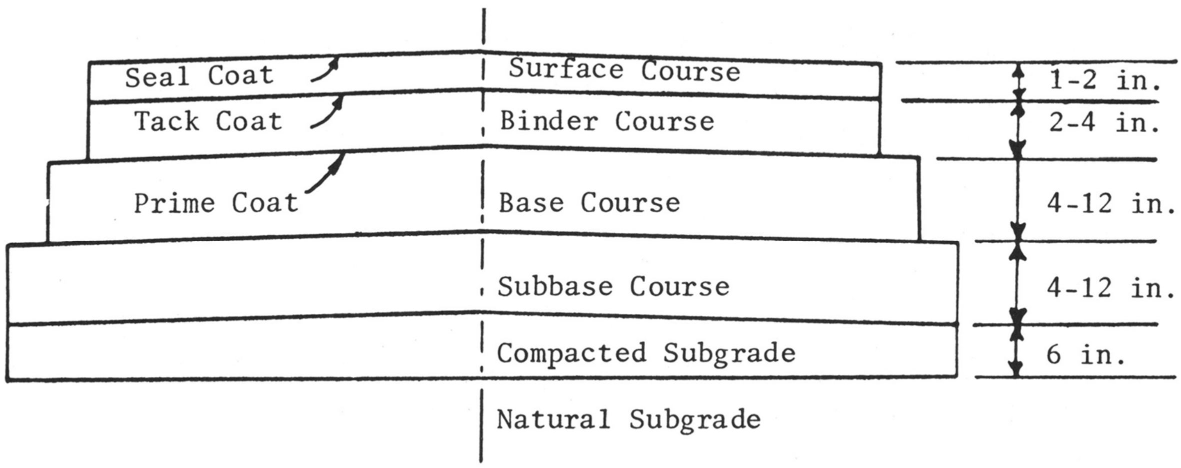

Figure 2. 1 Typical cross section of the layered system in conventional flexible pavement

2.2.1 Viscoelastic properties of HMA Pavement

The materials which store some of the mechanical energy and dissipate the rest in response to any mechanical stress are defined as viscoelastic materials. In 2000 (Robert. N. H) described bitumen as a viscoelastic material and this behaviour is dependent on both temperature and the time of loading. The bitumen once at low temperature and short loading behaves as an elastic solid, whereas at higher temperatures and loading behave has a viscous material. At intermediate temperatures the material behaves in a very complex nature.

The HMA pavements have bitumen as a binder which makes the HMA mix a viscoelastic material also. The Figure 2.2 shows the response of elastic, viscous and viscous elastic material under same stress. In the elastic materials the strains produced in the material are proportional to the stresses applied, and once the load is removed the material recovers completely to its original position. Strains in viscous materials increase with time under constant loading, and once loading removed the material stays in the deformed state. The behaviour of viscoelastic materials is a mix of both viscous and elastic materials, the constant stress increases the strain and once the load is removed the materials recovers but some deformation is retained by the material.

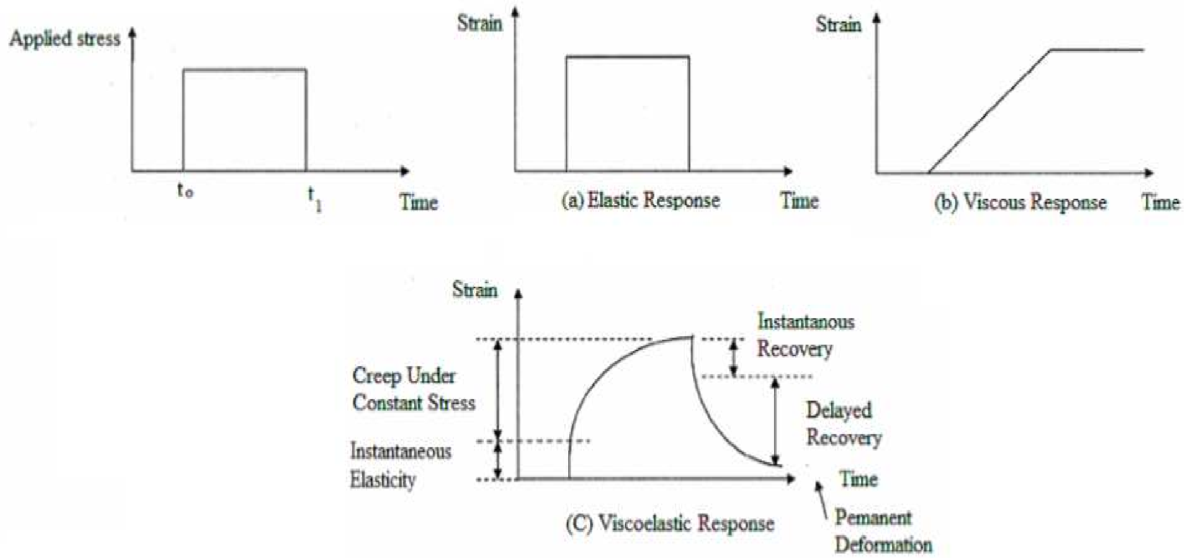

Figure 2. 2 Response of material under constant stress loading (Van der Poel, 1954)

2.2.2 Stress & Strain in HMA Pavement

The structure of the flexible pavement generally consist of an asphaltic layer on top (asphaltic wearing course and asphaltic base course), then comes the base and sub base layer and then the compacted and natural subgrade as shown in Figure 2.1. The top layer of the pavement needs to be smooth to provide a comfortable ride and at the same time strong enough to resist the stresses applied on it. Basically flexible pavements are defined more accurately as asphalt bound layer laid on a granular base that rests on the natural subgrade soil. The property which defines a flexible pavement is actually the response of the pavement structure once loaded, the pavement structure bends with the applied load.

The pavement is distributed into three main layers which flex under the applied loading: surface course, base course and sub-base (AASHTO 2000). The HMA pavement consist of a viscoelastic binder that makes the mixture have the property to flex and return to original state under a moving load, the HMA pavement should have a balance of stiffness and flexibility so that with high stiffness it is capable of resisting permanent deformation and also sufficient tensile strength that it is able to resist fatigue cracking at the bottom of the asphaltic layer after many load repetitions. Figure 2.3 shows the orientation of principal stresses (vertical, horizontal and shear stress) induced in the flexible pavement with the rolling wheel passing over it.

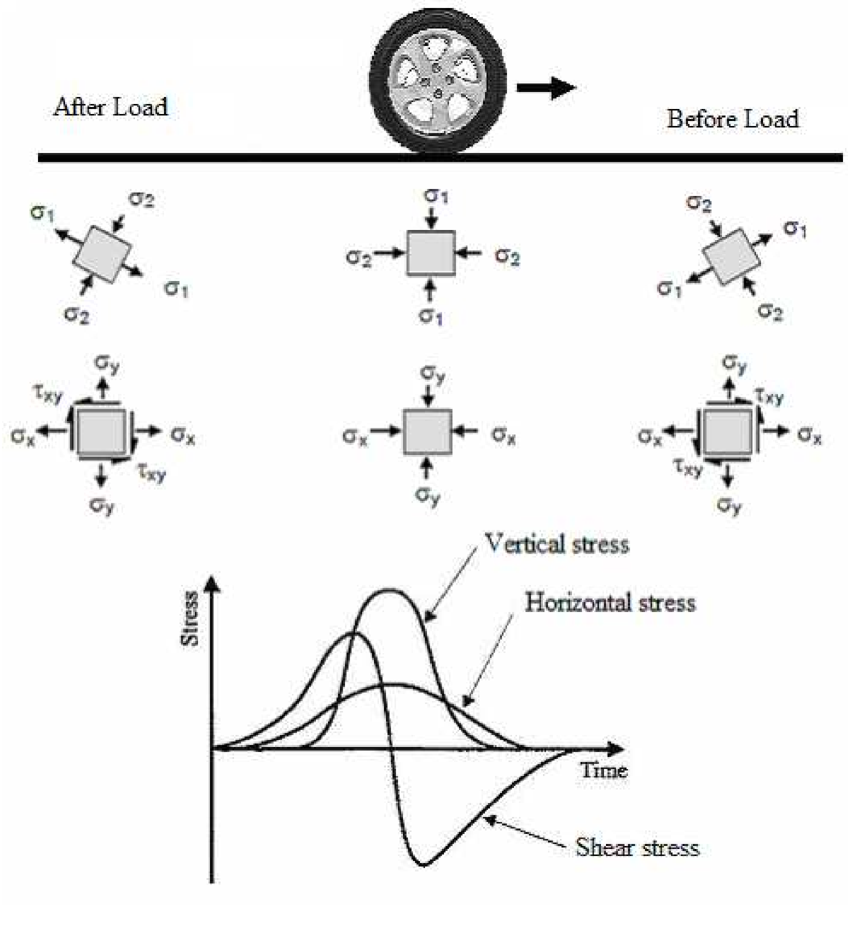

Figure 2. 3 Principle stresses under the rolling wheel load (Shaw, 1980)

2.2.3 Distresses in HMA Pavements

Distress is the most important factor to be considered in the pavement design as it is directly related to the pavement performance. Each of the failure criteria defined under distresses needs to be used in the mechanistic-empirical design approach. Among the various distress some are caused due to the deficits in materials, construction and proper maintenance and are not related to the pavement design directly. The distress evaluation in pavements is an important part of the pavement management system, if the pavements are evaluated properly and a strategy is developed in an effective method then proper maintenance and rehabilitation can be performed at the right time.

Typical pattern observed in deterioration of HMA pavements is rutting, this develops rapidly in the initial years and then levels off to a much slower rate. The fatigue cracking usually does not occur until several repeated loadings, once it starts then it increases rapidly as the pavement is weakened. Generally the main causes of the failure of HMA pavements are the defect in quality of material used along with the method of construction and quality control during construction, the surface and subsurface drainage problem, increase in traffic volume and the magnitude of wheel load, deformation in foundation, and the environmental factors including heavy rainfall, snow, rising water table, frost action. The distresses in pavement are classified into three major groups named as cracking, deformation and surface defects according to (Miller and Bellinger, 2011).

2.3 FATIGUE CRACKING

Fatigue cracking in flexible pavements are a series of interconnected cracks caused by the fatigue failure of asphalt concrete subjected to repeated loading. Fatigue is generally defined as “the phenomenon of fracture under repeated or fluctuating stress having a maximum value generally less than the tensile strength of the material” (Pell, P.S., 1971). The definition has been applied to the pavements with the assumption that the only mechanism producing stresses and strains in the pavements are the wheel load. The definition of fatigue was further improved and defined as “the phenomenon in bituminous pavements causing cracking, consisting of two phases of crack initiation and crack propagation, and caused by tensile strains generated in the pavement not only by traffic loading but also temperature variation and construction practices” (Wu, F., 1992).

In 1971, Terrel mentioned the importance of acquiring the understanding of crack mechanism of asphalt pavements in order to improve the fatigue performance. Fatigue cracking is the reason for fatigue failure of the asphaltic layers and the temperature, loading rate and aging are among the many factors that affect the fatigue mechanism. Due to the complex interaction of all these factors advanced mechanics principles like viscoelasticity, damage mechanics and fracture mechanics are used. Monismith, et al. in 1985 divided the damage in the structure of the HMA pavement into cracking and deformation, both of which are due to the environment and the repeated loading. Fatigue cracking decreases service life of the pavement which leads to the breakdown of pavement structure. Further defined the factors that affect the pavement performance and may lead to distresses in pavement such as the frequency and magnitude of load density, the duration for the application of load and the variation in temperature of pavement.

The cracks generally initiate at the bottom of the HMA layer where the tensile stresses and strains are the most under wheel load in the layered system. In 1994 Lytton, et al. explained the two phases of fatigue cracking, the crack initiation phase followed by the crack propagation. The conjoining of micro-cracks to form a macro crack due to repeated application of tensile strains is defined as the crack initiation phase, while the crack growth is the escalation of macro cracks through the mix once the tensile strains are further applied. Many complex tests have been developed to measure the crack initiation phase but still no reliable method developed to measure the crack propagation. Fatigue properties of HMA mix cannot be studied alone but the stiffness of the material is to be considered as this determines the magnitude of tensile strain experienced by the mixture. HMA mixtures under traffic loading at high temperature are not capable to maintain their original shape resulting in rutting in the pavement, and at lower temperatures the stiffer structure of HMA pavement tends to become brittle and is unable to resist the internal stresses caused by the traffic loading resulting in cracking (AASHTO, 2002). Wide range of testing has been has been carried out since the fifties and throughout different number of test setup have been developed. Some of the tests are classified according to the method of loading being applied to the specimen. The main classifications according to the loading method are:

- Simple Flexural
- Direct Axial Loading
- Diametric Loading

Figure 2.4 gives a preview of the schematic representation of some of the tests that are used mostly. The arrows in the figure represent the load applied on the specimens causing fatigue failure due to the stresses and strains produced in the specimens.

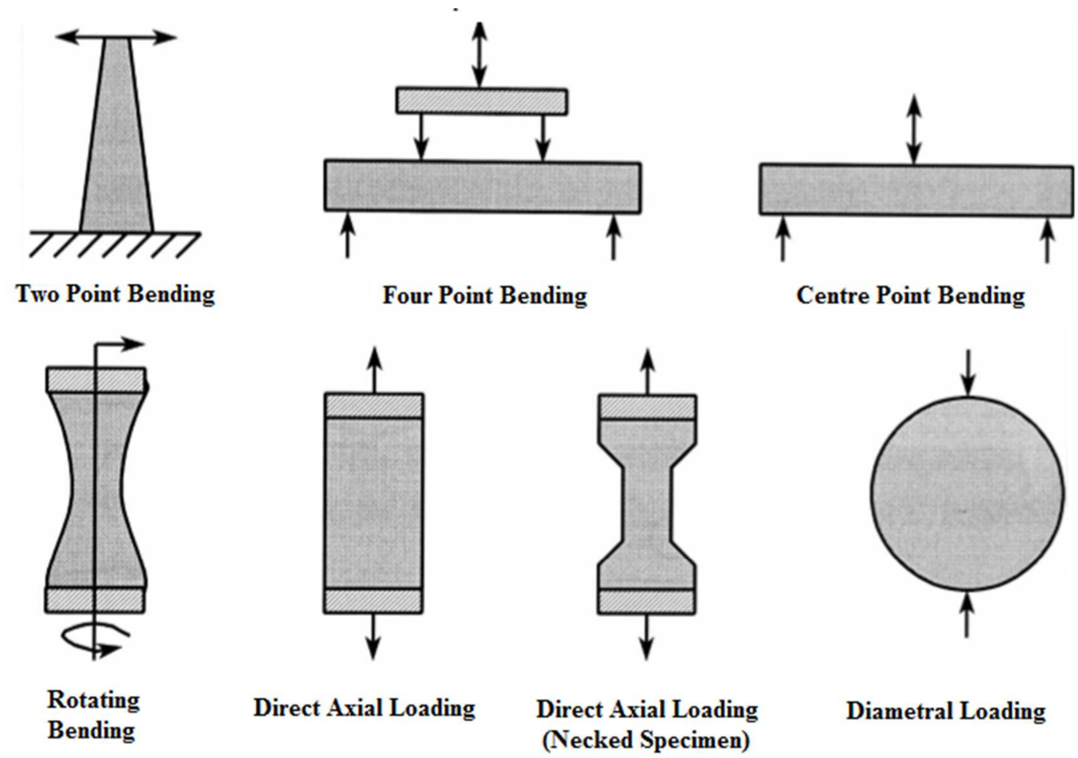

Figure 2. 4 Schematic representation of fatigue tests

As shown in Figure 2.4 the simple flexural tests include the four point bending test, centre point loading test, rotating cantilever beam flexure and two point flexure test using trapezoidal cantilever specimens. The cylindrical specimen and necked cylindrical specimen in tension and compression come under direct axial loading test, and the diametral loading is shown. The three tests methods have their own advantages and disadvantages and these are summarised in Table 2.1 in a summarized form as discussed by Judycki (1991).

Table 2. 1 Advantages and disadvantages of fatigue test with respect to mode of loading

Tests	Advantages	Disadvantages
Simple Flexural	• Well known and widespread • Used for both material evaluation and pavement design • Results can directly be used to estimate tendency of cracking in pavement structure • Stress controlled for design of thick and strain controlled for design of thin pavements • Failure in four point bending is initiated in region of uniform stress helping to reduce the coefficient of variation of results	• Validation of laboratory to filed test difficult due to requirement of shift factor • Costly, time consuming and require specialised equipment • State of stress uniaxial, unlike pavement structure • Centre point loading not suitable for materials with stiffness less than 3000 MPa • The clamping in centre point loading affects the accuracy • Tests do provide inadequate data for thickness of pavement between 50 and 150 mm (state of intermediate loading between stress and strain mode)
Direct Axial Loading	• Less costly, simpler and testing time shorter compared to flexural tests • Tensile stresses and strains are measured easily • Specimen fabrication is easier as mostly cylindrical sample required • Pure state of stress/strain with no shear reduces the complexity in result analysis	• The test does not simulate the field conditions of stress and strains in the pavement structure

Diametral Loading	• Relatively simple to conduct • Equipment can be used for other tests also • Filed cores can be tested • Biaxial stress represent the field condition better than the uniaxial stresses • Failure initiated in area of relatively uniform tensile stress not affected by surface conditions • Fewer specimens required due to low coefficient of variation relative to other test	• Ratio of tensile and compressive stresses at the centre of specimen cannot be varied to duplicate field condition • Stress concentration and distribution at the point of loading are different compared to field • Stress reversal in field cannot be achieved • Permanent deformation occurs during test that is not allowed in flexural test • Fatigue life determined vary significantly from those determined by other tests

2.4 FACTORS AFFECTING FATIGUE

Fatigue is one of the major distress in HMA pavements and the factors affecting fatigue in any HMA mixture are the mode of loading, the stresses induced in the pavement, the loading pattern and rest periods, and the mixture variables. It is necessary to know how loading is applied to the pavement structure in order to simulate loading condition in tests. Figure 2.3 shows the different principal stresses developed with time as the wheel moves over a particular point on the HMA pavement. The loading time depends on the speed of the vehicle, and the depth of the pavement surface below the wheel. As an example a 150 mm thick pavement the vehicle moving at a speed of 60 km/h will be simulated by a loading cycle of 0.015 sec (Collop and Cebon, 1995). HMA pavement are bituminous materials which are viscoelastic in nature and the properties are time dependant and is directly related to the magnitude of the tensile strain developed resulting in fatigue failure. In 2014, Gazi and Khalid investigated the combined effect of stress level, loading frequency and temperature on the fatigue life of HMA mixtures using the indirect tensile fatigue test.

2.4.1 Mode of Loading

In fatigue tests there are two basic modes of loading used for either thick pavements or thin pavements as follows:

- Strain Controlled
- Stress Controlled

Strain controlled mode of loading is used to simulate conditions in thinner pavements as generally thin pavements experience tensile strains at the bottom of the HMA layer and due to the strains develop cracks are initiated and further loading aids in there propagation, while the stress controlled mode of loading is used for thicker pavements as the cracking occurs on the top of the HMA layer due to the localised stresses developed because of the tire pavement interaction. The mechanism of the modes of loading is shown in Figure 2.5, in stress controlled mode the amplitude of the load applied to the specimen is kept constant during the test and in strain controlled mode the amplitude of the deformation applied to the specimen is kept constant.

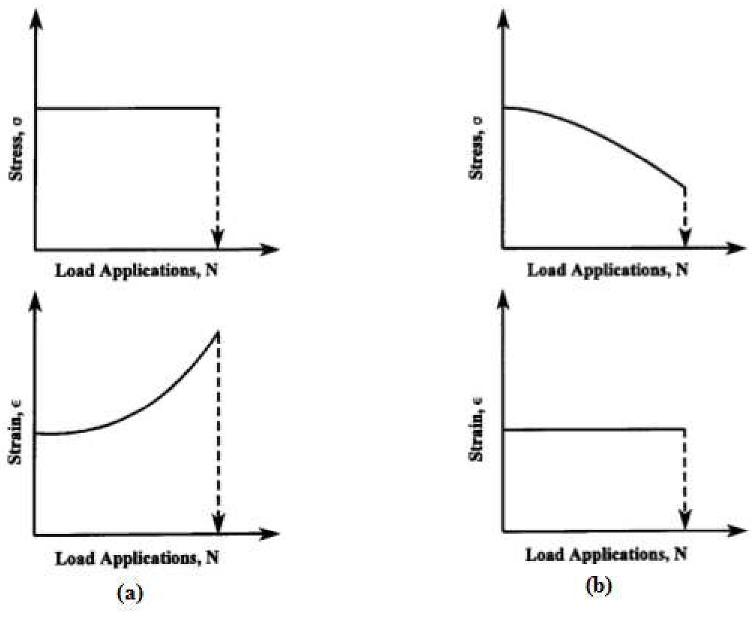

Figure 2. 5 Modes of controlled loading for Fatigue Tests (Epps and Monismith 26)

The stress and strain controlled tests for the same HMA mixture under same conditions have different results, and this difference is explained by the mechanism of failure by Brown (1978). The failure is in two phases as mentioned earlier, the cracks are developed a distinct points where the stresses are of higher concentration and then the cracks propagate through the mixture until complete failure is occurred. In a stress controlled test the crack propagation is very fast as the propagation phase is dependent on the intensity of stress at the tip of cracks. Meanwhile in strain controlled test the stress steadily decreases after the initiation phase as the stiffness of the material significantly decreases after that, and due to that reason the propagation phase in strain controlled mode is much longer. In the stress controlled mode of loading the fatigue life decreases with the increase in temperature. Also, increasing the frequency of loading increases the fatigue life of the HMA pavements. (Gazi and Khalid, 2014)

Further physical explanation of the modes of loading in pavement structure are presented by Brown (1978). The HMA pavement is as a whole layered structure that is subjected to stress controlled loading, but the layers which have significant thickness and stiffness are also stress controlled. The thin layers are basically deflected by the underlying structural layers which result in a controlled strain mode of loading. The explanation was further validated by work done in which the pavement structure was analysed using multilayer elastic theory and deduced the following (Monismith and Salam, 1979):

- Strain controlled mode of loading is characteristics of asphalt layers less than 50 mm
- Stress controlled mode of loading is characteristics of asphalt layer greater than 150 mm
- Thickness of asphalt layer from 50 mm to 150 mm some intermediate mode of loading is to be assumed

2.4.2 Load Waveform

The load waveform or the shape of loading wave have a significant effect on the fatigue life of HMA mixtures, and the phenomenon is explained by the energy that is applied into system for each loading cycle(Irwin. L.H., 1977). The same stress amplitude reduces the fatigue life of a specimen more if greater energy is applied for each cycle. The energy applied to the system is proportional to the area covered by the load waveform in the stress/ strain against time plots (Raithby and Sterling, 1972). The different types of loading waveforms are shown in Figure 2.6

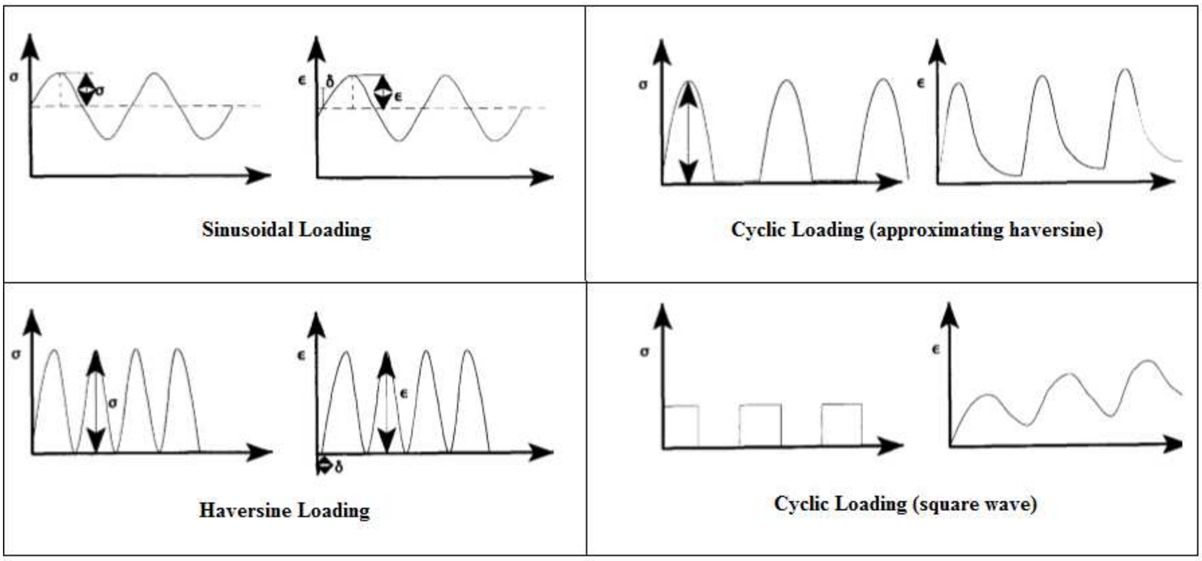

Figure 2. 6 Types of loading waveforms

Apart of the type of loading waveform the frequency of loading and the duration also have a significant effect on the fatigue life of a particular HMA mixture. By decreasing the duration of loading keeping the frequency constant increases the stiffness resulting in the fatigue life. Vice versa increasing the frequency of the load pulse increase the fatigue life of a particular HMA pavement. To simulate the effect of field in laboratory tests there is a need to use a waveform which gives same loading as that in the field, and out the loading waveforms shown in Figure 2.6 the haversine loading best indicates the loading pattern in field.

Decreasing the loading duration in a waveform increases the rest period, and a rest period is the time between two consecutive load applications in the loading waveform. The rest period is important in case of viscoelastic materials as they allow the time for healing in cracks due to the viscous flow of bitumen in the HMA mixtures. The rest period for a particular HMA pavement is different and for different times of the day also. The general conclusion drawn from many studies, conducted to investigate the effect of rest period on the fatigue response of HMA pavements, that the rest period increases the fatigue life of a particular mixture by 5 to 25 times depending on the ratio of loading and rest period.

2.4.3 Mixture Variables

The basic ingredients in HMA mixtures are the aggregates and the bitumen, and the factors affecting the fatigue property of any mix are the types of aggregates being used, the gradation followed, the type of bitumen and the amount of bitumen in the mixture. The primary material properties affecting the fatigue life of a particular mix are the bitumen content, the stiffness of bitumen and the air voids present in the mix. Aggregate gradations, shape angularity and type have a more limited effect as they do not affect the mixture properties directly but indirectly by changing the bitumen content for each type of HMA mix. A lot of work has been done to check the significance of material variable on the fatigue life of HMA mixtures, but significant work has been done by Cooper and Pell (1974). The mixture variables having a significant effect on the fatigue life are as follows:

Mixture Stiffness – the stiffness can be affected by the type of bitumen, loading speed, compaction and the temperature, but the factors which affect the fatigue life the most are the temperature and the speed of loading. In a strain controlled mode of loading higher stiffness results in lower fatigue life while in the stress controlled mode the response is opposite, high stiffness results in higher fatigue life. However the results in the stress controlled mode are presented using the initial strain and the cycles to failure, and the relationship is not dependent on the stiffness of the HMA mix (Pell, P.S., 1973 and Brown et al. 1995). The mixtures with higher stiffness should be used in thicker pavements and lower stiffness mixtures to be used in thin pavements which are subjected to strain controlled conditions.

Bitumen Content – the bitumen content of any particular mix is determined once calculating the optimum bitumen content for the mix. The bitumen content has a significant effect on the fatigue life of a HMA mixture. Increasing the bitumen content increases the resistance of a mixture to fatigue failure, but the bitumen should be within a practical limit. Using the maximum bitumen allowable within the limits according to the deformation limits can provide a longer fatigue life (Gibb, J.M.,1996).

Bitumen Properties – the stiffness and thermal susceptibility are the most important properties of bitumen for the fatigue evaluation of a particular HMA mixture, these properties are generally expressed by terms like stiffness modulus, viscosity, penetration and softening point (Shell Handbook 1990). As mentioned earlier also, the fatigue response is influenced by the loading mode and the stiffness of the mixture. Stiffer bitumen used in a test under stress controlled loading provides better results than same test under strain controlled loading conditions. The phenomenon has been validated in the laboratory by Epps and Monismith (1971) using strain controlled mode and stress controlled mode by Copper and Pell (1974). Based on earlier work at University of Nottingham Brown et al, (1982) suggested the use of 50 pen grade bitumen instead of 100 pen grade for the conventional materials, the analysis showed that there was a considerable amount of increase in fatigue life that could be compensated in reduced thickness of the pavements resulting in reduced costs.

Void Content **–** there evaluation has a direct relation with the compaction of the HMA mixture, studies have evaluated that reducing the air voids will result in higher fatigue life (Judycki 1991). Lesser the voids more the packing of aggregates and more the bitumen filled in the voids increasing the stiffness of the mix. On the other hand there has to be an optimum solution as increasing the fatigue susceptibility of a mix compromises the ability to resist permanent deformation, reducing the air voids means filling the voids with bitumen and increasing the bitumen will push the aggregates apart making the mix more prone to rutting (Gibb, J.M., 1996). Not only the percentage of voids in HMA mixture but also the size, shape and degree of interconnection of aggregate in HMA mix have much importance.

Aggregate **–** these are the building blocks of any HMA mixture as they provide a skeletal structure to the mixture through which load is distributed. Study was conducted by Dukatz (1989) to present the effect of aggregate properties on the fatigue performance of HMA mixtures, and the conclusions drawn from the study show that the durability, toughness, and hardness of aggregate have a dominant effect on the fatigue characteristics of a mixture. Other major properties of aggregate affecting the fatigue performance are the shape, morphology and gradation followed by physical properties of aggregates (absorption, specific gravity, composition and solubility).

The charge on the surface of aggregate and the texture of surface have an insignificant effect on the fatigue life of HMA mixtures. The effect of the gradation keeping it within the permissible limits has very less impact of the fatigue life (Pell and Cooper, 1974), the nominal maximum aggregate size also effects the resistance to fatigue of a particular HMA mixture insignificantly (Moutier et al, 1988).

Filler **–** the effect of a filler material in a HMA mixture to the resistance of fatigue failure studied by many researchers (Barksdale, R.D., 1978 and Bolk et al, 1982). In a controlled stress mode of loading the increase in the amount of filler improves the resistance to fatigue, but the percentage change in mineral filler is less effective than the percentage change in bitumen content. Decreasing the amount of filler below a certain level may result in sharp decrease in the fatigue resistance.

2.5 TRADITIONAL FATIGUE RELATIONSHIPS

One of the major causes of cracking in the HMA pavements is fatigue which is a process of cumulative damage. Traditionally the approach used for fatigue uses the assumption that fatigue failure of a specimen occurs due to the damage caused by repeated dynamic loading. The relations developed to calculate the number of cycles of load repetition are based on stress, strain, energy or the fracture mechanics.

2.5.1 Stress or Strain Based Approach

A number of tests are used to determine the fatigue life of HMA mixtures including direct tension test, repeated flexural test, or diametral test carried out at different stress or strain levels. In 1985, Monismith et al. mentioned that the fatigue characteristics of any HMA mix can be expressed as a relation between the number of cycles to failure and the initial stress or strain. Further, in 2001 Khattak and Baladi reported that the use of controlled stress loading and controlled strain loading to be used. As discussed earlier the strain is kept constant and the load or stress is decreased with the number of repetitions in strain controlled mode, while in stress controlled mode the stress is kept constant but the strain is increased with the number of repetitions. In constant stress mode the failure occurs more quickly and it is more easily defined. In 2014, Gazi and Khalid also verified that the relation between the number of cycles to failure and initial strain is best represented using exponential functional form. The relation between initial stress or strain and the number of cycles to failure can be presented by the following equations:

$$N_f = a\left(\frac{1}{\varepsilon_o}\right)^b \times \left(\frac{1}{S_o}\right)^c$$

$$N_f = d\left(\frac{1}{\sigma_o}\right)^e \times \left(\frac{1}{S_o}\right)^f$$

Where: N_f = Number of Cycles to Failure

ε_o = Initial Strain

σ_o = Initial Stress

S_o = Mixture Stiffness

a, b, c, d, e & f are the coefficients determined experimentally

2.5.2 Energy Based Approach

The amount of energy during repeated dynamic loading is transferred to the material, and some part of the energy is stored by the material dissipating the remaining once the loading is removed. In 2001, Ghazlan, K.A. documented that the fatigue behaviour of HMA mixtures can be predicted using the energy approach. The amount of energy dissipated by the specimen during test relates to the fatigue damage being done. Several energy-dependent models have also been used to predict the fatigue behaviour of different HMA mixtures. The decrease in mechanical properties of HMA mixtures, such as stiffness, during the test can be explained by their dissipated energy.

The energy balance in a HMA mixture relies of the rheological properties of the bitumen and mixture, which in turn depend on the temperature, loading and frequency. Cheng, in 2002 explained that the dissipated and stored energies in the viscoelastic materials can be a reason for fatigue damage. Dissipated energy and the number of cycles are used to evaluate the development and accumulation of damage in HMA mixtures. The initial phase angles between the stress and strain waveform indicate the viscous or elastic nature of a material. The dissipated energy per unit volume per cycle for viscoelastic material is given by the following equation:

$$W_i = \pi\sigma_i\varepsilon_i \sin\delta_i$$

Where:

W_i = Dissipated Energy at load cycle i

σ_i = Stress amplitude at load cycle i

ε_i = Strain amplitude at load cycle i

δ = Phase angle between stress and strain waveforms

Dissipated energy versus the number of cycles to failure could be characterized as follows:

$$N_f = K1\left(\frac{1}{W_i}\right)^{K2}$$

Where:

N_f = Number of cycles to failure

W_i = Dissipated Energy

K1, K2 are the experimentally determined coefficients

2.5.3 Fracture Mechanics Based Approach

The energy required to break the mechanically loaded HMA mixture specimen is measured using fracture mechanics test. The fracture energy and fracture toughness are the two key parameters that can be obtained from the fracture mechanics tests. The fatigue is considered to develop gradually through three phases of crack initiation, stable crack growth and unsable crack propagation. In 2004, Marasteanu et al. experimented many different test methods based on fracture mechanics, including Disk-Shaped Compact Tension Test, Semicircular Bending Test and the Bending Beam Test.

2.6 INDIRECT TENSILE FATIGUE TEST

The Indirect Tensile Fatigue Test due to its simplicity compared to other alternative tests is very appealing, and the cylindrical specimens used in the test are easy to produce in the laboratory or from coring of pavement in the field. Kennedy et al. (1975) in early seventies carried out work to evaluate the performance of Indirect Tensile Fatigue Test in comparison to other test methods. The study concluded that Indirect Tensile Fatigue Test presented much shorter fatigue lives to failure, based on log-log relationship, than the bending beam test or the trapezoidal cantilever test method. The Strategic Highway Research Program (SHRP) of United States evaluated the Indirect Tensile Fatigue Test in comparison to four point bending beam and trapezoidal cantilever test, and the conclusions drawn from the evaluation are shown in the Table 2.2. Indirect Tensile Fatigue Testing subjects the HMA materials to repeated line loading along the vertical diameter of the cylinder shaped specimens. The relative stress distribution along the cylindrical specimen are shown in Figure 2.7. The vertical loading applied to the specimen produce vertical compressive stress and horizontal tensile stress on the diameter of the specimens. The magnitude of stress is maximum at the centre of the specimen. The maximum strain at the centre of the specimen can be calculated taking the following assumptions:

- Material is homogeneous and behaves in linear elastic fashion
- Material behaves in isotropic manner
- Poisson’s ratio for the material is known
- The force is applied as line loading
- Specimen is subjected to plan stress conditions

Table 2. 2 List of advantages and disadvantages of ITFT

Test	Advantages	Disadvantages
Indirect Tensile Fatigue Test	• Test is relatively simple • Response from the test and field correlation can be used to design the HMA mixture and pavement to resist fatigue • Equipment can be used for other tests also • Failure initiated in region of relative uniform tensile stress • Biaxial state of stress better represent field conditions as compared to flexural test • Test can also be performed on field cored samples • Discrimination between mixtures containing different binders can be done on the bases of stiffness and cycles to failure • Repeatability of test for cycles to failure is much better than both trapezoidal or beam flexure test	• Impossible to vary the horizontal and vertical components to replicate the state of stress at critical locations in pavement • Method significantly underestimates the fatigue life is the damage is determined using tensile stress • Absence of stress reversal and accumulation of permanent deformation • Reliability to measure stiffness in not as good as trapezoidal or beam flexural test

Once all the assumptions are met, the stress condition in the cylindrical specimen are given by closed form solution of the theory of elasticity. The maximum tensile strain and stress at the centre of the specimen can be calculated using the following formula:

$$\sigma_0 = \frac{2P}{\pi \times t \times D}$$

$$\varepsilon_0 = \left[\left(\frac{2\Delta H}{D}\right) \times \left(\frac{1+3v}{4+\pi \times v-\pi}\right)\right]$$

Where:

σ_o = Tensile stress at the centre of specimen

ε_o = Tensile strain at the centre of specimen

P = Maximum load

t = Specimen height

D = Specimen diameter

ΔH = Horizontal deformation

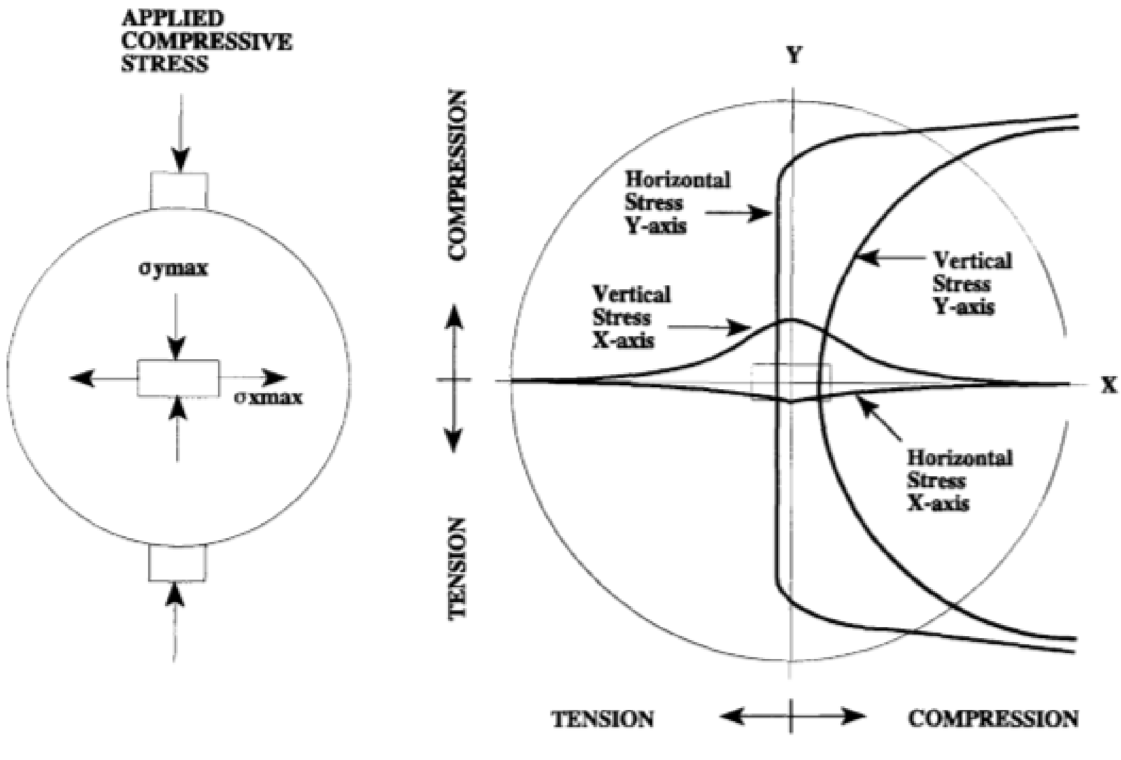

Figure 2. 7 Relative stress distribution along the cylindrical specimen

In 1974 Cooper et. al carried out four years of testing to study the effect of the mix variables on the fatigue strength of the bituminous materials. The fatigue testing was conducted out in stress controlled mode so the results could be analyzed using the applied strains. A great number of mixes were tested under multiple test conditions, like variable binder content, binder type, aggregate gradations and type. The research concluded that the binder type and content, and the shape of the aggregate are the prime factors that affect the fatigue life of different mixes. Also the aggregate gradation has an indirect effect on the fatigue performance as the change in gradation has a direct relation with the binder content of the mix.

Further in 1975 Adedare et. al carried out a research to study the tensile characterization of highway pavement materials. As a part of this research the study of the fatigue and resilient characteristics of asphalt mixtures by repeated-load indirect tensile test was included. The testing for fatigue and repeated load were carried out on a range of temperatures including 50, 75 and 100 °F (10, 24 and 38 °C) along with a sweep of stress levels in the range of 8 and 120 psi. Relationship between fatigue life and other numerous test variables and mix properties were evaluated, and from that different equations were developed to predict the fatigue life of a particular mixture using the initial strain and the ratio of repeated tensile stress to the average indirect tensile strength.

In 2000, Rodrigues developed a model for predicting fatigue cracking in asphaltic pavements on the bases of mixture bonding energy. The damage analysis performed by keeping in view the sequential loss in the bond energy existing in asphaltic concrete mix. Several factors, including the shape of the loading pulse and traffic speed, were considered in the model. The model developed describes a process to analyse the propagation of crack through the asphaltic concrete without calculating the stress intensity factor. Hartman et. al in 2001 carried out research to study the effect of mixture compaction on the indirect tensile stiffness and fatigue. In the study two standard Irish bituminous mixtures were subjected different laboratory compaction techniques including rolling compactor, marshall, vibrating hammer and gyratory compactor to simulate the field compaction and the different orientations and distribution of voids and aggregate particles. The study concluded that the rolling compactor produced specimens similar to the field compaction which produced specimens with lowest stiffness, and the higher fatigue strength was observed in the specimens that were compacted in such a manner to facilitate reorientation of the aggregate particles as is the gyratory compactor.

Further in 2002, Ramsamooj worked on an analytical model to predict the fatigue life of asphalt concrete along with the effect of the size. The fatigue life for 54 types of mixes were used for model prediction in which the effect in mineral properties for each variable, the content and type of asphalt, the additive and filler amount, were accounted for by the creep compliance and fracture, dynamic modulus in bending and flexural tensile strength. The model developed in the study facilitates in the task of improving the resistance to fatigue of the asphaltic concrete or develop new materials with fatigue resistance much greater than those used in the study. Al Qadi and Nassar calculated the shift factors for fatigue used to predict the HMA performance in 2003. The difference of field and laboratory data is accounted generally by a shift factor which caters for the difference in loading, material properties and specimen fabrication process. In this study four different types of shift factors are mentioned including traffic wander, stress state, material properties and HMA healing out of which the stress state and traffic wander are approached.

In 2004 Mesut et. al carried out a research to estimate the fatigue life of asphalt concrete by applying ultrasonic method in the testing. The purpose of the study was to find the possibility of determining the fatigue life of the asphalt concrete specimens without any damage by exploring the ultrasonic method. The research has been carried out in two phase on the same samples, first using the ultrasonic method to characterize the specimens and then the same samples to be tested by applying repeated load in indirect testing equipment. The study concluded that by addition of the new parameters of the ultrasonic analysis in the conventional fatigue models the fatigue life of the specimens is possible to be predicted not including the destruction of the specimens. Additional in 2004, Bhattarcharjee et. al. evaluated the use of accelerated loading equipment in laboratory to determine the performance of different asphaltic mixtures under fatigue. In this study Model Mobile Load Simulator 3 was used to subject hot mix asphalt pavement constructed in laboratory under repeated load application. Various strain gauges were attached to the test slabs to collect data for loading and strains at the bottom so as to analysis it to study the effect of wheel load on the fatigue performance in terms of cracking and strains. Further finite element modelling was used to describe the behaviour of the pavement under different loading conditions and varying pavement thicknesses. The study concluded that the strain is divided into three phases, namely primary, secondary and tertiary with secondary phase most dominant in the case of longitudinal strains. The study also suggested that the number of cycles to failure for field data are higher than the laboratory testing and the newer testing method of loading closely simulates the field conditions. Chatti & Mohtar also in 2004 studied the effect on the fatigue life of asphaltic mixtures under different axle configurations. Trucks varying from 8 axle groups to 11 axles were included in the study, and the indirect tensile cyclic load test was used to load the samples simulating the passage of an entire axle group. The results of the analysis done on the data by using the dissipated energy approach indicated that the damage per load was decreased as the axles were increased in the loading group.

In 2007, Awanti et. al. studied the influence of the rest period on fatigue characteristics of bituminous concrete mixes modified using SBS polymer compared with neat 80/100 penetration grade bitumen. The ratio of rest period duration to loading duration, loading ratio, was increased gradually and in result the different mixes showed increased fatigue life with increase in loading ratios. Also the modified bituminous concrete mixes performed much better than the virgin bituminous mixtures with respect to the fatigue life. Maria and Sanchez used the damage theory approach, in 2008, to represent the behaviour of asphalt concrete during fatigue test. A model on the base of continuous damage has been developed to formulate a method to estimate fatigue curves. Three HMA mixtures were studied in the research using the proposed model and compared with the standard, the results of curves obtained using the model came to be within 95% confidence interval. In 2008, Masad et. al. developed a method to unify the different loading modes in fatigue testing, that are the controlled-strain and controlled-stress conditions. The study uses dynamic mechanical analyser to characterize the fatigue resistance of three different HMA mixes under stress-controlled mode and strain-controlled mode. The unified method is depending on the different mechanisms of energy dissipation during fatigue cracking related to change in stiffness, phase angle and permanent deformation. The study derived two fatigue parameters with reasonable lower coefficient of variation than the conventional parameters.

Weise et. al in 2009 conducted a research to determine the fatigue behaviour of asphaltic base course mixes using both the four point bending test and the indirect tensile test. In this research the testing was conducted on three different asphalt base mixes using the Indirect Tensile Test and Four Point Bending Test to detect a linear correlation between the fatigue functions developed using these test procedures. The results of the research indicate that under the same testing conditions (stress controlled mode and test temperature) similar fatigue relations are developed by both the Indirect Tensile Test and the Four Point Bending Test. Qunshan et. al investigated the fatigue properties along with the dynamic response of fibre-modified asphalt mixes in 2009. There were three fibres used as modifier with different percentages by total weight of the asphalt mixture. The study established that the stiffness of the modified asphalt mixtures was decreased increasing the flexibility which effected the viscoelastic properties of asphalt mixtures. The conclusion of the study was that the fibre modified samples showed better resistance to fatigue as compared to the control samples.

In 2011, Salami and Chatti evaluated the rutting and fatigue prediction models for asphaltic concrete pavement under multiple axle loads. The study compares the results of different methods used to account for the passage of a given axle group using laboratory fatigue and rut data from repeated cyclic loading. The results of the study demonstrate that the dissipated energy and strain area method for fatigue have the best correlation with the laboratory testing, implying the importance of considering the entire strain pulse to calculate the damage due to fatigue subjected to multiple axle loading rather than considering the peak or mid-way method. The study concluded that the procedure used in the MEPDG for calculating the strain under multiple axles underestimates both fatigue and rutting damage, also the calibration procedure does not improve the underestimation. Mogawer et. al. in 2011 evaluated the effect on the fatigue and rutting performance, also the MEPDG distress prediction models of the density of hot mix asphalt. In the study two plant produces mixtures following the superpave gradations of 9.5mm and 12.5mm were used to prepare varying percentages, 88, 91, 94 and 97%, of theoretical maximum specific gravity. Overall the study concluded that the specimens with higher stiffness perform better in fatigue and rutting performance.

In 2013, Wen developed the fatigue model using the fracture density data from the indirect tensile testing of the mix design selected for the study. In this study a performance indicator was to be determined to predict fatigue parameter in the pavement design, also a fatigue model. The fracture work density from the indirect tensile testing was found to have high correlation with the field performance of the same mixes. Therefore, a fatigue model was developed in this study based on the fracture work density to characterize the field fatigue performance. Wen et. al. in 2014 modelled the effect of various factors, including the temperature and loading rate, on the fatigue properties of hot mix asphalt pavement. The study focussed on the critical strain energy density (CSED) as a material property that could be used for fatigue cracking prediction. Indirect tensile test was performed at different temperatures and loading rates to determine hot mixed asphalt properties. The study concluded that time-temperature superposition principal is not valid for IDT strength at both intermediate and low temperatures.

Further in 2014, Gazi and Khalid studied the effect on the fatigue life of asphalt paving mixtures under varying temperature, loading frequency and stress levels using the indirect tensile fatigue test setup. The indirect tensile test was conducted using five stress levels and four loading frequencies (simulating the truck speed of 12.5 to 45 km/h) at two intermediate temperature levels of 20°C and 30°C. The study concluded that the fatigue life increases exponentially by increasing the loading frequency. On the other hand the fatigue life decreased by increasing the temperature. Also, non-linear power model is the best suited model for the data of fatigue at different loading frequencies.

2.7 SUMMARY

This chapter comprises of a comprehensive review of the fatigue life of the HMA pavement and the different test methods used including the Indirect Tensile Fatigue Test. The diametric fatigue test has its advantages and disadvantages over the other flexural and direct tests. The chapter also includes a brief review of the factors, like bitumen type, bitumen content, aggregate and air voids, which affect the fatigue performance of different HMA mixtures. Along with the factors, different approaches used for the fatigue evaluation of the mixes has also been discussed. In the end a brief overview has been given about the research being carried out recently on the HMA mixtures using the Indirect Tensile Fatigue Tests.

Chapter 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

The chapter covers the methodology that is used in this research to achieve the objective mentioned earlier in chapter number one. The material characterization of aggregate and bitumen, along with the details of the various tests carried out, is explained. The chapter also includes the comprehensive procedure for the Marshal Mix design methods for the calculation of the optimum bitumen content for the HMA mixes used in this research. The method for compaction and sample preparation for the performance test using the Superpave Gyratory Compactor has also been discussed. Then there is a brief review of the performance test, that is the indirect tensile fatigue test, is also discussed.

In this study four (4) different gradations for the wearing course are being tested using aggregate of Margalla Quarry and bitumen sources are ARL 60/70 & NRL 40/50.The testing is done using stress controlled conditions at a temperature of 25°C, the average temperature for Pakistan, by applying a constant vertical compression load diametrically on the specimen. This diametric compression load produces an indirect tension in the horizontal direction. The IDT fatigue test is to be stopped when actual failure on specimen is observed. A crack typically occurs in the vertical direction, which indicated that the specimen has reached fatigue failure in the stress-controlled mode. Cylindrical specimens for the performance test are prepared by coring and saw cutting from 6 inch cylindrical specimens which are prepared using different asphalt mixes by Superpave Gyratory Compactor. The detailed procedures for the previous mentioned processes are explained further in the chapter. The methodology carried out for the research is illustrated in Figure 3.1.

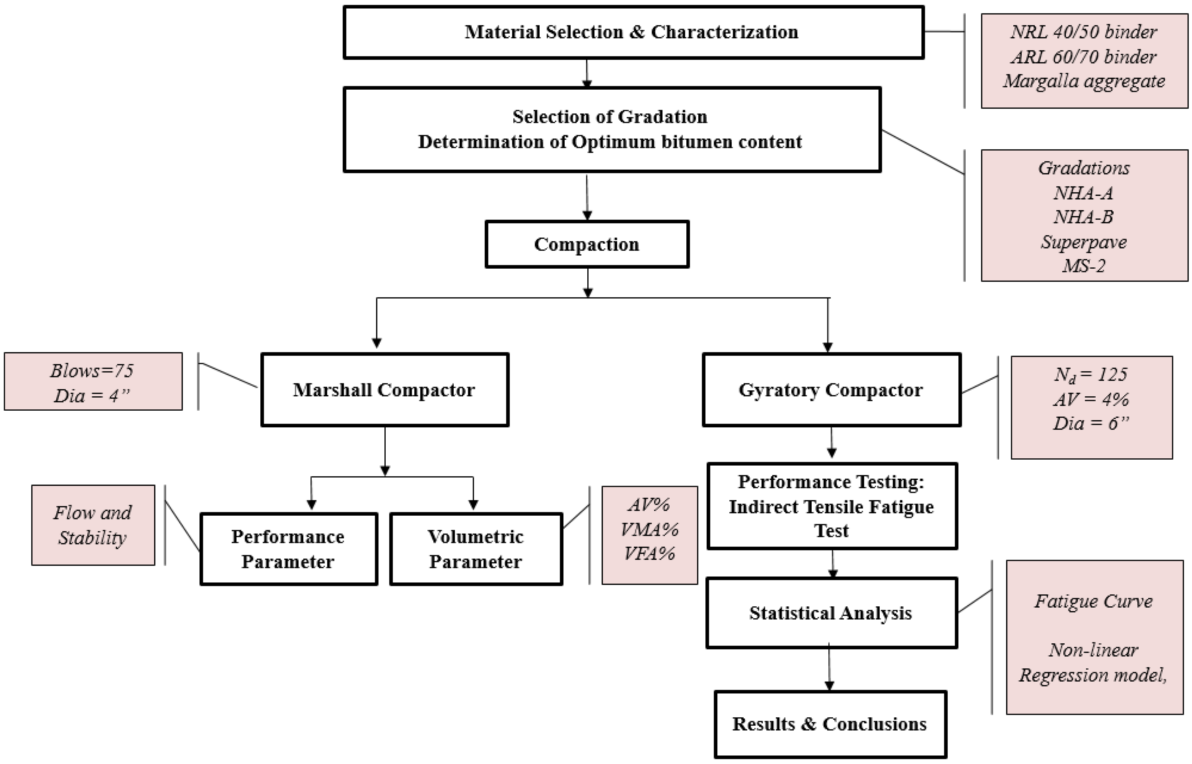

Figure 3. 1 Research methodology

3.2 MATERIAL SELECTION AND CHARACTERIZATION

The main ingredients in the composition of a Hot Mix Asphalt are aggregates, bitumen and air. The combination of aggregates and bitumen by weight normally consists of 95% of aggregate and the remaining 5% is the bitumen, and the air having no weight has no percentage in the mix. While by the respect of volume, the combination of a typical hot mix asphalt mixture is 85% of aggregate, 10% of the bitumen and the remaining 5% is the volume of air as the air voids. A proper selection of the materials, the aggregate and the bitumen, require detailed laboratory testing to meet the required standard of the hot mix asphalt. The aggregate used for the research are Margalla and Sargodha, but only Margalla is used for the performance testing along with bitumen source of ARL 60/70 and NRL 40/50.

3.2.1 Course and Fine Aggregates

The term “Aggregate” is used for the mineral materials such as gravel, sand and crushed stone collectively. Aggregates can either be natural or manufactured. The natural aggregates are mostly mined from large rock formations in an open excavation, also known as a quarry. These rocks extracted are then usually crushed into usable sizes. Aggregates provide the skeletal structure of the hot mix asphalt and are highly responsible for the load bearing capability of a pavement as the transfer the load from the moving vehicles to the under laying layers after distributing it. For that reason, it is very important to select that type of aggregate which meets the standard requirements of the specifications according to the load they are subjected to. The basic strength properties of asphalt concrete are greatly influenced by the characteristics of aggregate such as the size, gradation, surface texture and its shape. Aggregates for asphaltic concrete are generally required to be durable, hard, tough, strong, properly graded with low porosity, and to have clean, rough and hydrophobic surfaces. In this research the material characterization of two aggregate sources has been done, aggregate from Margalla and Sargodha. There are a number of tests carried out on the aggregates in the laboratory, and the tests can be broadly classified as either quality tests or the property test. Tests that have been performed on the aggregates are presented in Table 3.1. The selection of aggregate is important to consider for preparation of hot mix asphalt and the Table 3.1 shows the standard tests used for both fine and coarse aggregates to determine their suitability and to establish their properties.

Table 3. 1 Test standards for the quality and property tests of aggregates

QUALITY TESTS		
1	Fractured Particles	ASTM D 5821
2	Flat and Elongated Particles	ASTM D 4791
3	Resistance to Degradation	ASTM C 131
4	Durability and Soundness	ASTM C 88
5	Deleterious Materials	ASTM C 142
6	Un-compacted Voids	ASTM C 1252
7	Sand Equivalent	ASTM D 2419
PROPERTY TESTS		
1	Water Absorption, Bulk Specific Gravity, SSD Specific Gravity, Apparent Specific Gravity	ASTM 127
2	Gradation	ASTM 136
3	Unit Weight, Loose & Rodded	ASTM 29

3.2.1.1 Fractured Particles (ASTM D5821)

Fractured particle is a particle of aggregate having the least number of fractured faces as specified, and a fractured face is termed as that surface of an aggregate particle that is rough, angular or has been broken due to crushing, by nature or by any artificial means. This test method determines the percentage, by count or by mass, of a course aggregate sample that consist of a fractured particle meeting the above mentioned requirements. The purpose of the requirement is to provide maximum shear strength to the bound or unbound aggregate mixtures by increasing the friction between the particles. Also to provide stability to the aggregates in surface treatment, and to increase the friction of aggregates that are to be used in pavement surface. This test is conducted according to ASTM D 5821 for course aggregates only and the minimum requirement for the aggregate to pass the test is to have a percentage more than 90%, which the results in Table 3.2 show that both Margalla and Sargodha are in the acceptable range.

Table 3. 2 Results of fractured particles test

Sieve Size (inch)	Margalla	Sargodha
1 ½ to 1 **1 to ¾** **¾ to ½** **½ to 3/8** **3/8 to No. 4**	100% Crushed Aggregate	100% Crushed Aggregate
Minimum Requirement	90% Min.	

3.2.1.2 Flat and Elongated Particles (ASTM D4791)

Shape of the particles of course aggregate influence the properties of bound or unbound aggregate mixtures and may also affect the compaction and consolidation of the particular mix type. This test help to give a check the compliance of the aggregate with the specific requirements and to determine the characteristics of the relative shape of the course aggregates. The test method comprises of the percentage of elongated particles, flat particles or both flat and elongated particles.

There are two procedures that can be followed. The first procedure or Method A gives the reflection of the original process developed which is intended for all non-Superpave applications. While the other process or Method b compares the maximum particle dimension to the minimum and is intended to be used for Superpave specification. Flat or elongated particles have a tendency to lock up more readily during the compaction process which makes compaction difficult as compaction requires reorientation of the aggregate particles, and consequently they also tend to break during compaction making the aggregate gradation finer and possibly to cause a lower VMA value than expected. The test has been performed for both the Margalla and Sargodha course aggregates only, and the Table 3.3 shows the results of the average of three replicate tests. According to the standard ASTM D 4791 the percentage elongated and flat should be less than or equal to 15%, and Sargodha aggregate lies just on the line in comparison of flatness.

Table 3. 3 Results of flat and elongated particles test

Sieve Sizes (inch)	Margalla			Sargodha		
	Wt. of 100 Particles (g)	Wt. of Flat Particles (g)	Wt. of Elongated Particles (g)	Wt. of 100 Particles (g)	Wt. of Flat Particles (g)	Wt. of Elongated Particles (g)
1 to ¾	1791	259	78	1779	188	24
¾ to ½	616	44	14	590	105	7
½ to 3/8	223	47	0	230	61	8
3/8 to No. 4	100	21	15	100	51	11
Total Mass	2726	371	106	2699	404	50
Percentage	100%	**13.6%**	**3.9%**	100%	**15%**	**1.9%**

3.2.1.3 Resistance to Degradation (ASTM C131)

The resistance to degradation of an aggregate is checked using the Los Angles Abrasion test, this test gives a confirmation of the toughness and also the abrasion characteristic of the aggregate. The aggregates are used in mixtures which are further subjected to high repeated load levels which might lead to crushing, degradation and fragmentation, and that is the reason the property of resisting the abrasion is so important to be checked for the aggregates. The test involves placing a certain weight of coarse aggregates (above sieve No. 12) and also some steel balls in a rolling mill which is then subjected to rotation up to some number of revolution. Once the revolutions are complete the material is passed through a No. 12 sieve and the percentage loss in the retained material. According to the NHA specifications an abrasion value of 30% or less is satisfactory for the coarse aggregates. The test has been performed following ASTM C 131 on both Margalla and Sargodha aggregate and the results are shown in Table 3.4.

Table 3. 4 Results of Los Angeles abrasion test

Sr. No.	Margalla				Sargodha			
	Total Mass	Retained #12	Passing #12	Resistance to Degradation	Total Mass	Retained #12	Passing #12	Resistance to Degradation
	(gm)	(gm)	(gm)	(%)	(gm)	(gm)	(gm)	(%)
1	5008	3653	1372	27.4	5000	4445	555	11.1
2	5000	3672	1328	26.6	5000	4417	583	11.6
3	5005	3598	1407	28.1	5000	4369	631	12.6
Avg	5004	3635	1369	**27.4**	5000	4410	590	**11.8**

3.2.1.4 Durability and Soundness (ASTM C88)

The aggregates that are resistant to the action of weathering are much more durable and are less prone to degrade in the field to cause a premature failure of the pavement. Therefore the soundness test is carried out to check the resistance of aggregate to disintegration and fragmentation by the action of weathering, particularly weathering due to the freeze thaw cycles. In the test the aggregates are repeatedly submerged in magnesium sulphate or sodium sulphate solution for 24 hr causing the solution to penetrate into the aggregate pores and once these start to crystalize this simulates the action of the formation of ice crystals in the freeze thaw cycles. Once the cycles are complete the aggregates are washed with barium chloride to remove the salt solution from the pores of the aggregates. The aggregates are passed through the particular set of sieves mentioned in the standard and the change in mass is the percentage degradation. The Table 3.5 shows the test results performed according to ASTM C 88 of the soundness of Sargodha aggregate only as the test was not performed on the Margalla aggregates.

Table 3. 5 Results of durability and soundness test

Sieve Size	Sargodha
Coarse Aggregate 1 ½ to No. 4	0.7%
Fine Aggregate No. 4 to No. 30	6.37%
Specification Requirement	12% Maximum

3.2.1.5 Deleterious Material (ASTM C142)

The presence of excess amount of silt and clay, any organic particles or any other substance that absorbs water can be unfavourable to durability, water tightness and strength in concrete. The primary purpose of this test is to determine the amount of clay lumps present in the aggregates. This test is an approximate method to determine the clay and other friable particles present in the aggregates used for hot mix asphalt as these might cause loss of bonding between binder and the aggregate. The Table 3.6 shows the average result of the test performed in accordance with ASTM C 142 on both the Margalla and Sargodha aggregate using three trials each.

Table 3. 6 Results of deleterious materials test

	Margalla		Sargodha	
	Coarse Aggregate	**Fine Aggregate**	**Coarse Aggregate**	**Fine Aggregate**
Wt. Before Washing (gm)	5000	500	5367	500
Wt. After Washing (gm)	4976	485.7	5350	486
Percentage Clay (%)	**0.481**	**2.867**	**0.300**	**2.87**

3.2.1.6 Un-compacted Voids (ASTM C1252)

The test for un-compacted voids provide a comparative estimate of the sphericity, angularity and the surface texture of the aggregates. Once the void content of the fine aggregate is measured it can indicate what effect the fine aggregate will have on the workability of a particular mixture. There are three methods to determine the measure the voids, out of which two use the graded fine aggregate on the whole while one method uses different size fractions. The test is only performed according to ASTM C 1252 for fine aggregates and the average results of the three trials are shown in Table 3.7 for both the Margalla and Sargodha Aggregate.

Table 3. 7 Results of un-compacted voids in fine aggregate

	Margalla	**Sargodha**
Void Content (%)	39.3	48.8

3.2.1.7 Sand Equivalent

Similar to the test for the deleterious materials in the aggregate, sand equivalent is a rapid field test to show the undesirable soil particles that coat the fine aggregates and hinder the proper binding between the bitumen and aggregate. In the test fine aggregates passing No. 4 sieve are poured into a graduated cylinder along with small among of flocculating agent. These are mixed or agitated so as to lose the bond between the clay and sand particles. After the sedimentation time mentioned in the standard the sand equivalent is determined as the ratio of height of sand to clay. More the sand equivalent value the lesser the clay particles present. The test was conducted for both Margalla and Sargodha aggregate according to ASTM D 2419 and the results are shown in Table 3.8.

Table 3. 8 Results for sand equivalent test

	Margalla	Sargodha
Clay Reading (inch)	4.27	4.02
Sand Reading (inch)	3.27	3.52
Sand Equivalent (%)	**76.6**	**87.5**

3.2.1.8 Water Absorption and Specific Gravity

The rate of water absorption and specific gravity of aggregates is regularly used by the engineers and practitioners for the design and construction of pavements. Specially, in the asphalt mix preparation the specific gravity and water absorption of both the coarse and fine aggregates is very important. The most important factors in the quality control of bituminous mixes, the voids in mineral aggregate and the amount of bitumen absorbed, are evaluated on the basis of bulk specific gravity. The test includes the determination of the average density of the coarse particles on whole ignoring the voids that are present in between the particles, the specific gravity also termed as the relative density, and the percentage of absorption in the aggregates. The densities are termed as oven dried (OD), saturated surface dried (SSD) or apparent density depending on the procedure that is being used for the test. The specific gravity is generally the ratio of the density of a particular material to the density of water at a constant temperature, and the basic measurements to be taken for the calculation are the volume and the mass of the particles.

Bulk Specific Gravity is also called as Bulk Dry Specific Gravity (Gsb). In this the volume is including the volume of aggregates as well as the volume of the voids in between the particles, while on the other hand the mass is only the mass of the solid aggregate particles as the air present in the voids has no mass.

Saturated Surface Dry Specific Gravity involves the measurement of volume of the aggregate as well as the volume of the permeable voids filled with water. Same as the volume the mass measured include the mass of the aggregate and the mass of water filled in the permeable voids of the aggregate.

Apparent Specific Gravity measures only the mass and volume of just the aggregate particles, not even the volume of the permeable voids. This is intended to provide the specific gravity of only the solid.

The test was performed according to ASTM C 127 and ASTM C 128, and the results are shown in Table 3.9 for the Sargodha aggregates.

Table 3. 9 Results of the specific gravity of Sargodha aggregate

Size of Aggregate	Specific Gravities			
	Bulk	SSD	Apparent	Absorption
20 – 38 mm	2.83	2.84	2.85	0.098 %
10 – 20 mm	2.79	2.8	2.83	0.09 %
5 – 10 mm	2.6	2.67	2.8	2.7 %
0 – 5 mm	2.6	2.65	2.75	2.09 %

3.2.1.9 Gradation

The test is performed to determine the particle size distribution of aggregates. The distribution of particle sizes is one of the most important quality of aggregates that effect the composition of hot mix asphalt. The particle size distribution not only effect the volumetric but also the workability and permeability of the hot mix asphalt. The test is performed by measuring the mass of the dry aggregate on each progressive sieve once the aggregate sample is passed through a nest of sieves. After the mass of the particles is known then a percentage can be calculated from the total mass of the sample and a plot can be made of the percentages known as the gradation chart. The test is performed according to ASTM 136 for both the aggregates of Margalla and Sargodha.

3.2.1.10 Unit Weight

The test covers the method to determine the bulk density of aggregate in both loose and compacted conditions, further the voids between the particles either fine, coarse or mixed together. This particular test can only be performed for aggregate sizes not exceeding a nominal maximum size of 5 inches, 125 mm. The bulk density measured in this test can also be useful in purchasing of bulk materials. Unit weight is a term traditionally used to describe the property determined by the weight over unit volume concept. The test is performed in accordance to ASTM 29 standard. The results of the test are shown in the summary Table 3.10.

3.2.1.11 Summary of Aggregate Characterization

Table 3.10 shows the summarised results for the aggregate characterization. The detailed results are shown previously.

Table 3. 10 Summary of the results of aggregate tests

Standard Test Method		ASTM-C127 & C128				C-131		C-88	C-142	D-4791	D-5821	D-4791	D-2419	C-1252	C-29	
Quarry Source	Size of Aggregate (mm)	Specific Gravities				Wear by L.A Abrasion %		Soundness %	Clay Lumps %	Elongation %	Fractured Faces %	Flakiness %	Sand Equivalent %	Void Content %	Unit Weight Kg/m^3	
		Bulk	SSD	App.	Abs. %	Class A	Class B								Loose	Rodded
Margalla Aggregate	20~30	2.64	-	-	1.14	27.4	-	-	0.48	3.58	100% crushed aggregates	13	76.6	-	**1543**	**1625**
	10~20	2.63	-	-												
	10 ~ 5	2.62	-	-												
	5 ~ 0	2.59	-	-	2.27			-	2.87					39.3	1570	1780
Sargodha Aggregate	20~30	2.83	2.84	2.85	0.098	11.8	-	0.7	0.3	1.9	100% crushed aggregates	15	87.5	56.8	1410	1590
	10~20	2.79	2.8	2.83	0.09											
	10 ~ 5	2.6	2.67	2.8	2.7											
	5 ~ 0	2.6	2.65	2.75	2.09			6.37	2.87					48.8		

3.2.2 Asphalt Binder

Asphalt is a known to be as a dark brownish to blackish coloured viscous hydrocarbon that is produced from the distillation of residues of petroleum. This distillation either occurs naturally which result in asphalt lakes, or in a petroleum refinery from the residue left after the distillation of crude oil.

The physical properties of asphalt binders largely influence the performance of HMA mixes. Properties of asphalt changes over time and its age is an important factor in prediction of its behaviour over time. The new Superpave tests, also known as the Performance Grading (PG) system, developed in SHRP research program measure the physical properties of asphalt that can directly relate to field performance. The Performance Grading (PG) system emphasis strongly to control the viscosity at low temperature, but this is not an issue in Pakistan due to the temperate climate. The check on the suitability of both the aggregate and bitumen for the hot mix asphalt preparation is necessary. There are a variety of tests including property and performance test which need to be performed before the bitumen is used for hot mix asphalt preparation. Three different bitumen grades are tested including NRL 40/50, NRL 60/70 and ARL 40/50. Further there were two bitumen grades selected for the performance testing that are NRL 40/50 and NRL 60/70. Tests shown in Table 3.11 are performed on the different sources of bitumen to assess particular properties of asphalt binders.

Table 3. 11 Test standards for property and performance test of bitumen

PROPERTY TESTS		
1	Flash and Fire Point	ASTM D 92
2	Penetration	ASTM D 5
3	Ductility	ASTM D 113
4	Softening Point	ASTM C 36
PERFORMANCE TESTS		
1	Rotational Viscometer (RV)	AASHTO T 316
2	Rolling Thin Film Oven (RTFO)	ASTM D2872
3	Pressure Aging Vessel (PAV)	ASTM D 6521
4	Bending Beam Rheometer (BBR)	ASTM D 6648

3.2.2.1 Flash and Fire Point (ASTM D 92)

The flash point of an asphalt binder is that temperature at which the sample suddenly flashes due to the presence of an open flame, on the other hand the point at which the binder gives a constant flame that temperature is termed as the fire point. Flash and fire point test are performed according to ASTM D 92 and an apparatus known as the Cleveland Open Cup (COC) is used in the test. The procedure involves filling a brass cup with asphalt binder, up to a certain volume, and heat the brass cup at a constant rate passing a test flare above the cup at definite intervals. Once the above described conditions are achieved the temperature for the flash and fire point are recorded. Flash and fire point tests were conducted using three trials for each binder. The flash point according to the specifications should be greater than 232°C. Table 3.12 shows the results for flash and fire point testing.

3.2.2.2 Penetration (ASTM D 5)

Penetration test has been one of the oldest tests to measure the consistency of the asphalt binder, and the test is performed using the ASTM D 5 test. To perform the penetration test binder is heated to a suitable temperature to help it flow, but not too much that the properties of the binder are affected, and poured into a test container. The samples are brought to the standard test temperature of 25°C using temperature controlled water bath. The containers are then placed in the penetrometer equipment and a total load of 100g is applied to the needle for 5 seconds to penetrate into the binder. Penetration test was performed using two specimens of each binder and the reading were taken at five points in each sample. The results of the penetration test are shown in Table 3.12 which show satisfactory results.

3.2.2.3 Ductility (ASTM D 113)

The physical property of asphalt binder, ductility, is considered to be an important characteristic. This particular test measures the ductility of asphalt binder by elongating a standard sized piece, dog bone like shaped, of asphalt binder to a point it is broken or has passed the criteria of ASTM D 113 standard test specification. The test like penetration test is performed at 25°C in a constant water bath. Once placed in the assembly the specimen is pulled out at a speed of 5 centimetre per minute until the sample breaks. The samples having a ductility value greater or equal to 100 cm are considered satisfactory. The test has been performed according to ASTM D 113 and the results are shown in the summarised Table 3.12.

3.2.2.4 Softening (Point ASTM C 36)

The temperature at which the bitumen specimen does not sustain the weight of a 3.5 g steel ball is known as the softening point of bitumen. To perform this test a ring and ball apparatus is used according to the standard of ASTM D36. First of all the binder is heated to a certain temperature, to make it flow but keep the properties unchanged, and poured into a mold to form horizontal disks of bitumen. Once in the apparatus the steel balls are placed on the disks and the temperature is increased up to a point the disks soften enough to let the ball fall a distance of 25 mm. the temperature recorded at the point is the softening point of the bitumen. Softening point test were conducted using three specimens of each binder and the results are shown in the Table 3.12.

3.2.2.5 Rotational Viscometer (RV) (AASHTO T 316)

Rotational viscometer is used to determine the viscosity of asphalt binder at higher temperatures, simulating temperatures at pumping, mixing and compaction. This test can be conducted at various temperatures according to the need, but generally it is conducted at 135°C as mentioned in AASHTO T 316. Temperature-viscosity graphs can be developed using the rotational viscometer for assessing the mixing and compaction temperatures used in the mix design. This test measures the torque of a cylinder-shaped shaft immersed in asphalt binder at a constant rotational speed of 20 rpm, and the torque is further processed to viscosity by the equipment. Tests were performed on each bitumen grade using three replicates at two different temperatures. Table 3.12 shows the results for Rotational Viscometer (RV) testing.

3.2.2.6 Bending Beam Rheometer (BBR) (ASTM D 6648)

Low temperature stiffness of asphalt binders are determined using the bending beam rheometer (BBR) test. The standard test specification of AASHTO T 313 is used for this test, and it gives view of the capability of the asphaltic binder to resist low temperature cracking. The elementary test involves applying load to the middle of simple supported asphaltic beam, dipped in cold liquid bath, giving deflection measured against time. Using the measured deflections and the beam properties the stiffness is determined at a particular low temperature. This type of thermal cracking at low temperature is related to the m-value and the creep stiffness of the asphalt binders used in hot mix asphalt. The test is also performed on aged samples, and the long term aging of the binder is done in the laboratory using Pressure Aging Vessel (PAV) according to the standard of ASTM D 6521 and the short term aging is done using Rotating Thin Film Oven (RTFO) following the standard ASTM D 2872. The test was carried on the three type of bitumen at three different temperatures of 0°C, -6°C and -12°C to get a complete characterization at low temperature. Tests were carried out on aged samples which were put through the Rotating Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) before testing them in the Bending Beam Rheometer. The results of the testing are shown in Table 3.12 in the summarized results.

3.2.2.7 Summary Binder Characterization

The summary of all the tests performed on the three bitumen sources is shown in Table 3.12. The results show that all the three sources satisfy the penetration grade requirements according to the ASTM standards. The performance test results whereas show that NRL 40/50 is the most viscous grade of bitumen followed by NRL 60/70 and ARL 60/70 respectively. For the purpose of research NRL 40/50 and ARL 60/70 were selected out of the three to perform the performance tests.

Table 3. 12 Summary of test results of bitumen

	Penetration Test			Flash & Fire Point Test			Softening Point Test			Ductility Test			RV Test (Pa.s)				BBR Test (MPa)			
Standard	ASTM D5/ AASHTO T49			ASTM D92/ AASHTO T49			ASTM D36			ASTM D113			AASTO 316				ASTM D6648/ AASHTO T313			
Bitumen	ARL 60/70	NRL 60/70	NRL 40/50	ARL 60/70	NRL 60/70	NRL 40/50	ARL 60/70	NRL 60/70	NRL 40/50	ARL 60/70	NRL 60/70	NRL 40/50	**Temp.**	ARL 60/70	NRL 60/70	NRL 40/50	**Temp.**	ARL 60/70	NRL 60/70	NRL 40/50
Results	63	66	43	328°C & 362°C	329°C & 360°C	335°C & 359°C	48°C	46°C	52°C	Greater than 100 mm			**135°C**	0.225	0.338	0.486	**-12 °C**	232.506	241.310	427.410
													160°C	0.073	0.204	0.083	**-6 °C**	86.055	65.236	120.65
													-	-	-		**0 °C**	N/A	31.117	58.643

3.3 BITUMINOUS MIX PREPARATION

The design of hot mix asphalt bases on the concept of determining the best possible combination of aggregate and asphalt binder to give the pavement structure a long lasting performance. The aggregate structure is the main concern in asphalt mix design to prevent deformation, so the mix design should provide a stable mixture resistant to further densification under traffic. A well-designed mix needs to be constructed so that very little change takes place in the air voids after construction. The HMA mixture must not only have high shear strength to resist rutting but also have high tensile strength and flexibility to provide sufficient fatigue life to resist cracking. Many laboratory procedures have been developed to determine the necessary percentages of materials that are to be used in the HMA mix and these procedures include the determination of correct aggregate blend to produce proper gradation on mineral aggregates along with the type and amount of asphalt binder to be used. Among the many methods developed for the preparation of HMA mixes Marshall Method is mostly preferred which was developed by Bruce G. Marshall in 1939 at the Mississippi Highway Department and the standard test specification followed is ASTM D 6926. The Marshall method is originally applicable to only the hot mix asphalt paving mixtures which contain aggregates with a maximum size of lesser and equal to 1 inch (25 mm). For hot mix asphalt mixtures containing aggregates with maximum sizes up to 1.5 inch (38 mm) the modified Marshall method is used.

The heavy axle loads present in Pakistan impose high stresses on the aggregate structure, and for that even the 75 number of blows in Marshall for wearing course may not be sufficient enough to produce a worthy structure. A good quality aggregate with suitable gradation can increase the shear strength of HMA mixture. The air voids in the mixture are one component for the selection of a good mix design. The purpose of adequate air voids is to ensure that the mix does not rut due to loss in shear strength at low air voids or has durability issue due to open structure with high voids. The correct air voids are subjected to the voids in mineral aggregate, the aggregate structure in terms of the gradation, nominal maximum aggregate size, amount of fines, compaction level and the bitumen content.

3.3.1 Test Sample Preparation

There are a series of test samples prepared for a range varying bitumen content in determining the design bitumen content for a particular gradation of aggregates so that well defined curves a developed for the data. Each of the test sample generally requires around 1200 g (2.7 lb) of aggregate, and to get an adequate amount of data at least three replicate test samples are to be prepared for every bitumen content. The standard test sample has a diameter of 4 inch (102 mm) and height of 2 ½ inch (64 mm), and for the modified test the samples have a diameter of 6 inch (152.4 mm) and a height of 3.75 inch (95.2 mm). The detail of the equipment to be used in the test for both the standard and the modified Marshall test are present in the Asphalt Institute Manual Series No. 2 (MS-2). The steps involved in the preparation of the test specimens are as following:

1. **Number of Samples –** Prepare at least three replicate samples for each of the combination of aggregate gradation and bitumen content. There were a total eight type of mixes used in the research and the Table 3.13 shows the total number of samples prepared for the determination of optimum bitumen content.
2. **Preparation of Aggregates (Selection of Gradation) –** Dry the aggregates up to a constant temperature at 105 °C to 110 °C, and once dried then separate the aggregates

into the required sizes using the dry sieving technique. The effect of gradation of the aggregate on the performance of hot mix asphalt in an issue which many different agencies around the world cater by using different gradations keeping in consideration the maximum aggregates size. Even if the different hot mix asphalt mixtures use the same source of aggregate, meaning that the physical and chemical properties remain the same, but by changing the gradation can alter the performance of the aggregate and bitumen blend under the same loading and environmental conditions. In order to study the effect of gradation four different wearing course gradations were used in the research that are shown in Table 3.14. Out of the four gradations NHA-A and NHA-B gradation are coarser with a maximum nominal aggregate size of 19 mm whereas the other two gradations, Superpave-1 and MS-2, are or the finer side with a maximum nominal aggregate size of 12.5 mm.

3. **Determination of Mixing & Compaction Temperature –** The temperature versus viscosity plots for the bitumen being used in the mix are helpful to get the required temperature needed to get a viscosity of 170 ± 20 centistokes kinematic and 280 ± 30 centistokes kinematic for mixing and compaction respectively.
4. **Preparation of Mold & Hammer** – The sample mold assembly should be thoroughly clean and heated to a temperature between 95 °C and 150 °C.
5. **Preparation of Mixture** – Generally a trial sample is to be prepared to prepare the aggregate batch. The aggregates should be placed in the mixing bowl (Shown in Figure 3.4) and dry mix thoroughly, once the aggregate blend and bitumen are within the limits of the mixing temperature mix the aggregate and bitumen as quickly and thoroughly as possible to achieve a uniform consistency.
6. **Packing the Mold** – Place the entire batch of aggregate and bitumen in the mold in which paper disk has been placed and scoop the mixture with a spatula or trowel around the perimeter and in between to get a slightly rounded shape.
7. **Compaction of Sample** – Place the mold on the compaction assembly and apply 75 number of blows for heavy traffic, once the blow are completed then repeat the sample compaction on reverse side of the mold also. Remove the sample using a jack or other compressive device after cooling.

Table 3. 13 Number of samples for Marshall Compaction

Type of Mixture	Aggregate Gradation	Bitumen	No. of Sample to Determine OBC	No. of Sample for Verification
A	NHA – A	NRL 40/50	15	2
B		ARL 60/70	15	2
C	NHA – B	NRL 40/50	15	2
D		ARL 60/70	15	2
E	Superpave – 1	NRL 40/50	15	2
F		ARL 60/70	15	2
G	MS – 2	NRL 40/50	15	2
H		ARL 60/70	15	2

Table 3. 14 Aggregate gradations for asphalt wearing course

Sieve Size	Cumulative Percentage Passing (%)			
	NHA – A	NHA – B	Superpave – 1	MS – 2
1 ½ inch (37.5 mm)	100	100	100	100
1 inch (25.4 mm)	100	100	100	100
¾ inch (19 mm)	95	100	100	100
½ inch (12.5 mm)	76	82	94	95
3/8 inch (9.0 mm)	63	70	87	82
¼ inch (6.4 mm)	51.5	59	74	69
No. 4 (4.75 mm)	42.5	50	65	59
No. 8 (2.36 mm)	29	30	37	43
No. 16 (1.18 mm)	20	20	21	30
No. 30 (0.6 mm)	13	15	14	20
No. 50 (0.3 mm)	8.5	10	9	13
No. 100 (0.15 mm)	6	7	7	8.5
No.200 (0.075 mm)	5	5	5	6
Pan	0	0	0	0

3.3.2 Test Procedure

The Marshall method subjects each and every compacted sample to test for the bulk specific gravity, the stability and flow of the sample and the density and air void analysis in order to determine the optimum bitumen content of a particular blend of aggregate and bitumen. The equipment required for the performance of the mentioned tests is a compression testing device known as the Marshall Testing Machine, this apparatus should conform to the ASTM D 1559 standard.

3.3.2.1 Bulk Specific Gravity

The bulk specific gravity test may be performed as soon as the freshly-compacted specimens have cooled to the room temperature according to the ASTM D 1188. The process of determining the bulk specific gravity of the particular compacted hot mix asphalt specimen requires taking the weight of the dry sample, the weight of the sample submerged in the water for a time until the voids are filled with water and the weight of the samples using the saturated surface dry method. The tests were performed for all the different types of mixtures mentioned in Table 3.13 and the representative results of the calculated bulk specific gravities are shown in Table 3.15.

Table 3. 15 Results of bulk specific gravity for different mixes

Mix Type	Bitumen Content (%)	Bulk Specific Gravity	
		ARL 60/70	NRL 40/50
NHA – A	3.5	2.382	2.614
	4.0	2.399	2.6115
	4.5	2.417	2.609
NHA – B	3.5	2.330	2.346
	4.0	2.360	2.346
	4.5	2.399	2.372
Superpave – 1	4.5	2.312	2.305
	5.0	2.335	2.315
	5.5	2.348	2.330
MS – 2	4.5	2.308	2.353
	5.0	2.350	2.369
	5.5	2.369	2.390

3.3.2.2 Stability & Flow Test

Once completed for the test of bulk specific gravity, as the test is non-destructive the same samples are then subjected to stability and flow test, to determine the stability and flow values of the particular mixes. The value got from the stability test is actually the maximum load, in Newton (Ib.), the standard Marshall Test sample can resist at a temperature of 60 °C, and to achieve that the standard samples are dipped into a water bath at 60 °C ± 1 °C for almost 30 to 40 minutes before the test. The Marshall Testing Machine applies the load by increasing the load at a rate of 50.8 mm/minute until the maximum load is achieved, and the Marshall stability is the load recorded at the point when the load just starts to decrease. As the test is being performed a dial gauge is also attached to the frame in which the sample is placed and the deformation in the vertical direction is recorded in the increment of 0.25 mm. the deformation at the point the maximum load is noted is the flow value of the sample. The tests were performed for all the different types of mixtures mentioned earlier in Table 3.13 and the representative results of the reading of stability and flow are shown in Table 3.16. The stability of any hot mix asphalt is associated with the friction and cohesion between the aggregates and subsequently related to the resistance capability of hot mix asphalt to rutting and shear stresses. The cohesion between the aggregates in a hot mix asphalt is due to the biding force provided by bitumen and also the interlocking of aggregates with each other.

Table 3. 16 Results of stability and flow tests for different mixes

Mix Type	Bitumen Content (%)	Stability (kg)		Flow	
		ARL 60/70	NRL 40/50	ARL 60/70	NRL 40/50
NHA – A	3.5	1330	1460	9.634	11.8
	4.0	1451	1446	11.356	11.2
	4.5	1276	1433	12.954	10.5
NHA – B	3.5	1499	1196	12.140	10.1
	4.0	1471	1095	13.380	10.3
	4.5	1531	1369	14.388	10.2
Superpave – 1	4.5	1247	1236.5	14.476	9.0
	5.0	1544	1201.4	12.530	9.2
	5.5	1409	1243.5	14.626	10.2
MS – 2	4.5	1609	1427	12.352	12.8
	5.0	1836	1470	11.772	10.8
	5.5	1876	1608	15.894	11.2

3.3.2.3 Density & Voids Analysis

The volumetric properties, or the density and void percentages, of a compacted hot mix asphalt provide some indication of the mixture's probable pavement service performance. Aggregates are porous minerals and have the tendency to absorb water and bitumen up to a certain level, and this absorption varies with every different type of aggregate. Therefore it is very important to determine these properties of aggregates on basis of three methods (bulk specific gravity, apparent specific gravity and effective specific gravity) that measure the specific gravity of aggregates differently defined by the volume of aggregate as the mass remains the same (MS – 2 Asphalt Institute). The Figure 3.2 shows the different volumes present in the compacted hot mix asphalt including volume of voids in mineral aggregate (**Vma**), Bulk volume of compacted HMA mix (**Vmb**), volume of void less paving mixture (**Vmm**), volume of voids filled with bitumen (**Vfa**), volume of air (**Va**), volume of bitumen (**Vb**), volume of absorbed bitumen (**Vba**) and volume of aggregate (**Vsb** by using bulk specific gravity and **Vse** by using effective specific gravity). The properties used for the volumetric are defined as following:

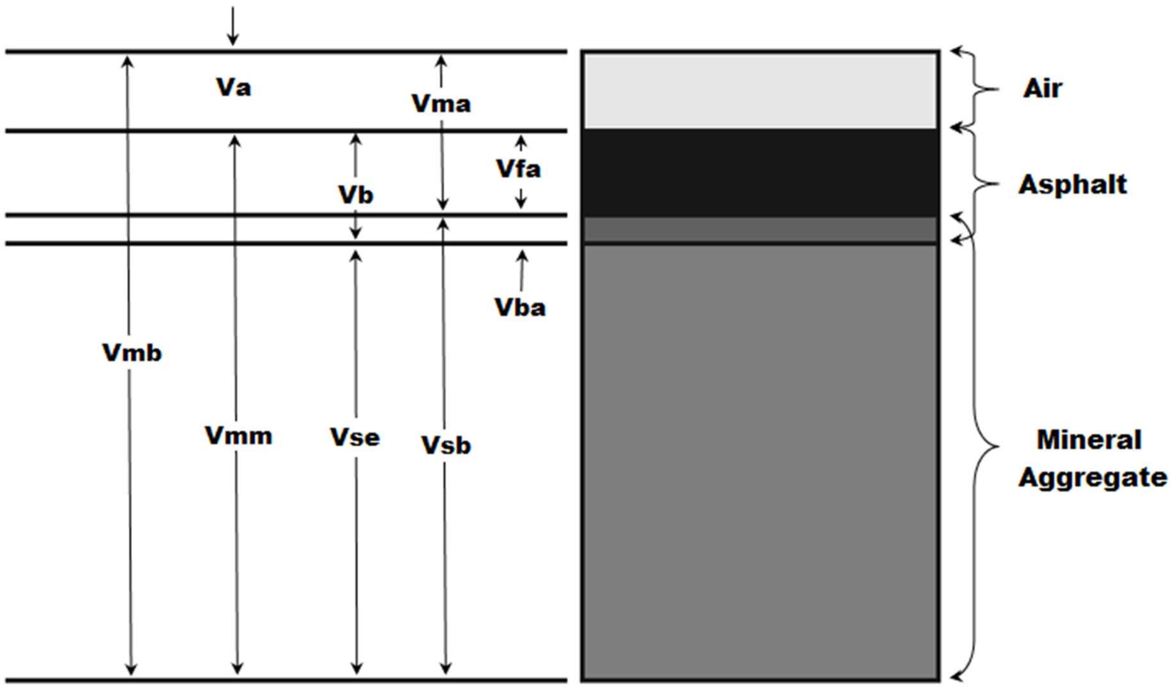

Figure 3. 2 Schematic drawing of volumes in compacted hot mix asphalt sample

Voids in Mineral Aggregates (VMA) **–** The volume of the voids between the aggregate particles in a compacted mix including the air voids and the effective bitumen that is not absorbed in the porous voids of the aggregates, as shown in Figure 3.2. The percentage VMA expressed with respect to the bulk volume of compacted mix is calculated using the bulk specific gravity of aggregate. The calculation is done as follows:

$$VMA = 100 - \frac{G_{mb}P_s}{G_{sb}}$$

Where:

VMA	=	Percentage of voids in mineral aggregate by bulk volume
P_s	=	Percentage of aggregate by total weight of mix
G_{sb}	=	Bulk specific gravity of aggregate
G_{mb}	=	Bulk specific gravity of compacted mixture

Effective Bitumen Content (Pbe) **–** The volume of bitumen in the compacted mix that is not absorbed by the porous aggregate voids, the bitumen that coats the aggregates on the outside and are significant in the performance of the bituminous mixes. The formula used for the calculation is as follows:

$$P_{be} = P_b - \left(\frac{P_{ba}}{100} \times P_s\right)$$

Where:

P_{be}	=	Percentage effective bitumen content by the total weight of mix
P_b	=	Percentage bitumen content by total weight of mix
P_{ba}	=	Percentage bitumen absorbed by total weight of aggregate
P_s	=	Percentage of aggregate by total weight of mix

Air voids (Va) – The total volume of the air present in the small gaps between the coated aggregate particles in a compacted mix. The percentage air voids calculated by the weight of the compacted mix is as follows:

$$V_a = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}}$$

Where:

V_a	=	Percentage of air voids in compacted mix by total volume
G_{mm}	=	Maximum theoretical specific gravity (ASTM D 2041)
G_{mb}	=	Bulk specific gravity of compacted mix

Voids Filled with Asphalt (VFA) – The voids filled with asphalt consists of the part of the volume the void space in between the aggregates that is filled with bitumen only, not including the air and the absorbed bitumen in aggregates. The formula used to calculate these void percentage is as follows:

$$VFA = \frac{VMA - V_a}{VMA} \times 100$$

Where:

VFA	=	Percentage of voids filled with bitumen by VMA
VMA	=	Percentage of voids in mineral aggregate by bulk volume
V_a	=	Percentage of air voids in compacted mix by total volume

The testing for the volumetric properties, including the air voids, voids in mineral aggregate and voids filled with asphalt, for the selected mixes was performed according to standard, and the results of the representative samples have been shown in Table 3.17.

Table 3. 17 Results of the volumetric properties of HMA mixes

Mix Type	Bitumen Content (%)	ARL 60/70			NRL 40/50		
		Air Voids	VMA	VFA	Air Voids	VMA	VFA
NHA – A	3.5	5.22	12.07	56.77	4.40	12.68	65.62
	4.0	4.04	11.90	66.01	4.46	13.21	66.32
	4.5	2.58	11.70	77.91	4.52	13.73	67.03
NHA – B	3.5	6.91	13.89	50.22	6.94	13.29	47.78
	4.0	4.96	13.23	62.54	6.12	13.74	55.45
	4.5	2.81	12.27	77.09	4.37	13.26	67.03
Superpave – 1	4.5	6.28	15.21	58.68	7.62	15.47	50.73
	5.0	4.62	14.82	68.83	6.34	15.53	59.20
	5.5	2.90	14.79	80.42	5.04	15.43	67.35
MS – 2	4.5	6.55	15.41	57.52	5.49	13.76	60.11
	5.0	3.99	14.32	72.12	4.01	13.64	70.61
	5.5	1.73	14.08	87.74	2.35	13.32	82.32

3.3.3 Interpretation of Data to Determine Optimum Bitumen Content

There was a need to determine the optimum bitumen content (OBC) of the hot mix asphalt mixtures before the specimens for the performance test of Indirect Tensile Fatigue test were prepared. In accordance to that the required volumetric properties , the stability & flow of the hot mix asphalt mixtures was to be known including the percentage of air voids, voids in the mineral aggregates and the voids that are filled with asphalt. After the samples were subjected to rigorous testing to determine the density, voids and specific gravities the test results need to be compiled and organized so that meaningful data can be inferred from the results. The data of the tests performed earlier is used to develop graphical plots and best fit lines and curves were drawn according to the data set. The graphs plotted against the bitumen content to determine the optimum bitumen content of the selected mixes are:

- Stability against Bitumen Content
- Flow against Bitumen Content

- Unit Weight of Total Mix against Bitumen Content
- Percentage of Air Voids (Va) against Bitumen Content
- Percentage of Voids Filled with Bitumen (VFA) against Bitumen Content
- Percentage of Voids in Mineral Aggregate (VMA) against Bitumen Content

The study of the plotted graphs can be helpful in determining the sensitivity of the mix to the bitumen content. The trends generally note that the stability increases with increase in bitumen content up to a maximum value and then starts to decrease, likewise the flow value increase consistently with increase in the bitumen content. The air voids and voids in the mineral aggregate decrease with increase in the bitumen content showing an inverse trend, on the other hand void filled with asphalt tend to increase with the increase in bitumen content.The trends can be seen in Figure 3.3, these are the representative curves for the blend of NHA – A wearing course gradation with Margalla aggregate and bitumen source of ARL 60/70. The criteria used to check, whether the results are satisfactory or not, are for heavy traffic as recommended by Asphalt Institute. The stability of the sample is to be more than 816 kg and a flow value in between 8 to 14. The percentage of air voids can vary from 3 to 5 percent, while the voids filled with asphalt (VFA) are to be from 65 to 75 percent. The optimum bitumen content is determined as the bitumen content that produces 4 percent air voids, the other properties are then read from the graph and the confirmatory test samples are prepared which are tested to be in range of the properties determined from the graphs. The Table 3.18 shows results for the optimum bitumen content are corresponding property values of different mixes.

Table 3. 18 Results for the optimum bitumen content for the wearing course gradations

Mix Type	Bitumen Type	Bitumen Content (%)	Stability Kg	Flow	Air Voids (%)	VMA (%)	VFA (%)
NHA – A	ARL 60/70	4.0	1362	12.25	4.17	12.30	66.07
NHA – B		4.1	1291	12.65	4.51	12.95	65.16
SP – 1		5.0	1424	13.55	4.53	14.70	69.18
MS – 2		4.8	1554	13.12	4.68	14.52	67.73
NHA – A	NRL 40/50	3.9	1496	12.39	4.00	13.39	70.16
NHA – B		4.4	1250	8.72	4.89	13.48	63.73
SP – 1		5.6	1383	9.44	4.37	15.10	71.06
MS – 2		4.7	1586	10.72	4.90	13.62	64.03

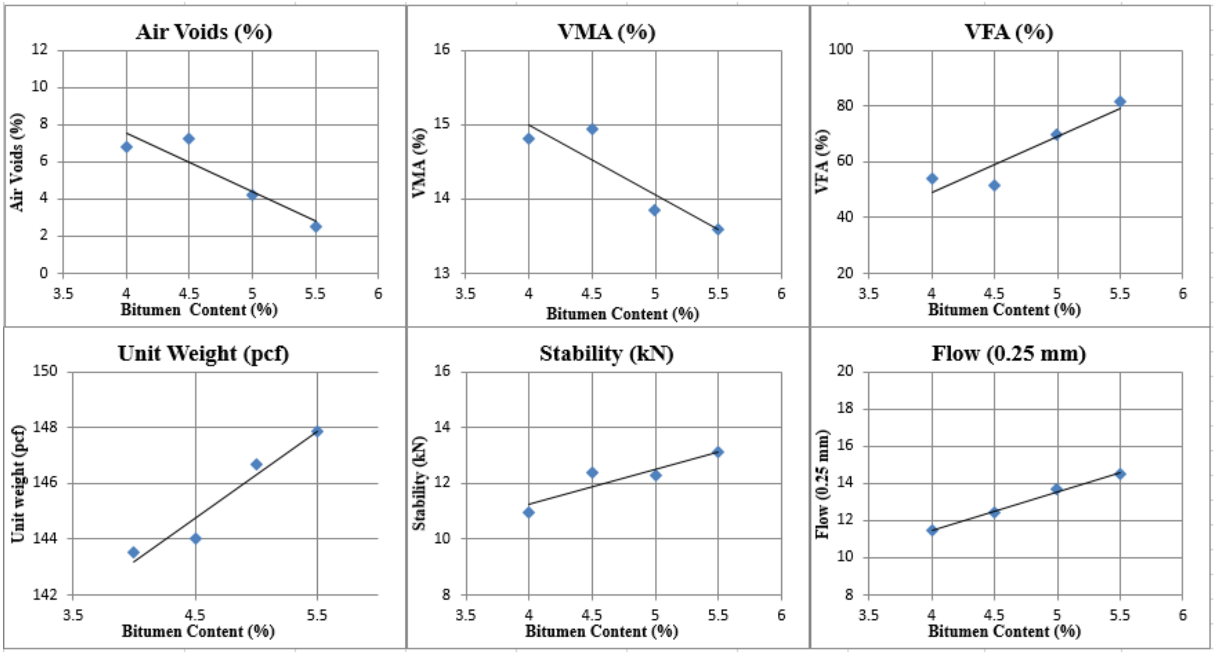

Figure 3. 3 Curves of the property test for hot mix asphalt design by Marshall Method

3.4 SAMPLE PREPARATION FOR PERFORMANCE TEST

Once the Marshall method has been completed to determine the optimum bitumen content (OBC) for each of the mix, the percentage of optimum bitumen to achieve the desired air voids, is used to prepare samples in the Superpave Gyratory Compactor for the performance tests. Several researches have been carried out to compare the field compaction to compaction in laboratory. Statistical analysis of the data has failed to establish a laboratory compaction method that produces the closest simulation to the field for all the properties of the compacted mix, however the gyratory compaction method has been the closest to all the other methods to simulate certain properties of laboratory compacted samples to field compacted samples. The super pave gyratory compactor provides a kneading action to the sample which orientates the aggregates present in the sample in the desired direction. The aggregate and bitumen are mixed at mixing temperature to get consistency using the mixing bowl shown in Figure 3.4.

Figure 3. 4 Mixing bowl used for blending the aggregate and bitumen together

The size of the samples prepared in the gyratory compactor used is 6 inch (150 mm) in diameter and 7 inch (177.8 mm) in height, and the gyrations were calibrated to 125 to achieve same void content as the samples produced in Marshall Method. The voids content and volumetric were used to back calculate the weight of the aggregate to produce an air void same as that produced in Marshall Compaction. After the samples were compacted using the gyratory compactor the samples were left for 24hr to come to the room temperature. Once the samples were at room temperature core cutting machine (as shown in Figure 3.5) accompanied by the saw cutting machine was used to core out 4 inch (100 mm) diameter specimens from the 6 inch (150 mm) samples.

Figure 3. 5 Core cutting machine

Further the saw cutting machine was used to cut the specimens into the required thickness, at least 1.57 inch (40 mm) for a maximum aggregate size of 25 mm as instructed in EN 12697 – 24, so that Indirect Tensile Test could be performed on the samples. The test samples should be placed in a temperature controlled chamber at the required testing temperature for at least 4 hr before test in performed. Table 3.19 shows the detailed matrix used for the performance testing of all the hot mix asphalt mixtures using Margalla aggregate and bitumen sources as mentioned.

Table 3. 19 Experimental design for Indirect Tensile Fatigue Test

Test Temperature		**25 ° C**					
Applied Stress		**2500 N**	**3000 N**	**3500 N**	**4000 N**	**4500 N**	**5000 N**
Mix Type	**Bitumen Type**						
NHA – A	ARL 60/70	√	√	√	√	√	√
NHA – B		√	√	√	√	√	√
SP – 1		√	√	√	√	√	√
MS – 2		√	√	√	√	√	√
NHA – A	NRL 40/50	√	√	√	√	√	√
NHA – B		√	√	√	√	√	√
SP – 1		√	√	√	√	√	√
MS – 2		√	√	√	√	√	√
Total		**144 Specimen with 3 replicates**					

Figure 3. 6 Prepared samples for performance testing

3.5 LABORATORY TESTING

The performance testing selected for the research is the indirect tensile fatigue test on cylindrical shaped samples to characterize the different HMA mixes used in the research under repeated load applied with constant load mode. The cylindrical shaped samples prepared in the laboratory are used in the test, cored samples from the field can also be used in the test to give a view of the conditions at site. The cylindrical shaped test samples are subjected to repeated compressive haversine load in the vertical direction. The vertical compressive load produces reasonably uniform tensile stress in the horizontal direction perpendicular to the load applied on the sample that is why it is known as an indirect tensile test as the tensile load is applied through compressive loading. The samples under the vertical compressive load fail by splitting along the vertical plane. Throughout the test, as the load is applied on the vertical dimension of the sample deformations are produced in the horizontal direction due to tensile stresses and those deformations are recorded which are further used to calculate the tensile strain at the centre of the sample using an assumed Poisson’s ratio.

The fatigue life of the sample is defined as the number of cycles before the sample fractures. The haversine load applied to the sample include a loading time of 0.1 seconds and a rest time of 0.4 seconds. The testing was performed for 25 °C only and a frequency of 2Hz. The samples were tested in UTM 25, using the jig assembly shown in Figure 3.7 along with the transducers attached on the diametric plane, at six different stress levels and at least three samples were tested for each level of stress. During the loading process deformation for the first 150 cycles were recorded and the transducer removed after that so that the fractured sample does not harm the sensitive transducers. The deformation reading of the transducers attached to the sample in the jig assembly were used to determine the initial strain at the centre of the sample that is the strain developed in the sample at the 100th cycle of loading. The testing is completed once the sample is fractured as shown in Figure 3.8. Once completed with all the testing of all the stress levels, the number of cycles to failure and the initial strain values are used to plot a log graph and from the graph equations can be developed for each type of mix.

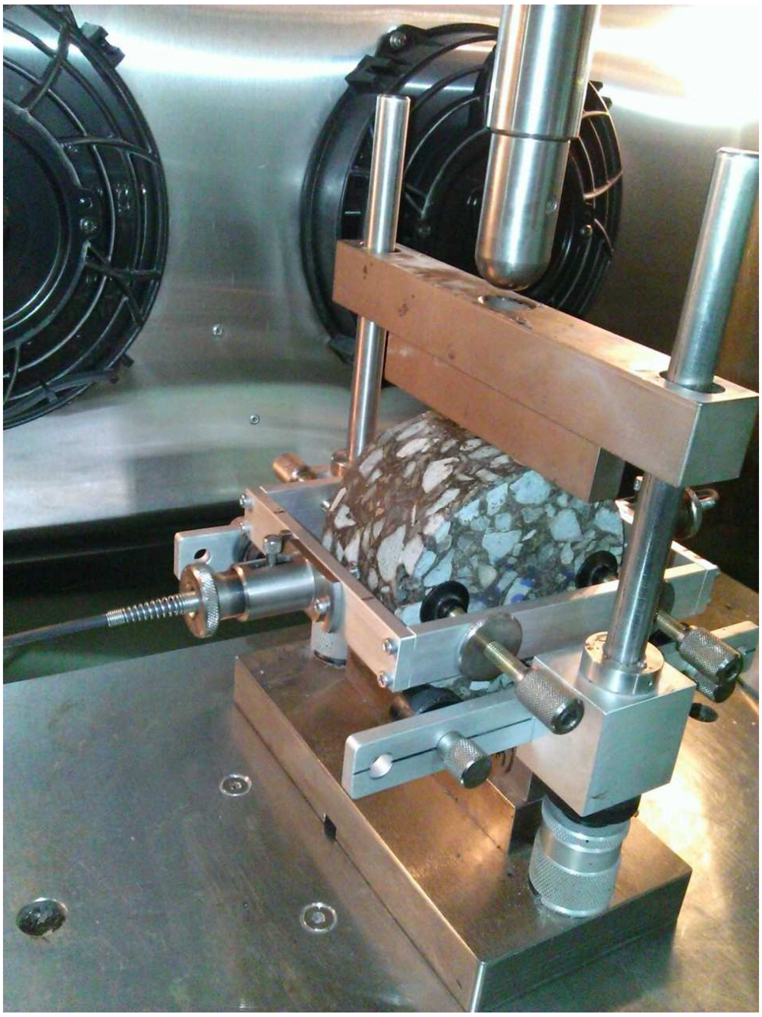

Figure 3. 7 Jig assembly used in UTM-25 to perform the Indirect Tensile Fatigue Test

Figure 3. 8 Fractured samples due to repeated load applied

3.6 SUMMARY

This chapter envelopes the methodology adopted for the research and also the material characterization for the HMA mix preparation. The mixes selected for research and the laboratory tests used to determine the properties of the mixes has been discussed. Only the Margalla aggregate source is used for performance testing in combination with ARL 60/70 and NRL 40/50, but the tests to characterize the physical properties is performed for both Margalla and Sargodha aggregate and also three types of bitumen including ARL 60/70, NRL 40/50 and NRL 60/70. Detailed methodology for the preparation of mixes for both Marshall Method and Superpave Gyratory Compactor have been discussed including the mixing, compaction and sample moulding. The Marshall Method was used to determine the optimum bitumen content for the different mixes which were further used in the sample fabrication for performance testing using the Gyratory Compactor accompanied by core cutter and saw cutter. In the end of the chapter the performance test, Indirect Tensile Fatigue Test, has also been elaborated to certain extent.

Chapter 4

RESULTS AND ANALYSIS

4.1 INTRODUCTION

This chapter comprises of the results obtained from the indirect tensile fatigue testing. The initial analysis, to determine the initial strain for each specimen, was performed using Microsoft Excel as the data from the output of the software did not include the initial strain values. Once the initial strain values were determined, the results were compiled to develop relationship between the log of number of cycle to failure and the log of initial strain values. The screened data was further analysed using SPSS and MINITAB-17 software to develop fatigue curves for each type of mix. The comparison of the different gradation and two different types of bitumen have also been shown. Further a nonlinear model has been developed for the overall data set to study the effect of various factors, like bitumen content and type and the aggregate gradation, in combination with the initial strain on the number of cycles to fatigue failure under repeated loading. The results established by analysing the data are presented using graphs, figures and residual plots.

4.2 ITFT RESULTS

The research included the performance test of Indirect Tensile Fatigue which was conducted on four wearing course gradations using an aggregate source of Margalla and two bitumen sources of NRL 40/50 and ARL 60/70. These combined to form 8 different HMA mixtures, and these mixes were all tested using same environmental conditions, 25 °C temperature with a frequency of loading of 2 Hz. The loading cycle was further divided into 100ms loading period and 400ms rest period. There were three replicate samples tested for each stress level in case of each different gradation, and a total of six stress levels were tested as shown in the test matrix in chapter 3. The test is run with the LVDT attached on the jig to note the deformations in the sample for the first 150 cycles only as there might be a chance of damaging the LVDT if they are kept attached throughout the test protocol. The horizontal deformations noted are then used to plot graph of deformation and number of cycles. The initial strain is calculated after the deformations are stabilised, normally before 60 number of cycles. The difference between the averages of total horizontal deformations of 5 load applications from 98 to 102 and from 60 to 64 is used to calculate the initial strain value for the particular specimen. The results shown in Table 4.1 and 4.2 are of the average number of cycles to failure and the average initial strain for the three replicates tested for each stress level.

Table 4. 1 Results for the different aggregate gradations using NRL 40/50

Bitumen Grade	NRL 40/50							
Aggregate Gradation	NHA-A		NHA-B		MS-2		SP-1	
Stress (N)	Cycles to Failure	Initial Strain (µm)	Cycles to Failure	Initial Strain (µm)	Cycles to Failure	Initial Strain (µm)	Cycles to Failure	Initial Strain (µm)
5500	904	283	-	-	1048	350	-	-
5000	1181	289	898	395	1611	431	-	-
4500	2381	268	1241	680	2548	259	774	591
4000	2876	159	1248	320	3588	203	941	483
3500	3981	131	4138	168	6734	158	1368	375
3000	9844	86	3208	192	-	-	2161	392
2500	-	-	15676	84	28451	83	2821	334
2000	-	-	-	-	-	-	7636	252

Table 4. 2 Results for different aggregate gradations using ARL 60/70

Bitumen Grade	ARL 60/70							
Aggregate Gradation	NHA-A		NHA-B		MS-2		SP-1	
Stress (N)	Cycles to Failure	Initial Strain (µm)	Cycles to Failure	Initial Strain (µm)	Cycles to Failure	Initial Strain (µm)	Cycles to Failure	Initial Strain (µm)
5500	-	-	-	-	-	-	-	-
5000	-	-	-	-	-	-	-	-
4500	451	432	-	-	524	702	-	-
4000	751	396	341	1113	861	414	274	588
3500	1341	321	398	946	1417	428	384	503
3000	1998	283	1178	327	3954	253	676	508
2500	4716	211	1534	312	6171	217	3191	309
2000	-	-	5061	109	23121	143	2578	381

4.3 FATIGUE CHARACTERIZATION OF HMA MIXES

Fatigue cracking is considered to be a function of pavement structure stiffness, binder type and content, aggregate type and gradation, as well as the environment factors. The main objective of the study as mentioned earlier was to characterize the different HMA mixtures, to relatively evaluate the performance of the four wearing course mixes using the same bitumen and also by varying the stiffness of the bitumen used. The effect of aggregate gradation was studied using the same bitumen for all the four wearing course gradation and applying similar set of stresses to develop fatigue curves. Similar procedure was adopted to study the effect of a bitumen with different stiffness using all the four gradations with different bitumen under similar set of stresses to develop fatigue curves.

4.3.1 Fatigue Curves

The data set, from the output of the software for performance test of Indirect Tensile Fatigue, was used to develop a linear relation between the log of number of cycles to failure and the log of initial strain values using the equations shown as following:

$$N_f = a\left(\frac{1}{\varepsilon_0}\right)^b \qquad \textbf{(4.1)}$$

$$\log N_f = \log(a) + b\log(\varepsilon_0) \qquad \textbf{(4.2)}$$

Where,

N_f = number of cycles to failure

ε_o = initial strain, in micro meter

"a" & "b" are the experimentally determined coefficients

Table 4. 3 Slope and intercept for the fatigue curve using NRL 40/50

	NRL 40/50			
	NHA-A	**NHA-B**	**MS-2**	**SP-1**
Slope, (b)	-1.281	-1.385	-1.670	-2.253
Intercept, (Log(a))	6.228	6.620	7.440	9.085
R squared	0.854	0.850	0.850	0.806
Adjusted R squared	0.844	0.840	0.840	0.792

Table 4. 4 Slope and intercept for the fatigue curve using ARL 60/70

	ARL 60/70			
	NHA-A	**NHA-B**	**MS-2**	**SP-1**
Slope, (b)	-2.453	-1.122	-2.002	-3.110
Intercept, (Log(a))	9.225	5.927	8.405	11.133
R squared	0.733	0.940	0.824	0.781
Adjusted R squared	0.711	0.934	0.810	0.762

Several models have been proposed based on the laboratory data, by Asphalt Institute and Shell, to predict the fatigue lives of pavements, and to develop these models shift factors based on field observations have been used to calibrate the laboratory results in order to provide reasonable estimate of in-service life cycle of a pavement. The slope and the intercept of the different mixtures have been shown in Table 3.3 and 3.4. The slopes of all the curves are negative shown that the number of cycles to failure are inversely proportional to the initial strain values, and this trend can be seen in all the gradations irrespective of the use of different bitumen. The slopes of the gradations using ARL 60/70 are relatively much steeper that those using the stiffer bitumen, NRL 40/50. The fitted line plots of all the HMA mixes are shown in Figure 4.1 to 4. 8. The number of cycles to failure and initial strain values are best presented by power functional form, the trends of the different HMA mixtures are shown in Figure 4.9 to 4.16.

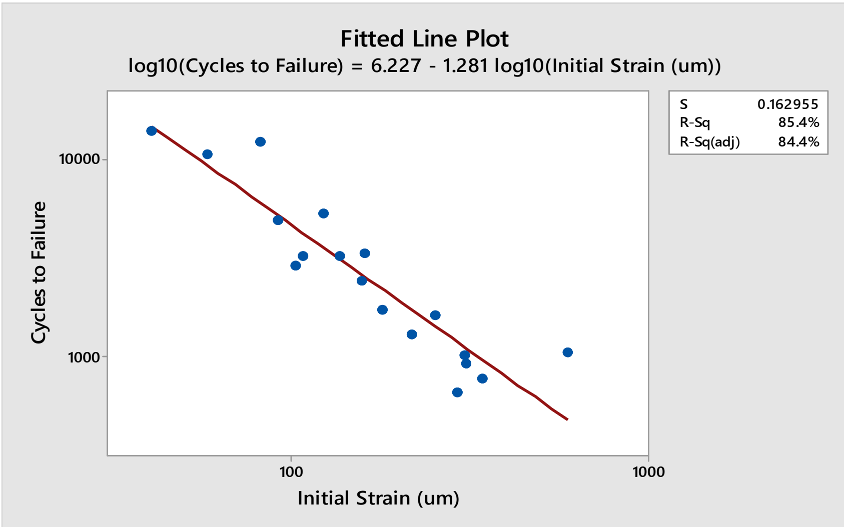

Figure 4. 1 Fitted line plot on log scale on both axis for NHA – A using NRL 40/50

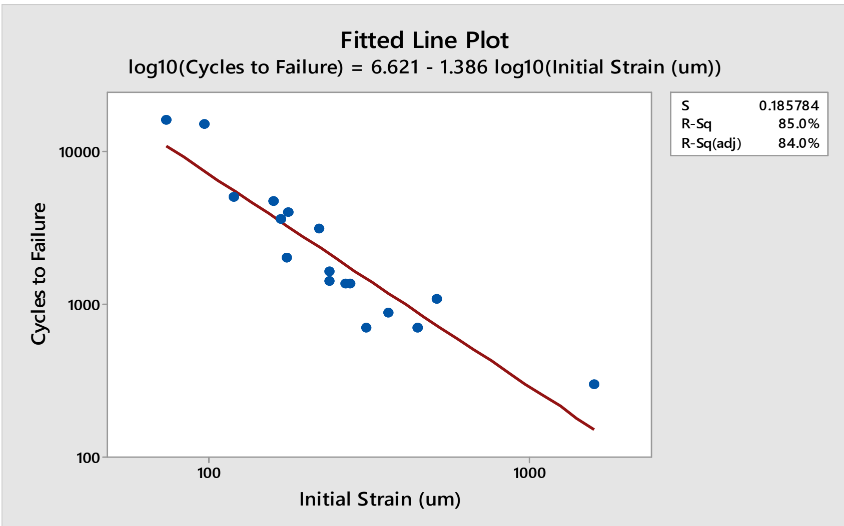

Figure 4. 2 Fitted line plot on log scale on both axis for NHA – B using NRL 40/50

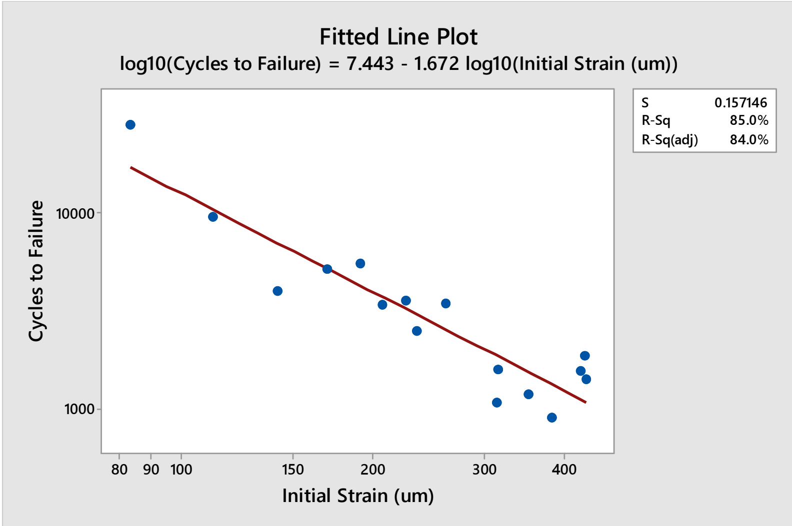

Figure 4. 3 Fitted line plot on log scale on both axis for MS – 2 using NRL 40/50

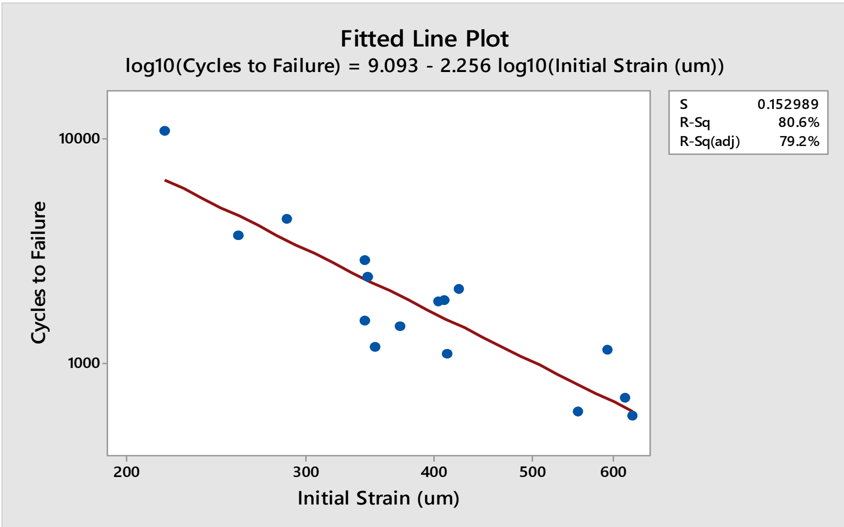

Figure 4. 4 Fitted line plot on log scale on both axis for SP – 1 using NRL 40/50

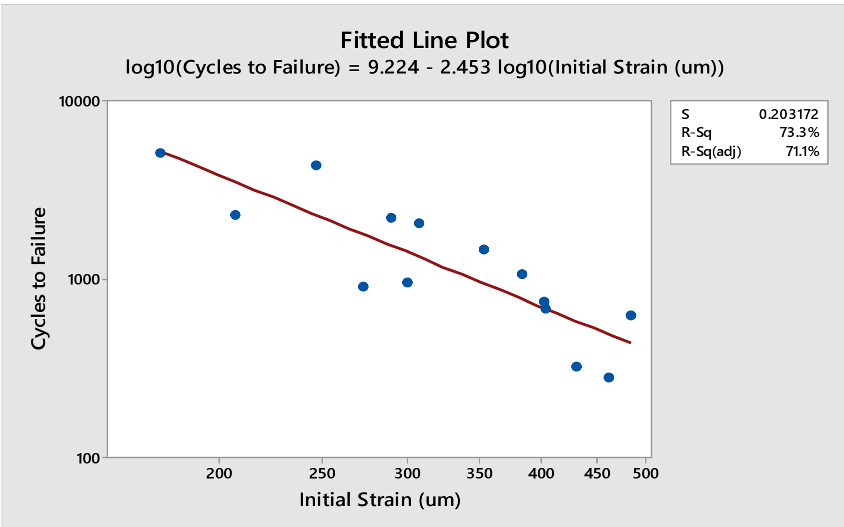

Figure 4. 5 Fitted line plot on log scale on both axis for NHA – A using ARL 60/70

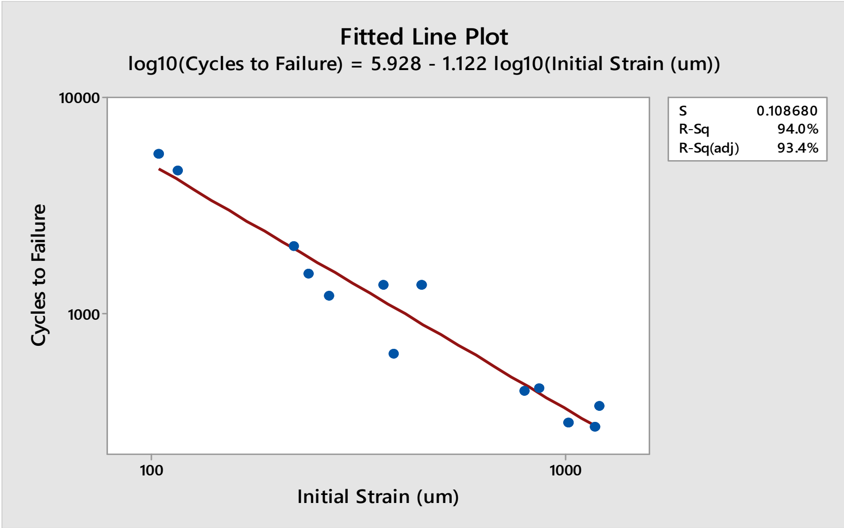

Figure 4. 6 Fitted line plot on log scale on both axis for NHA – B using ARL 60/70

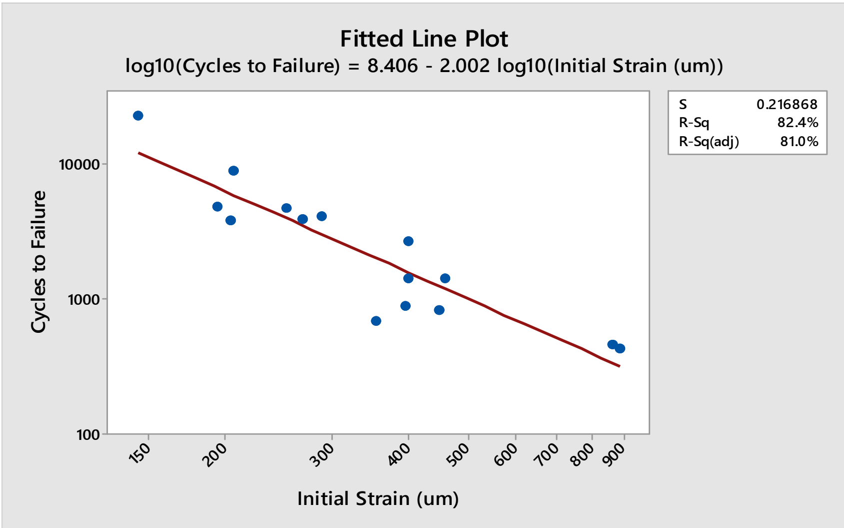

Figure 4. 7 Fitted line plot on log scale on both axis for MS – 2 using ARL 60/70

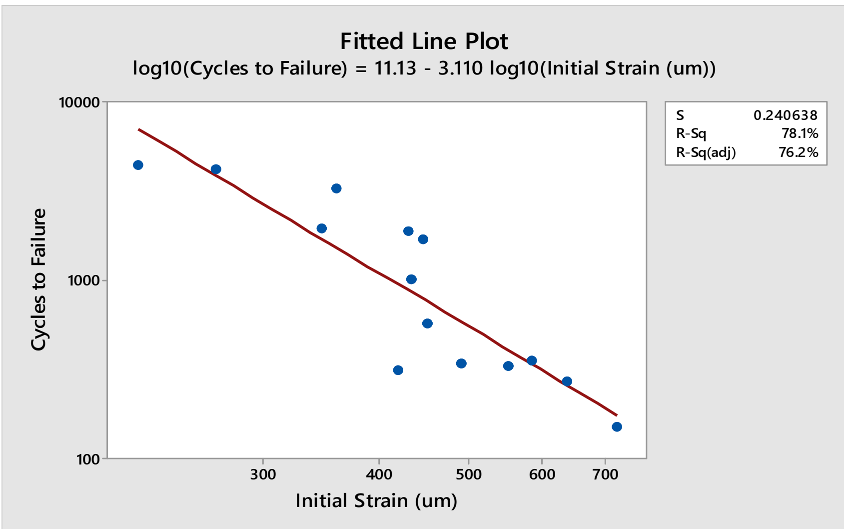

Figure 4. 8 Fitted line plot on log scale on both axis for SP – 1 using ARL 60/70

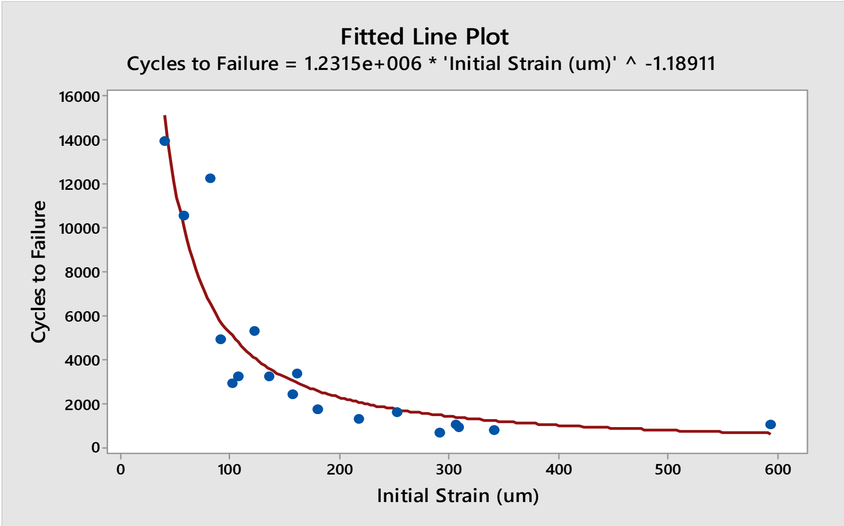

Figure 4. 9 Fitted line plot of the power function for NHA – A using NRL 40/50

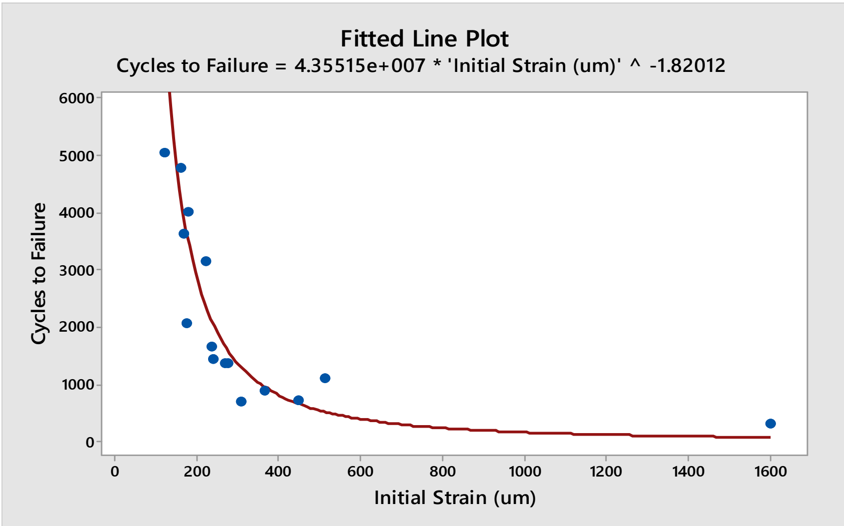

Figure 4. 10 Fitted line plot of the power function for NHA – B using NRL 40/50

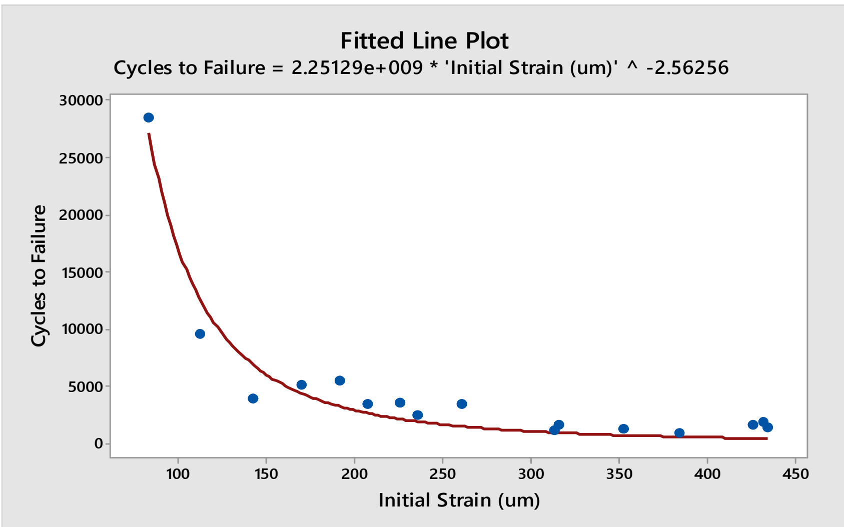

Figure 4. 11 Fitted line plot of the power function for MS – 2 using NRL 40/50

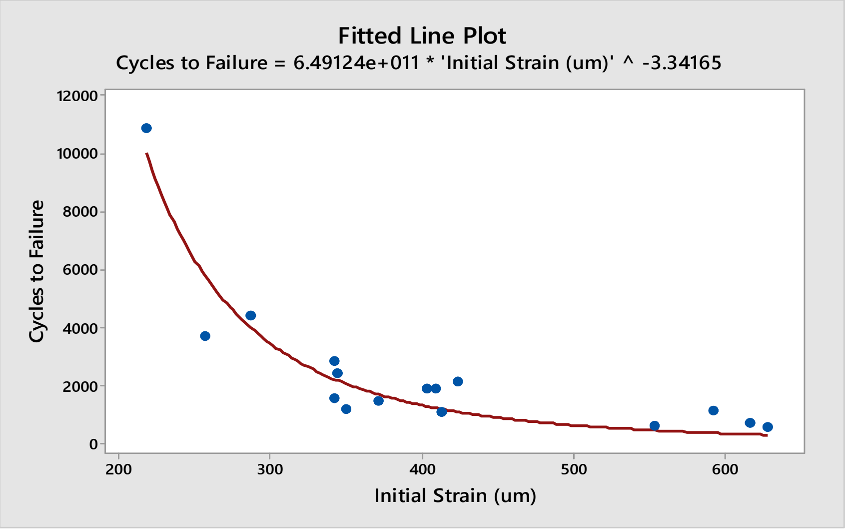

Figure 4. 12 Fitted line plot of the power function for SP – 1 using NRL 40/50

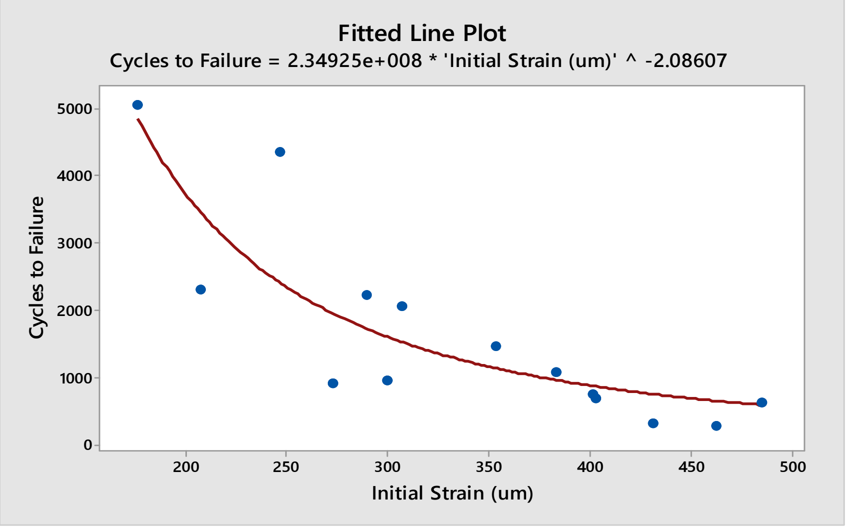

Figure 4. 13 Fitted line plot of the power function for NHA – A using ARL 60/70

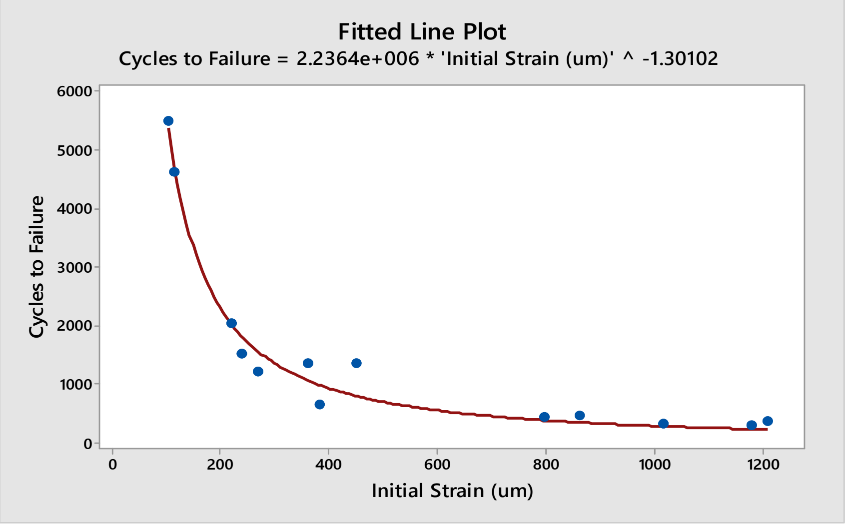

Figure 4. 14 Fitted line plot of the power function for NHA – B using ARL 60/70

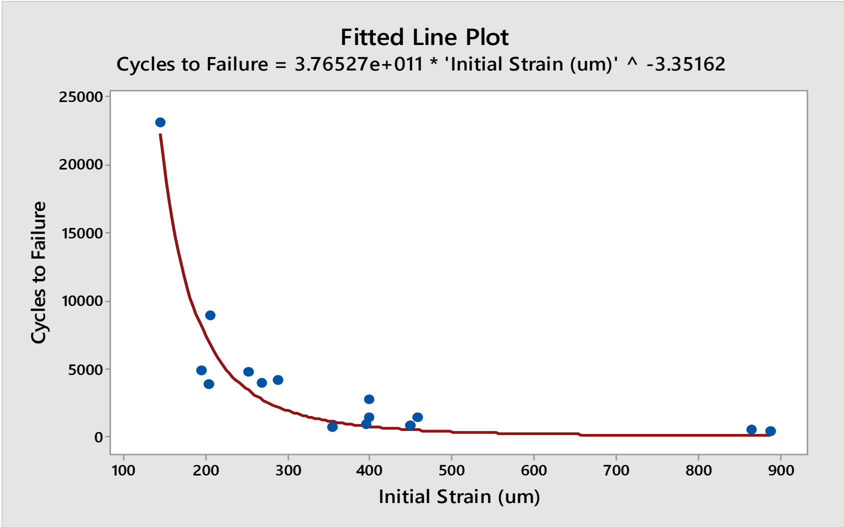

Figure 4. 15 Fitted line plot of the power function for MS – 2 using ARL 60/70

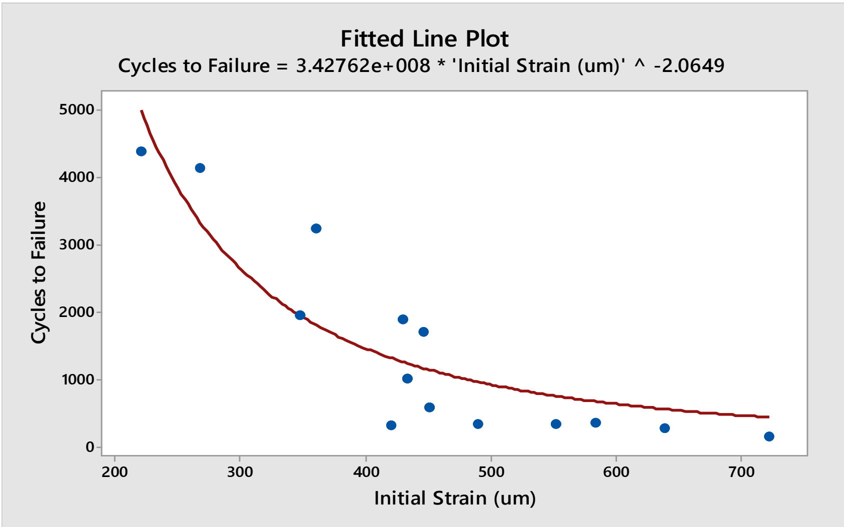

Figure 4. 16 Fitted line plot of the power function for SP – 1 using ARL 60/70

The number of cycles to failure to determine the fatigue limit have been proved by studies to be inverse in relation to the initial strain developed in the asphalt concrete, and the graph clearly show the relation as an inverse proportion using a power functional form. The R-squared vales of the graph also show a satisfactory relation between the two parameters, the R-squared values are mostly more than 70 % in all the linear plots on log scale and they prove that the response values in correlation to the predicted responses are in the acceptable range. The only purpose on taking the log scale on both the axis is to stream line the data and to get a better plot so that the predicted line fits more accurately in the observed data with very less variability in predicted and observed readings, gives a better R-squared value. The equations, both the linear and power can be seen in the figures showing the plots for cycles to failure against initial strain but they are compiled in Table 4.5 also.

Table 4. 5 Equations of the fatigue curves developed for different HMA mixes

Gradation	Bitumen Type	Linear	Power
NHA – A	NRL 40/50	$\log(N_f) = 6.227 - 1.281\log(\varepsilon)$	$N_f = 1.2315E6(\varepsilon^{-1.18911})$
NHA – B		$\log(N_f) = 6.621 - 1.386\log(\varepsilon)$	$N_f = 4.3551E7(\varepsilon^{-1.82012})$
MS – 2		$\log(N_f) = 7.443 - 1.672\log(\varepsilon)$	$N_f = 2.2513E9(\varepsilon^{-2.56256})$
SP – 1		$\log(N_f) = 9.093 - 2.256\log(\varepsilon)$	$N_f = 6.491E11(\varepsilon^{-3.34165})$
NHA – A	ARL 60/70	$\log(N_f) = 9.224 - 2.453\log(\varepsilon)$	$N_f = 2.349E8(\varepsilon^{-2.08607})$
NHA – B		$\log(N_f) = 5.928 - 1.122\log(\varepsilon)$	$N_f = 2.236E6(\varepsilon^{-1.30102})$
MS – 2		$\log(N_f) = 8.406 - 2.002\log(\varepsilon)$	$N_f = 3.765E11(\varepsilon^{-3.35162})$
SP – 1		$\log(N_f) = 11.13 - 3.110\log(\varepsilon)$	$N_f = 3.4276E8(\varepsilon^{-2.0649})$

4.3.2 Relative Performance

Fatigue cracking is the reason for fatigue failure of the asphaltic layers and complex interaction of the temperature, loading rate and aging are among the many factors that affect the fatigue mechanism. Fatigue cracking decreases service life of the pavement which leads to the breakdown of pavement structure. Among other various factors fatigue is one of the major distress in HMA pavements and the factors affecting fatigue in any HMA mixture are the mode of loading, the stresses induced in the pavement, the loading pattern and rest periods, and the mixture variables.

The literature states that the primary material properties having the most significance on the fatigue life of a particular HMA mix are the stiffness of the bitumen and the content of bitumen in the mix accompanied by the air voids. The mixtures were prepared to achieve a target air void content of 4% by volume of the overall mixture so this factor needs not to be studied, but the comparison of stiffness of the bitumen has been done for different mixes as shown in Table 4.6. The stiffer bitumen used in the research was NRL 40/50 and the number of cycles to failure for all four gradations using this bitumen type is almost 3 times more than the number of cycles to failure for the mixes using softer bitumen of ARL 60/70. Table 4.6 shows the comparison of number of cycles to failure of different HMA mixes for a repeated

4000 N haversine loading, this particular loading is selected as this was the common loading condition for all the different gradations. The stress levels for the different gradations needed to be adjusted to take into account the factor of initial strain values and also that the tests were completed in the particular testing time. It can be clearly seen in Table 4.6 that using a stiffer bitumen increases the fatigue life of HMA mixtures once under the stress controlled conditions, the trend in strain controlled mode will not be the same and verification for that is needed separately as the loading is different in both conditions as explained earlier.

The other significant factor that needed to be studied as stated in the literature is the bitumen content, more the bitumen content more the fatigue life of the HMA mixture. The Figure 4.17 shows the optimum bitumen content for all the HMA mixtures, it can clearly be seen that the coarser gradations require a lesser bitumen content and the finer gradations like superpave in our case require the most bitumen content to get an optimum desired results. The literature states that the aggregate gradation does not have a direct relation to the fatigue life of HMA mixtures as it is governed by the concept of varying bitumen content in every gradation. The gradations according to coarser to finer gradation are sequenced as NHA – A, NHA – B, MS – 2 and then SP – 1 and the optimum bitumen, for both types of bitumen, also increases in the similar fashion as the gradations move from coarser to finer shown in Figure 4.17. According to the literature, mentioned earlier also, the fatigue response of the HMA mixtures should also have a similar trend as that of the optimum bitumen content but the case is not same in our study as shown in Figure 4.18. For a repeated haversine loading of 4000 N the trend of increase in bitumen content increasing the fatigue life cannot be seen in Figure 4.18, and this can is only explained by the effect of gradations on the fatigue life which is considered to be insignificant and be indirectly effecting by changing the bitumen content. The results illustrated in Figure 4.18 show that there is a certain effect of the gradation on the fatigue life of the HMA mixture, not only by varying the bitumen content but also by providing different packing in the HMA mixtures which is dominated by the gradation of a particular mix. The trend is constant for both types of bitumen proving that gradations also have a certain level of effect on the fatigue life of the HMA mixtures. The trends show that the MS – 2 gradation shows the best susceptibility to fatigue followed by NHA – A and NHA – B and the least susceptible gradations is the SP -1.

Table 4. 6 Increase in fatigue life by using a stiffer bitumen relative to softer bitumen

Gradation / Bitumen Type	NHA – A	NHA – B	MS – 2	SP – 1
NRL 40/50	2876	1248	3588	941
ARL 60/70	751	341	861	274
Increase in Cycles to Failure	3	3	3	2

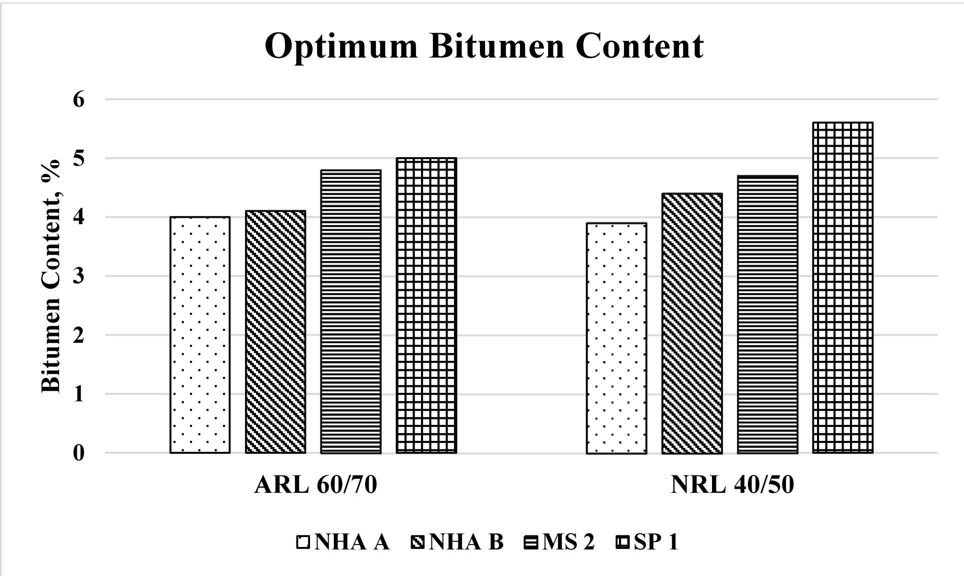

Figure 4. 17 Optimum bitumen content used for each HMA mix

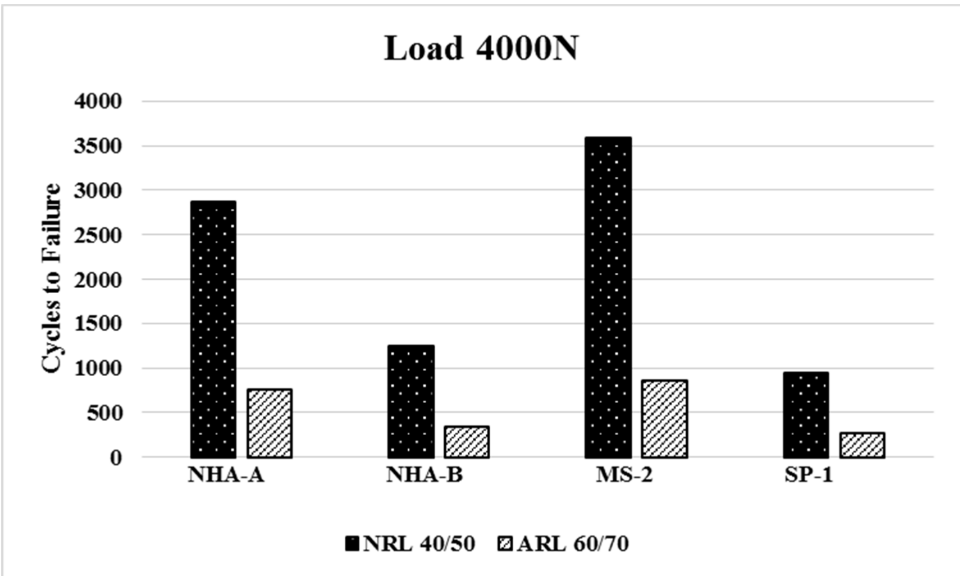

Figure 4. 18 Relative plot of cycles to failure for different HMA mixes under 4000N load

4.3.3 Fatigue Model

There are a number of tests used, as mentioned earlier, to determine the fatigue life of HMA mixtures and the test protocol followed in this research is the indirect tensile fatigue test. The stress controlled loading in this test was used to get response of different HMA mixtures at different stress levels, and the responses in the output of the performance test were the deformations at each loading cycle and the number of cycles to failure. The deformation responses were used to get the initial strain values for each and every specimen that is tested and further stress/ strain based approach is used to determine the fatigue curves for each mix which are shown earlier.

Once the fatigue curves were determined along with the relative performances of different mixes, there comes a need to develop a model to predict the number of cycles to failure using different factors such as the bitumen type, bitumen content and some variable to study the effect of gradation. This study is a part of a project of National Highway Authority, Pakistan for the "Improvement of Asphalt Mix Design Technology for Pakistan", the variable to be included in the model for studying the effect of gradation is the resilient modulus values for all the HMA mixtures at 25°C for 4 inch diameter specimens is taken from a similar study "Characterization of Various HMA Mixtures Using Resilient Modulus Test" carried out by National University of Science & Technology, Pakistan. The resilient modulus is also known as the elastic modulus and it is defined as the ratio of deviator stress and the recoverable strain under repeated loading. The resilient modulus basically determines the stiffness of a particular HMA mixture which is a factor of the bitumen type, bitumen content and the aggregate gradation. The effect of the other variables, bitumen type and bitumen content, are separately added to the model and the remaining effect of the resilient modulus is of the aggregate gradation that we need to incorporate in the model.

The statistical software MINITAB – 17 was used to determine the fitted line plots for the total data set of all the gradations combined, and the fitted line plot for cycles to failure versus the initial strain is shown in Figure 4.20 followed by the residual plot for the data set.

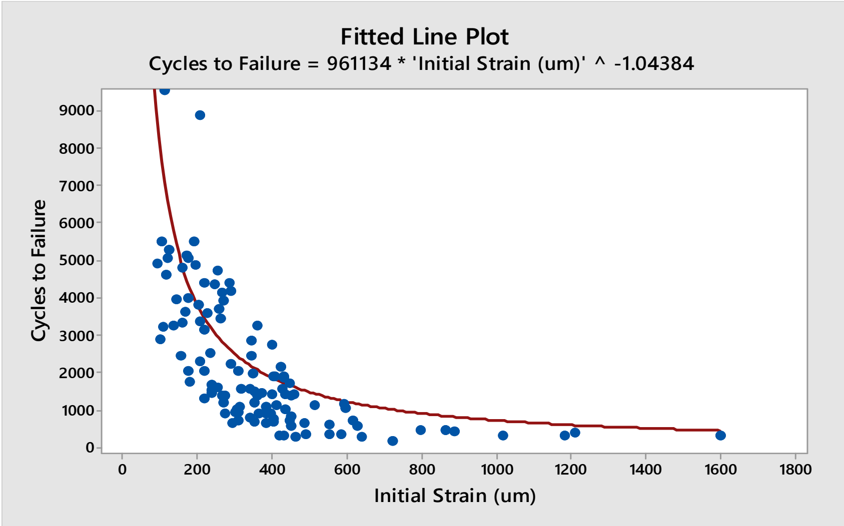

Figure 4. 19 Fitted line plot (power function) for combined data of all the HMA mixes

Further the data was plotted using log scale on both the x – axis and y – axis to get an intrinsically linear model and the fitted line for that plot is shown in Figure 4.21. The data converted to produce an intrinsically linear plot shows a confidence of 70%, shown by the r squared and the adjusted r squared values. The residual plots in Figure 4.23 show a normal trend in the data and the improvement in the fit of the plot can be seen clearly in Figure 4.20 to Figure 4.23.

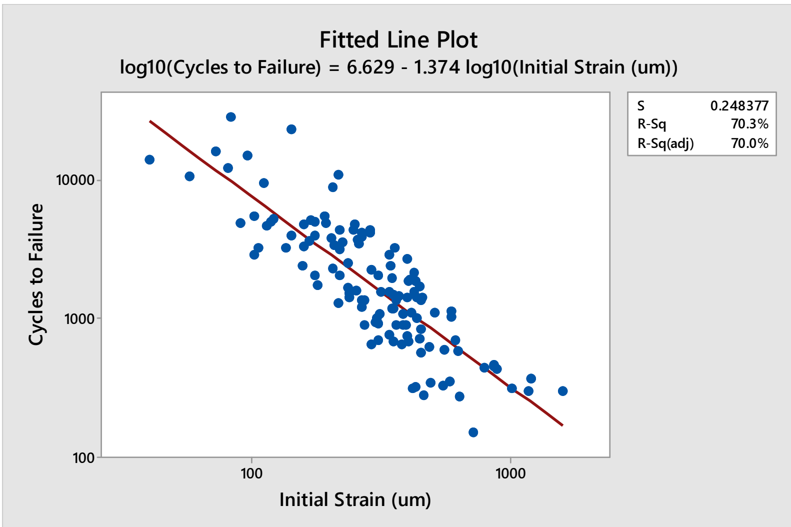

Figure 4. 201 Fitted line plot of log scale on both axis for combined data of all mixes

Once the plots and functions for both power and logarithmic form were developed the effect of the bitumen type and content and the aggregate gradations needed to be incorporated so the model was modified by introducing these three variables in the equation to capture their effect on the number of cycle to failure. The models developed are as following:

$$N_f = 959994.3(\varepsilon^{-1.044}) \tag{4.3}$$

$$\log N_f = 6.629 - 1.374 \log(\varepsilon) \tag{4.4}$$

$$N_f = 1.367 \times 10^{-8} \times \varepsilon^{-2.556} \times \eta^{-1.564} \times \upsilon_B{}^{9.154} \times E^{2.655} \tag{4.5}$$

Where,

N_f	=	Number of cycles to failure
ε	=	Initial strain, micro strain
η	=	Bitumen Viscosity, NRL 40/50 = 0.486, ARL = 0.225
υ_B	=	Optimum Bitumen Content, percentage
E	=	Resilient modulus, MPa

The Equation 4.3 shows the relationship between the number of cycles to failure and the initial strain values for all the data set of all the HMA mixtures as a power function and the r squared value comes out to be 49.3% and the validation of the model predicted has been done by the MAPE value which is 0.904 for the particular model. The data set was converted to linear for by taking log on both sides and the model generated is shown by Equation 4.4, the r squared value increase to 70% by making an intrinsically linear model. Further the variables were added in the model to produce both nonlinear power function and a multi linear log function. Many models have been tried and tested but the best possible model developed are shown by Equation 4.5 with an r squared value of 85.6%. The validation of the model has been done by the MAPE value which comes out to be 0.455. The preferable model developed is shown by Equation 4.5 as it represents the direct relations developed between the response variable and the predictor values. The t – Stat values shown in Table 4.7 for the ANOVA of the non-linear regression model shows that the initial strain value, the bitumen content of the gradations and the type of bitumen represented by the different viscosities show significant effect on the number of cycles to failure if 95% confidence is assumed.

Table 4. 7 ANOVA table for non-linear regression model

Parameter	Estimate	Std. Error	t – Stat	R^2 (%)	95 % Confidence Interval	
					Lower Bound	Upper Bound
a	1.367E-8	0.00	0.00	85.6	-2.308E-7	2.581E-7
b	-2.556	0.105	-24.3		-2.763	-2.348
c	-1.564	0.242	-6.41		-2.043	-1.085
d	9.154	0.738	12.4		7.691	10.617
e	2.655	0.816	3.25		1.038	4.273

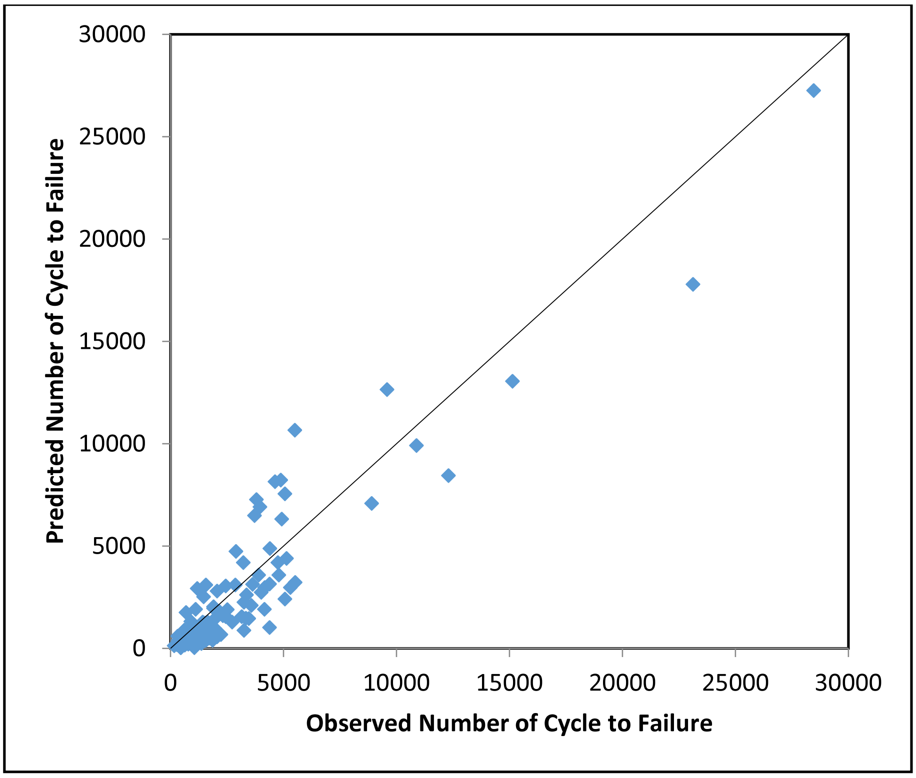

Figure 4. 22 Validation plot for the non-linear model

4.4 SUMMARY

The chapter encompasses the complete analysis of the results obtained by the indirect tensile fatigue testing. The output from the performance test for all the HMA mixtures were used to develop the fatigue curves for the respective mixes. The fatigue curves were developed using the power functional form, to get a better fitted line plot the axis were converted to log scale and the linear model was generated to get an inverse relation between the number of cycles to failure and initial strain values. The stress/strain based approach was basically used to develop the relationship.

The characterization of HMA mixtures were done according to the susceptibility to fatigue failure by comparing the number of cycles to failure at a particular load level. The comparison concluded that softer bitumen produce mixes more prone to fatigue failure than stiffer bitumen. The fact also established by the comparison of bitumen content of different HMA mixtures that gradation also has a part in the fatigue resistance. The MS – 2 gradation came out to be the most resistant gradation, to fatigue failure, using both the bitumen types. The main factors taken in study, bitumen type and content and the aggregate gradation, were further introduced in the model to increase the reliability of the model to predict the fatigue failure of a particular mix more accurately.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY

The current study is a part of the first phase of the project entitled "Improvement of Asphalt Mix Design Technology for Pakistan" initiated by National Highway Authority, Pakistan in collaboration with National University of Science & Technology, Pakistan. The overall aim in the current phase and specifically this study has been to characterize the HMA mixtures using indirect tensile fatigue test. There were four wearing course gradations used in this study including NHA – A, NHA – B, MS – 2 and SP – 1. Each of the gradation was used in samples preparation for the performance test using two types of bitumen, a stiffer bitumen source of NRL 40/50 and the softer bitumen ARL 60/70. The samples for the testing were compacted in superpave gyratory compactor (SGC) to produce 6 inch diameter specimens which were fabricated to produce the required dimension of 4 inch diameter and 2 inch thickness. The prepared samples were subjected to repeated haversine loading in Universal Testing Machine (UTM) at a temperature of 25°C until the sample failure occurred, at different load levels to generate a data set required for plotting fatigue curves. Further the effect of bitumen type, content and aggregate gradations has been introduced to prepare a model for number of cycles to failure of compacted specimens subjected to repeated haversine loading.

5.2 CONCLUSIONS

The following conclusions can be drawn based on the performance test of indirect tensile fatigue executed on the given HMA mixtures comprising of the four gradations with NRL 40/50 and ARL 60/70 bitumen type and the aggregate source of Margalla:

- The finer gradations require more bitumen to coat the aggregate particles completely as the surface areas increases by decreasing the coarseness of a particular gradation, and the trend of optimum bitumen content for the different gradations show a particular trend that superpave gradation is the most finer among the other four gradations followed by MS – 2 and NHA – B and the courser gradation NHA – A have the minimum optimum bitumen content among all, irrespective of the type of bitumen being used.
- Using the stiffer bitumen of NRL 40/50 the relative performance of MS – 2 gradation is much better among the four gradations followed by NHA – A, NHA – B and SP – 1.

These trends were consistent with all the stress levels, the number of cycles to failure is used as a parameter for the comparison.

- Likewise, using the softer bitumen of ARL 60/70 verify that the relative performance of MS – 2 is far better among the four gradations followed by NHA – A, NHA – B and SP – 1 being the least resistant to fatigue failure.
- Comparing the two bitumen sources of stiffer NRL 40/50 and softer ARL 60/70 show that the NRL 40/50 produces stiffer mixes in all gradations having number of cycles approximately 3 times the number of cycles for the same gradations using ARL 60/70. This is the case in the stress controlled mode in the diametric loading, the results may vary when studying the strained controlled loading as permanent deformations are produced in the stress controlled mode. The comparison is studied for a loading condition of 4000 N only as it is the only loading common in tests performed on all the eight different HMA mixes.
- The data set generated for a range of stress level are used to develop fatigue curves for all the eight different HMA mixtures for both the power function and by converting the x –axis and y – axis to logarithm scale. The fatigue models develops are a step towards the shift functions for these HMA mixtures in collaboration with the field responses of the same mixtures under loading and environmental conditions of field.
- Statistical soft wares, SPSS, MINITAB – 17 and Excel, were used to develop models to incorporate the effect of bitumen type, bitumen content and the aggregate gradations. The r squared value for the relationship between number of cycles of failure versus the initial strain using the power and by taking log on both axis comes out to be 49.3% and 70% respectively. The nonlinear model was developed including the initial strain, bitumen type, bitumen content and the resilient modulus (to cater for the effect of aggregate gradation) as independent variables and the dependant variable as the number of cycles of fatigue failure. The model developed taking the mentioned independent variables into account has an r squared value of 85.6%, which is considered a good model.

5.3 RECOMMENDATIONS

The study as mentioned earlier is a part of a project to characterize the different HMA mixtures being used in Pakistan, and the indirect tensile fatigue test focuses on the fatigue parameter of the HMA mixes. The recommendations from this study are more focused on how further works needs to be done in this field to generate fatigue shift functions and also to completely characterize the different HMA mixes. The study included only Margalla quarry as an aggregate source, there are many other quarries running in Pakistan which need to be incorporated in the testing regime for complete characterization of materials of Pakistan. In addition to the aggregate source the bitumen sources also need to be increased so as to see the effect of different type of bitumen on the fatigue life and further compare them.

Apart from the materials variables, the environmental and loading variable are also needed to be included in the testing. The temperature sweep needs to be performed to test for the highest and lowest temperatures prevailing in Pakistan, and by doing so a contour can be established for using the particular set of HMA mixtures at particular locations throughout Pakistan. Before other bitumen types are added to the testing frame, there is a need to convert the penetration grading system to the performance grading system, so that the bitumen types are firstly characterized according to their performance then including them as a factor in the model for fatigue parameter.

The current study has been performed on the different HMA mixtures using the stress controlled conditions due to the limitation of the equipment available, there is a need to perform similar tests on the same mixes under the strain controlled mode of loading also as these gradations are to be used in the wearing course which is generally considered as a thin pavement and strain controlled mode of loading is used for the thinner pavements. The effect of strain mode of loading needs to be studied to verify the trends developed by the stress mode loading.

The effect of the gradation can only be studied if the factor of variable bitumen properties like the bitumen content and the air voids are kept constant, by keeping these factors constant then only the effect of varying the aggregate gradation can be observed regarding the fatigue life. There is also a need to perform the test using the same stress levels for all the different HMA mixtures so that the characterization can be done more effectively.

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APPENDICES

APPENDIX: A

SOFTWARE OUTPUT FOR INDIRECT TENSILE FATIGUE TEST USING UNIVERSAL TESTING SOFTWARE

Indirect Tensile Fatigue Test

Data file name: D:\Dropbox\NUST\Final Thesis\Performance Test\Performance Test\NRL 4050\MMS2\Software\2500N (1A).D013
Template file name:
Test date & time: 14/10/2014 12:41:12 PM
Project: MS2-1A(13th Oct, 2014)
Operator: Aniq
Comments:

Specimen Information

Identification: Dummy 1
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	51.0	51.0	51.0				51.0	
Width (mm)	100.0						100.0	
Thickness (mm)	80.0						80.0	

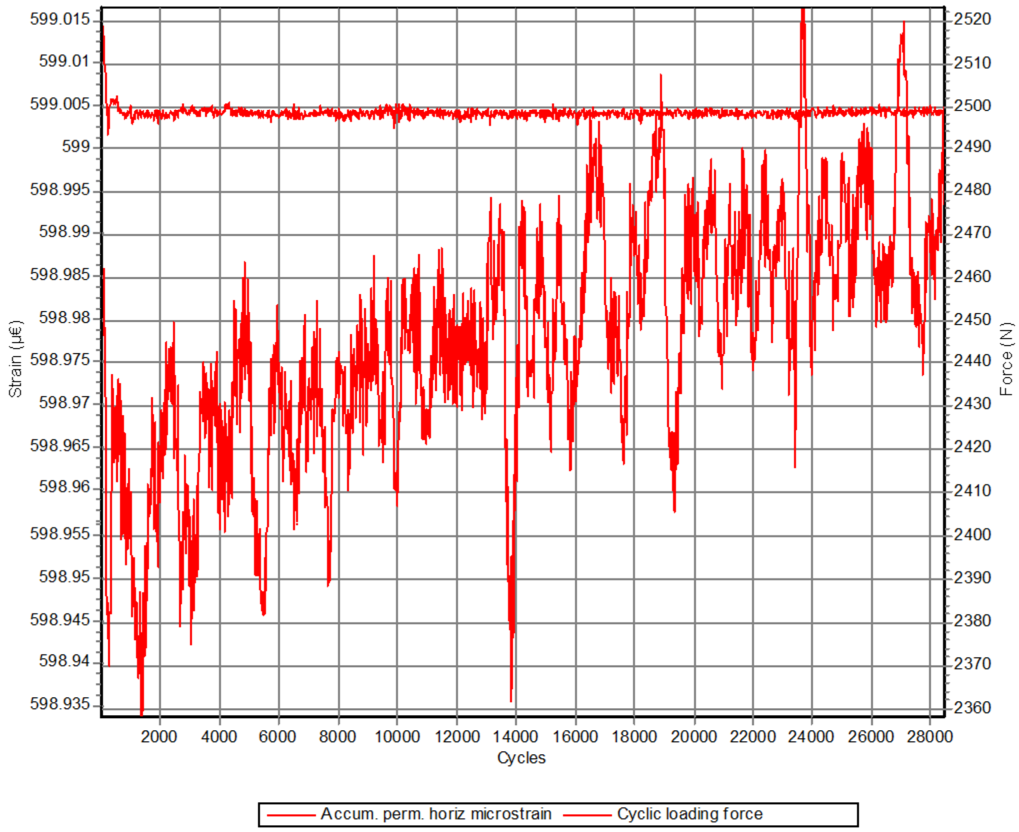
Cross-sectional area (mm²): 7854.0

Set up parameters

Transducer configuration: Std IT Jig
Cyclic loading force: 2500 N
Seating force: 50 N
Cycle duration: 100 ms
Cycle repetition time: 500 ms

Poisson ratio: 0.4
Target temperature: 25 °C

Termination cycle count: 40000
Termination max displacement: 9.0 mm



APPENDIX: B

INITIAL STRAIN CALCULATION FOR INDIRECT TENSILE FATIGUE TEST

Deformation values of cylindrical sample under repeated load for each cycle

Cycle	Total permanent horizontal deform. (mm)	Permanent horizontal deform. #1 (mm)	Permanent horizontal deform. #2 (mm)	Total permanent horizontal deform. (um)	Permanent horizontal deform. #1 (um)	Permanent horizontal deform. #2 (um)
1	0	0	0	0	0	0
11	-0.007	-0.008	-0.006	-7	-8	-6
21	-0.012	-0.014	-0.01	-12	-14	-10
31	-0.017	-0.02	-0.015	-17	-20	-15
41	-0.022	-0.025	-0.018	-22	-25	-18
51	-0.026	-0.029	-0.022	-26	-29	-22
61	-0.03	-0.034	-0.025	-30	-34	-25
71	-0.033	-0.038	-0.029	-33	-38	-29
81	-0.037	-0.042	-0.032	-37	-42	-32
91	-0.04	-0.045	-0.035	-40	-45	-35
101	-0.043	-0.049	-0.037	-43	-49	-37
111	-0.046	-0.052	-0.04	-46	-52	-40
121	-0.049	-0.055	-0.043	-49	-55	-43
131	0.008	0.008	0.009	8	8	9
141	0.008	0.008	0.009	8	8	9
151	0.008	0.008	0.009	8	8	9
161	0.008	0.008	0.009	8	8	9
171	0.008	0.008	0.009	8	8	9
181	0.008	0.008	0.009	8	8	9
191	0.008	0.008	0.009	8	8	9
201	0.008	0.008	0.009	8	8	9
211	0.008	0.008	0.009	8	8	9
221	0.008	0.008	0.009	8	8	9
231	0.008	0.008	0.009	8	8	9
241	0.008	0.008	0.009	8	8	9
251	0.008	0.008	0.009	8	8	9
261	0.008	0.008	0.009	8	8	9
271	0.008	0.008	0.009	8	8	9
281	0.008	0.008	0.009	8	8	9
291	0.008	0.008	0.009	8	8	9
301	0.008	0.008	0.009	8	8	9
311	0.008	0.008	0.009	8	8	9
321	0.008	0.008	0.009	8	8	9
331	0.008	0.008	0.009	8	8	9
341	0.008	0.008	0.009	8	8	9
3451	0.008	0.008	0.009	8	8	9

Plot for the deformation in horizontal direction against number of cycles

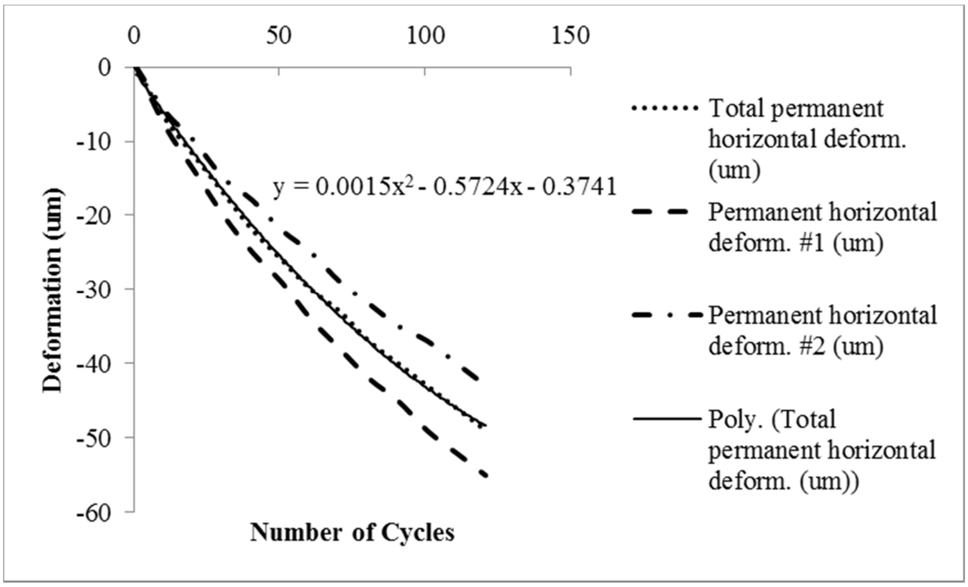


Table for initial strain calculation using the deformation values

Cycle	Total permanent horizontal deform. (mm)	Total permanent horizontal deform. (um)	Average permanent horizontal deform. (mm)
60	-0.0293181	-29.3181	-0.0300939
61	-0.029709	-29.709	
62	-0.0300969	-30.0969	
63	-0.0304818	-30.4818	
64	-0.0308637	-30.8637	
98	-0.0420633	-42.0633	-0.0426111
99	-0.0423402	-42.3402	
100	-0.0426141	-42.6141	
101	-0.042885	-42.885	
102	-0.0431529	-43.1529	
		Deformation (mm) =	0.0125172
		Initial Strain =	**260.35776**

APPENDIX: C

INDIRECT TENSILE FATIGUE TEST RESULTS

Table C-1 Indirect Tensile Fatigue Test Results for NHA-A using NRL 40/50

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
5500	1A	100	0.4	651	291.82	2.8136	2.4651
	2C	100	0.4	1291	217.20	3.1109	2.3369
	5B	100	0.4	771	341.22	2.8871	2.5330
5000	4B	100	0.4	1011	305.57	3.0048	2.4851
	5C	100	0.4	1611	252.61	3.2071	2.4025
	6C	100	0.4	921	308.41	2.9643	2.4891
4500	1B	100	0.4	3211	106.94	3.5066	2.0291
	3C	100	0.4	2891	101.98	3.4610	2.0085
	6A	100	0.4	1041	594.06	3.0175	2.7738
4000	2B	100	0.4	3321	160.29	3.5213	2.2049
	3A	100	0.4	10581	57.70	4.0245	1.7612
	6B	100	0.4	2431	157.21	3.3858	2.1965
3500	1C	100	0.4	5291	122.35	3.7235	2.0876
	4A	100	0.4	4921	91.13	3.6921	1.9597
	5A	100	0.4	1731	179.50	3.2383	2.2541
3000	2A	100	0.4	12301	81.41	4.0899	1.9107
	3B	100	0.4	13991	40.31	4.1458	1.6054
	4C	100	0.4	3241	136.03	3.5107	2.1336

Table C-2 Indirect Tensile Fatigue Test Results for NHA-B using NRL 40/50

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
5000	1C	100	0.4	1101	512.73	3.0418	2.7099
	4B	100	0.4	891	363.82	2.9499	2.5609
	6A	100	0.4	701	308.65	2.8457	2.4895
4500	3A	100	0.4	2051	174.92	3.3120	2.2428
	4C	100	0.4	1371	266.92	3.1370	2.4264
	5A	100	0.4	301	1599.53	2.4786	3.2040
4000	1B	100	0.4	1371	274.58	3.1370	2.4387
	3C	100	0.4	1661	237.12	3.2204	2.3750
	5C	100	0.4	711	448.24	2.8519	2.6515
3500	2A	100	0.4	4791	158.87	3.6804	2.2010
	3B	100	0.4	4001	176.18	3.6022	2.2460
	5B	100	0.4	3621	167.56	3.5588	2.2242
3000	2C	100	0.4	1431	237.52	3.1556	2.3757
	4A	100	0.4	5051	118.72	3.7034	2.0745
	6B	100	0.4	3141	220.21	3.4971	2.3428
2500	1A	100	0.4	15121	95.88	4.1796	1.9817
	2B	100	0.4	16231	72.97	4.2103	1.8631

Table C-3 Indirect Tensile Fatigue Test Results for MS-2 using NRL 40/50

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
5500	2A	100	0.4	891	384.21	2.9499	2.5846
	3A	100	0.4	1071	313.47	3.0298	2.4962
	4C	100	0.4	1181	352.68	3.0722	2.5474
5000	2C	100	0.4	1411	434.72	3.1495	2.6382
	5B	100	0.4	1561	426.18	3.1934	2.6296
	6C	100	0.4	1861	432.09	3.2697	2.6356
4500	2B	100	0.4	1571	316.16	3.1962	2.4999
	3C	100	0.4	2501	235.38	3.3981	2.3718
	6A	100	0.4	3571	225.90	3.5528	2.3539
4000	4B	100	0.4	3451	260.36	3.5379	2.4156
	5A	100	0.4	3361	207.64	3.5265	2.3173
	6B	100	0.4	3951	141.96	3.5967	2.1522
3500	1C	100	0.4	9571	112.16	3.9810	2.0498
	3B	100	0.4	5511	191.12	3.7412	2.2813
	5C	100	0.4	5121	169.49	3.7094	2.2291
2500	1A	100	0.4	28451	83.07	4.4541	1.9194

Table C-4 Indirect Tensile Fatigue Test Results for SP-1 using NRL 40/50

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
4500	6C	100	0.4	1141	591.61	3.0573	2.7720
	3B	100	0.4	581	627.50	2.7642	2.7976
	5B	100	0.4	601	553.28	2.7789	2.7429
4000	1A	100	0.4	1181	350.23	3.0722	2.5443
	4C	100	0.4	701	615.96	2.8457	2.7896
3500	4A	100	0.4	1451	371.01	3.1617	2.5694
	5A	100	0.4	1551	342.16	3.1906	2.5342
	6A	100	0.4	1101	412.67	3.0418	2.6156
3000	2B	100	0.4	2151	423.42	3.3326	2.6268
	4B	100	0.4	2431	344.38	3.3858	2.5370
	6B	100	0.4	1901	408.72	3.2790	2.6114
2500	1A	100	0.4	3711	256.64	3.5695	2.4093
	1B	100	0.4	2861	342.48	3.4565	2.5346
	3C	100	0.4	1891	403.42	3.2767	2.6058
2000	1C	100	0.4	4391	286.92	3.6426	2.4578
	2C	100	0.4	10881	217.52	4.0367	2.3375

Table C-5 Indirect Tensile Fatigue Test Results for NHA-A using ARL 60/70

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
4500	1B	100	0.4	321	431.40	2.5065	2.6349
	2C	100	0.4	281	462.46	2.4487	2.6651
	4C	100	0.4	751	401.52	2.8756	2.6037
4000	1A	100	0.4	681	403.03	2.8331	2.6053
	3A	100	0.4	621	484.99	2.7931	2.6857
	5B	100	0.4	951	299.88	2.9782	2.4769
3500	2A	100	0.4	1071	382.94	3.0298	2.5831
	4A	100	0.4	2051	307.07	3.3120	2.4872
	6A	100	0.4	901	272.73	2.9547	2.4357
3000	3C	100	0.4	1471	353.31	3.1676	2.5482
	5A	100	0.4	2301	206.93	3.3619	2.3158
	6B	100	0.4	2221	289.05	3.3465	2.4610
2500	2B	100	0.4	4371	246.45	3.6406	2.3917
	6C	100	0.4	5061	176.26	3.7042	2.2462

Table C-6 Indirect Tensile Fatigue Test Results for NHA-B using ARL 60/70

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
4000	3C	100	0.4	371	1210.89	2.5694	3.0831
	5C	100	0.4	311	1016.01	2.4928	3.0069
3500	1C	100	0.4	441	795.85	2.6444	2.9008
	3B	100	0.4	451	861.54	2.6542	2.9353
	5B	100	0.4	301	1180.44	2.4786	3.0720
3000	3A	100	0.4	1521	238.48	3.1821	2.3775
	4A	100	0.4	1361	361.21	3.1339	2.5578
	6A	100	0.4	651	382.55	2.8136	2.5827
2500	4B	100	0.4	2041	219.49	3.3098	2.3414
	5A	100	0.4	1361	449.29	3.1339	2.6525
	6C	100	0.4	1201	267.87	3.0795	2.4279
2000	1B	100	0.4	4621	114.61	3.6647	2.0592
	6B	100	0.4	5501	103.14	3.7404	2.0134

Table C-7 Indirect Tensile Fatigue Test Results for MS-2 using ARL 60/70

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
4500	2A	100	0.4	431	887.94	2.6345	2.9484
	3A	100	0.4	681	353.31	2.8331	2.5482
	4C	100	0.4	461	864.35	2.6637	2.9367
4000	2C	100	0.4	2721	398.36	3.4347	2.6003
	5B	100	0.4	891	395.20	2.9499	2.5968
	6C	100	0.4	831	449.11	2.9196	2.6523
3500	3C	100	0.4	1411	457.40	3.1495	2.6603
	4B	100	0.4	1422	399.55	3.1529	2.6016
3000	4A	100	0.4	4161	287.94	3.6192	2.4593
	4C	100	0.4	3801	203.37	3.5799	2.3083
	5A	100	0.4	3901	267.95	3.5912	2.4280
2500	1B	100	0.4	4871	193.80	3.6876	2.2873
	5C	100	0.4	8901	205.42	3.9494	2.3127
	6C	100	0.4	4741	252.14	3.6759	2.4016
2000	2B	100	0.4	23121	143.38	4.3640	2.1565

Table C-8 Indirect Tensile Fatigue Test Results for SP-1 using ARL 60/70

Load(N)	Sample	Average Specimen Diameter (mm)	Estimated Poisson Ration	Cycles to Failure	Initial Strain (um)	Log (Cycles to Failure)	Log (Initial Strain (um))
4000	3A	100	0.4	151	722.43	2.1790	2.8588
	4B	100	0.4	331	551.46	2.5198	2.7415
	5C	100	0.4	341	489.88	2.5328	2.6901
3500	2B	100	0.4	271	638.32	2.4330	2.8050
	5A	100	0.4	571	451.08	2.7566	2.6543
	6B	100	0.4	311	419.67	2.4928	2.6229
3000	1C	100	0.4	1001	432.82	3.0004	2.6363
	3B	100	0.4	351	583.87	2.5453	2.7663
2500	1B	100	0.4	4381	219.81	3.6416	2.3420
	4C	100	0.4	3242	359.47	3.5108	2.5557
	5B	100	0.4	1951	347.22	3.2903	2.5406
2000	2C	100	0.4	1881	429.50	3.2744	2.6330
	4A	100	0.4	4151	267.12	3.6182	2.4267
	6C	100	0.4	1701	445.47	3.2307	2.6488

APPENDIX: D

STATISTICAL OUTPUT FOR FATIGUE CURVES

Statistics Analysis for Fatigue Curve of NHA-A using NRL 40/50

Descriptive Statistics			
	Mean	Std. Deviation	N
Nf	3.4059	0.41314	18
IS	2.2021	0.29786	18

Correlation			
		Nf	IS
Pearson Correlation	Nf	1.000	-0.924
	IS	-0.924	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	18	18
	IS	18	18

Model Summary[b]									
Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.924[a]	0.854	0.844	0.16297	0.854	93.244	1	16	0.000

a. Predictors: (Constant), IS

b. Dependant Variable: Nf

ANOVA[b]					
Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	2.477	1	2.477	93.244	0.000[a]
Residual	0.425	16	0.027		
Total	2.902	17			

a. Predictors: (Constant), IS

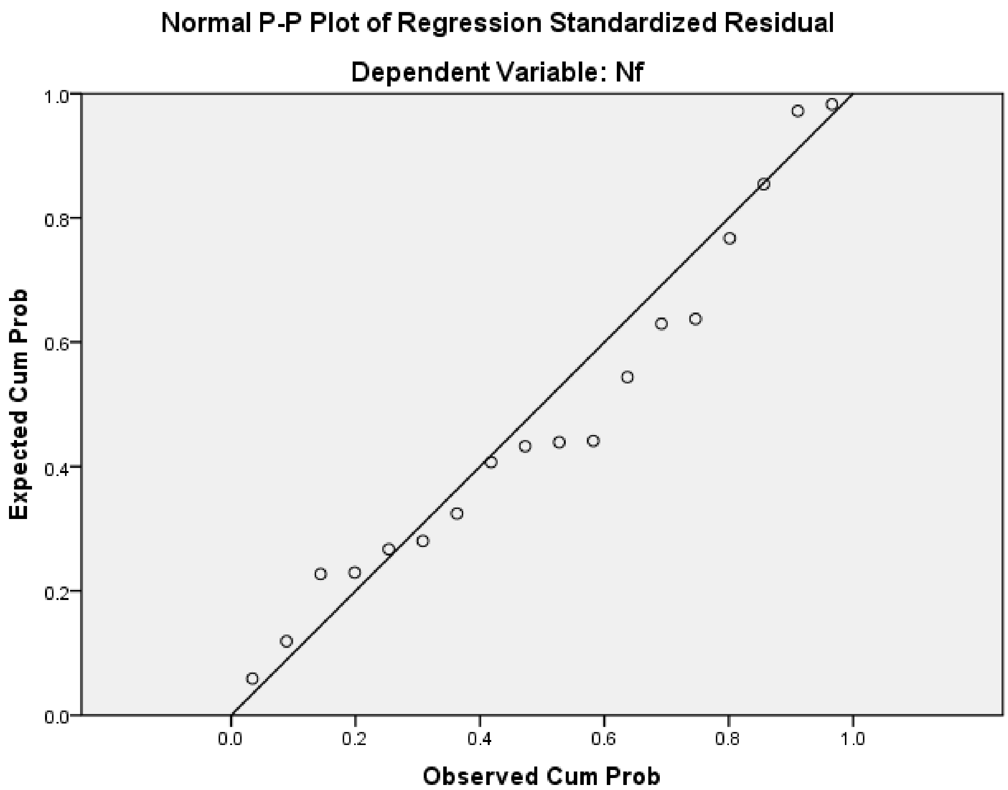
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	6.228	0.295		21.130	0.000
IS	-1.281	0.133	-0.924	-9.656	0.000

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.6730	4.1710	3.4059	0.38168	18
Residual	-0.2549	0.3440	0.0000	0.15811	18
Std. Predicted Value	-1.920	2.004	0.0000	1.0000	18
Std. Residual	-1.564	2.111	0.0000	0.970	18

a. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of NHA-B using NRL 40/50

Descriptive Statistics

	Mean	Std. Deviation	N
Nf	3.3272	0.46396	17
IS	2.3770	0.30875	17

Correlation

		Nf	IS
Pearson Correlation	Nf	1.000	-0.922
	IS	-0.922	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	17	17
	IS	17	17

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.922[a]	0.850	0.840	0.18585	0.850	84.718	1	15	0.000

a. Predictors: (Constant), IS

b. Dependant Variable: Nf

ANOVA[b]

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	2.926	1	2.926	84.718	0.000[a]
Residual	0.518	15	0.035		
Total	3.444	16			

a. Predictors: (Constant), IS

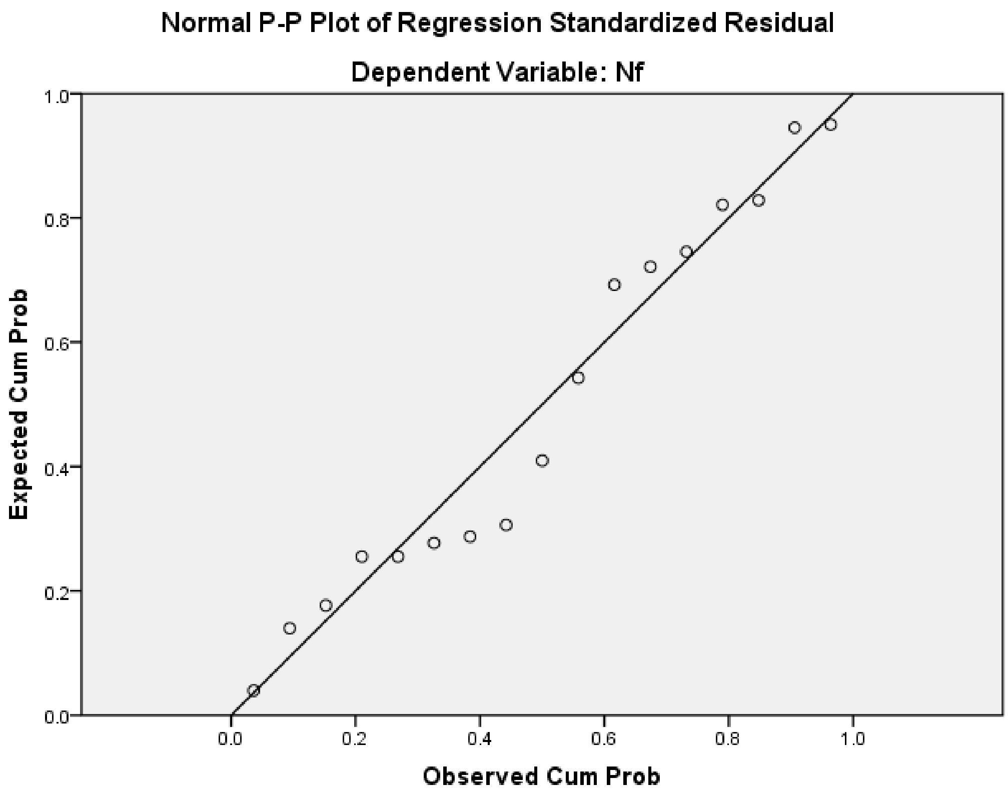
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	6.620	0.361		18.361	0.00
IS	-1.385	0.150	-0.922	-9.204	0.00

b. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.1817	4.0391	3.3272	0.42765	17
Residual	-0.3260	0.3057	0.0000	0.17995	17
Std. Predicted Value	-2.679	1.665	0.0000	1.000	17
Std. Residual	-1.754	1.645	0.0000	0.968	17

c. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of MS-2 using NRL 40/50

Descriptive Statistics

	Mean	Std. Deviation	N
Nf	3.4599	0.39250	16
IS	2.3826	0.21668	16

Correlation

		Nf	IS
Pearson Correlation	Nf	1.000	-0.922
	IS	-0.922	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	16	16
	IS	16	16

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.922[a]	0.850	0.840	0.15720	0.850	79.512	1	14	0.000

a. Predictors: (Constant), IS

b. Dependant Variable: Nf

ANOVA[b]

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	1.965	1	1.965	79.512	
Residual	0.346	14	0.025		0.000[a]
Total	2.311	15			

a. Predictors: (Constant), IS

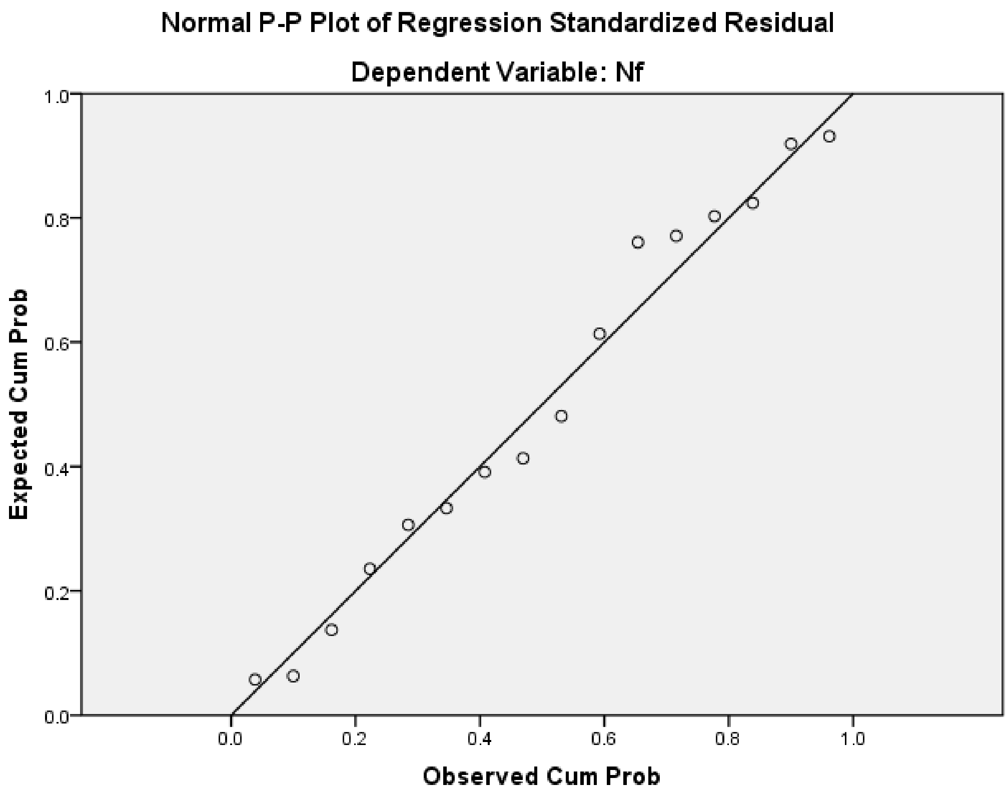
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	7.440	0.448		16.605	0.00
IS	-1.670	0.187	-0.922	-8.917	0.00

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	3.0333	4.2343	3.4599	0.36193	16
Residual	-0.2480	0.23334	0.0000	0.15187	16
Std. Predicted Value	-1.179	2.140	0.000	1.000	16
Std. Residual	-1.578	1.484	0.000	0.966	16

a. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of SP-1 using NRL 40/50

Descriptive Statistics			
	Mean	Std. Deviation	N
Nf	3.2434	0.33559	16
IS	2.5929	0.13370	16

Correlation			
		Nf	IS
Pearson Correlation	Nf	1.000	-0.898
	IS	-0.898	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	16	16
	IS	16	16

Model Summary[b]									
Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.898[a]	0.806	0.792	0.15319	0.806	57.898	1	14	0.000

a. Predictors: (Constant), IS
b. Dependant Variable: Nf

ANOVA[b]					
Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	1.361	1	1.361	57.989	0.000[a]
Residual	0.329	14	0.023		
Total	1.689	15			

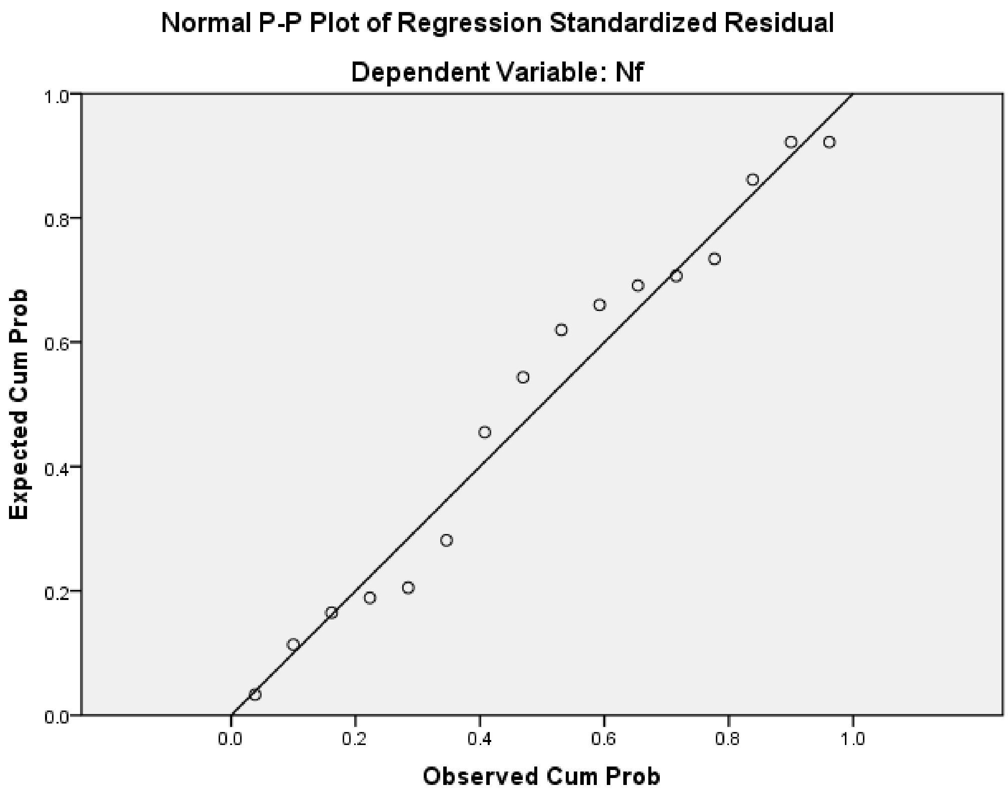
a. Predictors: (Constant), IS
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	9.085	0.768		11.829	0.00
IS	-2.253	0.296	-0.898	-7.615	0.00

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.7813	3.8198	3.2434	0.30120	16
Residual	-0.2814	0.21718	0.000	0.14799	16
Std. Predicted Value	-1.534	1.914	0.000	1.000	16
Std. Residual	-1.837	1.418	0.000	0.966	16

a. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of NHA-A using ARL 60/70

Descriptive Statistics			
	Mean	Std. Deviation	N
Nf	3.0682	0.37770	14
IS	2.5101	0.13185	14

Correlation			
		Nf	IS
Pearson Correlation	Nf	1.000	-0.856
	IS	-0.856	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	14	14
	IS	14	14

Model Summary[b]									
Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.856[a]	0.733	0.711	0.20310	0.733	32.959	1	12	0.000

a. Predictors: (Constant), IS

b. Dependant Variable: Nf

ANOVA[b]					
Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	1.360	1	1.360	32.959	0.000[a]
Residual	0.495	12	0.041		
Total	1.855	13			

a. Predictors: (Constant), IS

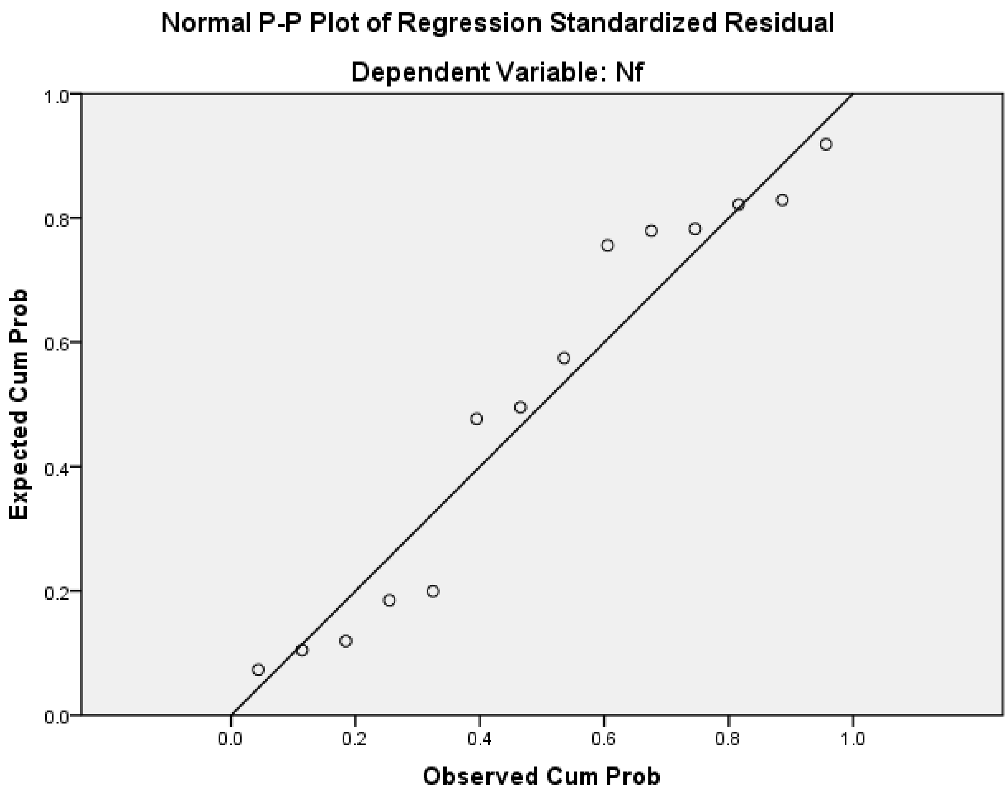
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	9.225	1.074		8.591	0.00
IS	-2.453	0.427	-0.856	-5.741	0.00

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.6367	3.1759	3.0682	0.32339	14
Residual	-0.2948	0.2832	0.0000	0.19513	14
Std. Predicted Value	-1.334	2.003	0.000	1.000	14
Std. Residual	-1.452	1.394	0.000	0.961	14

a. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of NHA-B using ARL 60/70

Descriptive Statistics

	Mean	Std. Deviation	N
Nf	2.9922	0.42386	13
IS	2.6162	0.36625	13

Correlation

		Nf	IS
Pearson Correlation	Nf	1.000	-0.969
	IS	-0.969	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	13	13
	IS	13	13

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.969[a]	0.940	0.934	0.10854	0.940	172.011	1	11	0.000

a. Predictors: (Constant), IS

b. Dependant Variable: Nf

ANOVA[b]

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	2.026	1	2.026	172.011	0.000[a]
Residual	0.130	11	0.012		
Total	2.156	12			

a. Predictors: (Constant), IS

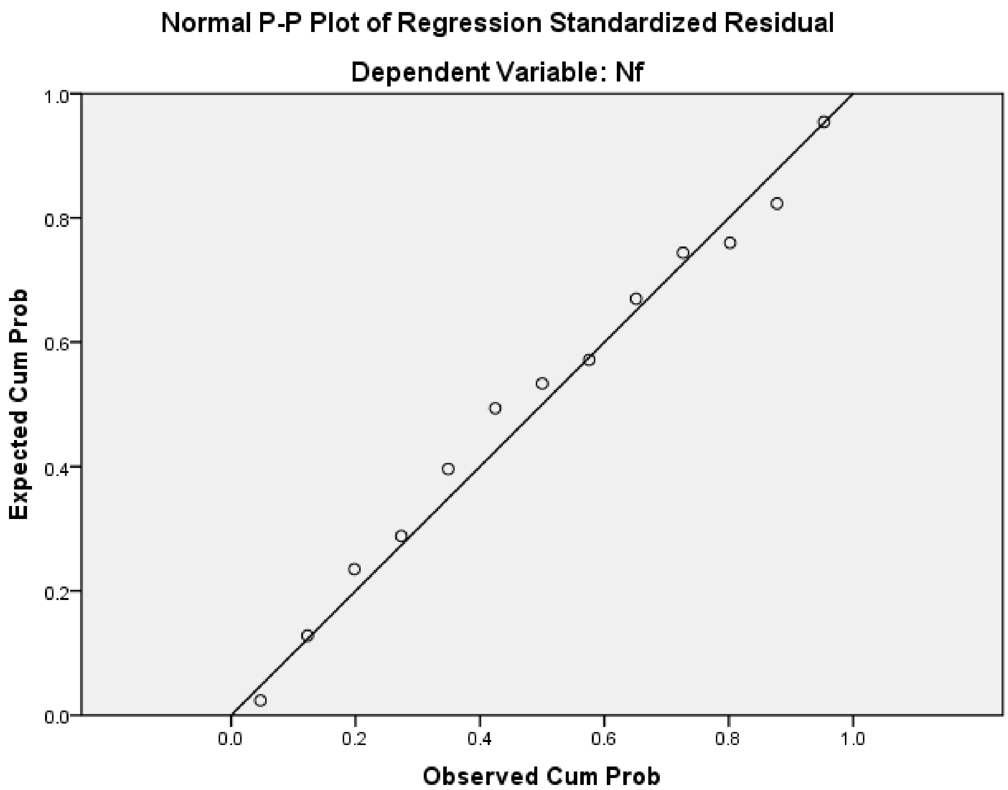
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	5.927	0.226		26.248	0.00
IS	-1.122	0.086	-0.969	-13.115	0.00

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.4686	3.6689	2.9922	0.41092	13
Residual	-0.2153	0.1831	0.0000	0.10391	13
Std. Predicted Value	-1.275	1.647	0.000	1.000	13
Std. Residual	-1.984	1.688	0.000	0.957	13

a. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of MS-2 using ARL 60/70

Descriptive Statistics			
	Mean	Std. Deviation	N
Nf	3.3471	0.49801	15
IS	2.5265	0.22583	15

Correlation			
		Nf	IS
Pearson Correlation	Nf	1.000	-0.908
	IS	-0.908	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	15	15
	IS	15	15

Model Summary[b]									
Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.908[a]	0.824	0.810	0.21681	0.824	60.864	1	13	0.000

a. Predictors: (Constant), IS

b. Dependant Variable: Nf

ANOVA[b]					
Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	2.861	1	2.861	60.864	0.000[a]
Residual	0.611	13	0.047		
Total	3.472	14			

a. Predictors: (Constant), IS

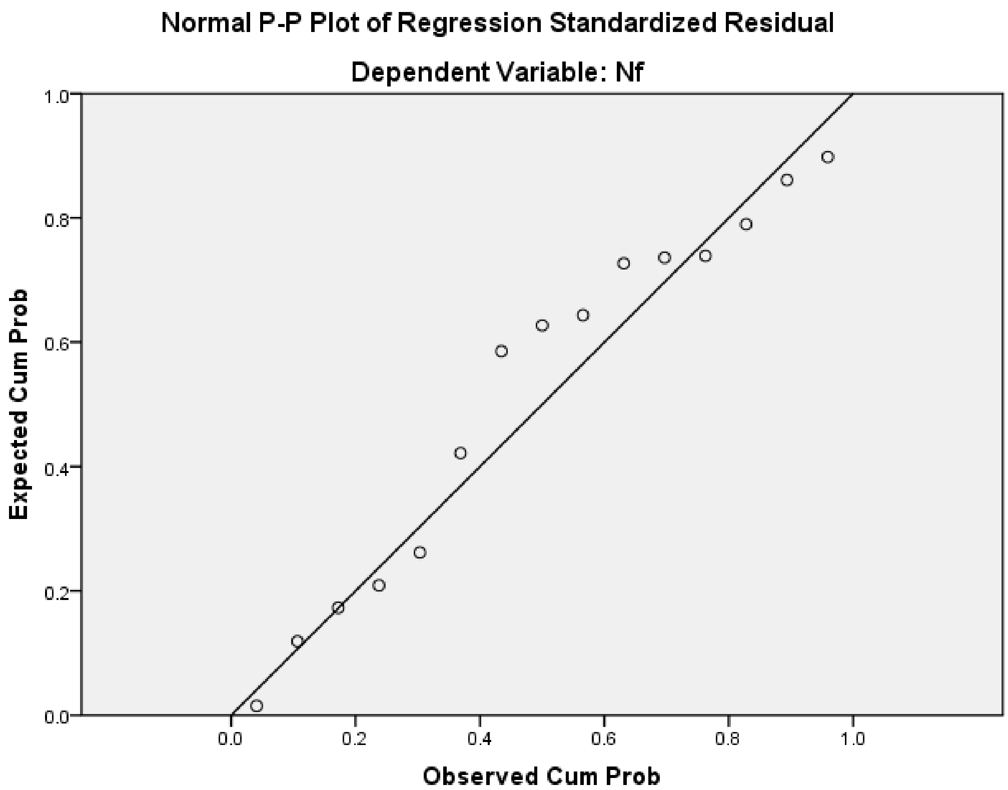
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	8.405	0.651		12.917	0.00
IS	-2.002	0.257	-0.908	-7.802	0.00

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.5032	4.0887	3.3471	0.45207	15
Residual	-0.4709	0.2753	0.0000	0.20893	15
Std. Predicted Value	-1.867	1.640	0.000	1.000	15
Std. Residual	-2.172	1.270	0.000	0.964	15

a. Dependant Variable: Nf



Statistics Analysis for Fatigue Curve of SP-1 using ARL 60/70

Descriptive Statistics

	Mean	Std. Deviation	N
Nf	2.3904	0.49358	14
IS	2.6374	0.14020	14

Correlation

		Nf	IS
Pearson Correlation	Nf	1.000	-0.883
	IS	-0.883	1.000
Sig. (1-tailed)	Nf	-	0.000
	IS	0.000	-
N	Nf	14	14
	IS	14	14

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.883[a]	0.781	0.762	0.24068	0.781	42.674	1	12	0.000

a. Predictors: (Constant), IS
b. Dependant Variable: Nf

ANOVA[b]

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	2.472	1	2.472	42.674	0.000[a]
Residual	0.695	12	0.058		
Total	3.167	13			

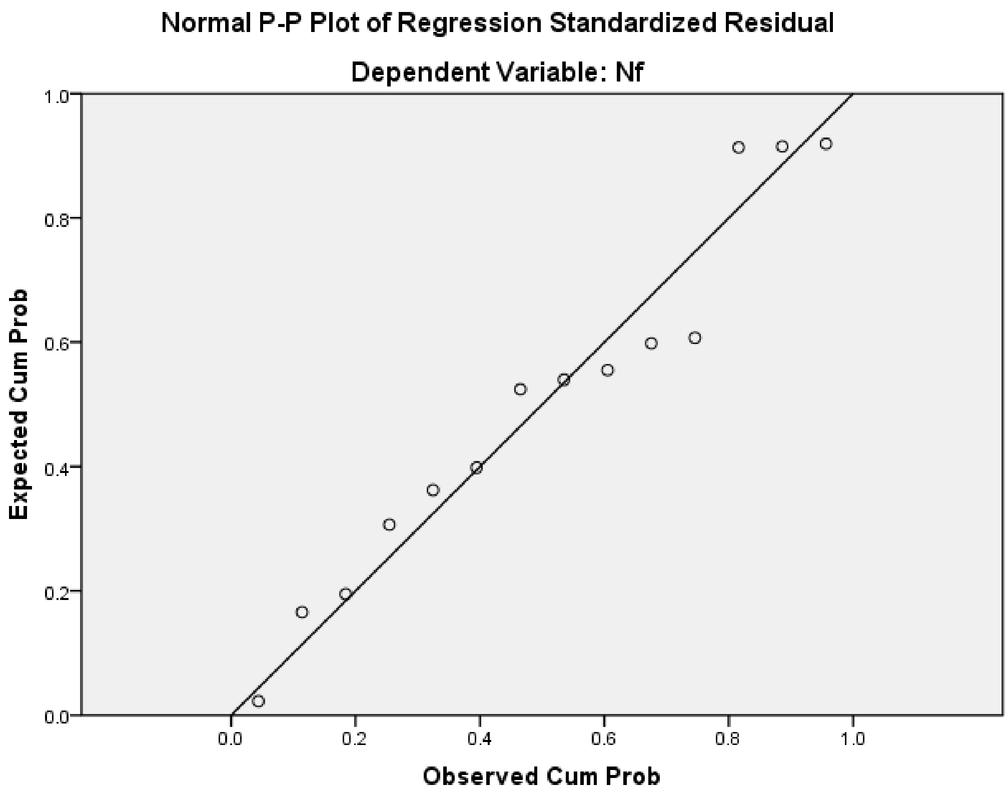
a. Predictors: (Constant), IS
b. Dependant Variable: Nf

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	11.133	1.257		8.855	0.00
IS	-3.110	0.476	-0.883	-6.533	0.00

a. Dependant Variable: Nf

Residual Statistics[a]					
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.2411	3.8491	2.9304	0.43607	14
Residual	-0.4820	0.3367	0.0000	0.23124	14
Std. Predicted Value	-1.581	2.107	0.000	1.0000	14
Std. Residual	-2.003	1.399	0.000	0.961	14

a. Dependant Variable: Nf



APPENDIX: E

INDIRECT TENSILE FATIGUE MODEL OUTPUT

Non Linear Regression

Iteration History[b]

Iteration Number[a]	Residual Sum of Squares	Parameter				
		a	b	c	d	e
1.0	2.719E9	.000	.000	.000	.000	.000
1.1	2.712E9	9.285	.000	.000	.000	.000
2.0	2.712E9	9.285	.000	.000	.000	.000
2.1	2.400E9	17.914	.149	.611	-.723	.103
3.0	2.400E9	17.914	.149	.611	-.723	.103
3.1	2.367E9	18.390	.153	.628	-.739	.106
4.0	2.367E9	18.390	.153	.628	-.739	.106
4.1	2.310E9	19.182	.159	.657	-.764	.111
5.0	2.310E9	19.182	.159	.657	-.764	.111
5.1	2.208E9	20.556	.170	.703	-.804	.119
6.0	2.208E9	20.556	.170	.703	-.804	.119
6.1	2.080E9	22.829	.182	.776	-.847	.131
7.0	2.080E9	22.829	.182	.776	-.847	.131
7.1	2.024E9	25.646	.168	.857	-.746	.147
8.0	2.024E9	25.646	.168	.857	-.746	.147
8.1	1.953E9	29.830	.130	.960	-.543	.170
9.0	1.953E9	29.830	.130	.960	-.543	.170
9.1	1.826E9	37.891	.033	1.153	-.252	.216
10.0	1.826E9	37.891	.033	1.153	-.252	.216
10.1	1.607E9	51.503	-.202	1.472	-.092	.301
11.0	1.607E9	51.503	-.202	1.472	-.092	.301
11.1	1.178E9	72.115	-.672	2.082	-.227	.447
12.0	1.178E9	72.115	-.672	2.082	-.227	.447
12.1	5.286E8	98.354	-1.528	3.693	-.573	.624
13.0	5.286E8	98.354	-1.528	3.693	-.573	.624
13.1	2.231E12	-174.095	-2.241	6.688	-.861	.798
13.2	4.644E8	101.008	-1.650	4.055	-.569	.635
14.0	4.644E8	101.008	-1.650	4.055	-.569	.635
14.1	3.793E8	101.578	-1.874	4.782	-.643	.629
15.0	3.793E8	101.578	-1.874	4.782	-.643	.629
15.1	2.924E8	78.837	-2.241	6.397	-.788	.568
16.0	2.924E8	78.837	-2.241	6.397	-.788	.568
16.1	1.904E13	-199.947	-2.413	7.480	-.984	.848
16.2	2.833E8	73.543	-2.315	6.715	-.842	.559

17.0	2.833E8	73.543	-2.315	6.715	-.842	.559
17.1	4.223E8	31.254	-2.410	7.255	-.905	.575
17.2	2.822E8	72.279	-2.329	6.778	-.852	.557
18.0	2.822E8	72.279	-2.329	6.778	-.852	.557
18.1	2.803E8	68.955	-2.355	6.907	-.866	.552
19.0	2.803E8	68.955	-2.355	6.907	-.866	.552
19.1	2.781E8	57.476	-2.399	7.160	-.893	.549
20.0	2.781E8	57.476	-2.399	7.160	-.893	.549
20.1	8.270E8	14.201	-2.440	7.444	-.938	.602
20.2	2.771E8	55.293	-2.408	7.213	-.903	.550
21.0	2.771E8	55.293	-2.408	7.213	-.903	.550
21.1	2.766E8	49.267	-2.424	7.306	-.915	.553
22.0	2.766E8	49.267	-2.424	7.306	-.915	.553
22.1	2.829E8	34.479	-2.442	7.434	-.934	.573
22.2	2.764E8	48.197	-2.427	7.326	-.919	.554
23.0	2.764E8	48.197	-2.427	7.326	-.919	.554
23.1	2.762E8	46.037	-2.432	7.357	-.923	.556
24.0	2.762E8	46.037	-2.432	7.357	-.923	.556
24.1	2.759E8	41.383	-2.440	7.411	-.930	.562
25.0	2.759E8	41.383	-2.440	7.411	-.930	.562
25.1	2.772E8	32.251	-2.450	7.481	-.942	.579
25.2	2.757E8	39.918	-2.443	7.430	-.934	.564
26.0	2.757E8	39.918	-2.443	7.430	-.934	.564
26.1	2.755E8	37.068	-2.448	7.458	-.938	.569
27.0	2.755E8	37.068	-2.448	7.458	-.938	.569
27.1	2.755E8	31.992	-2.453	7.497	-.945	.580
28.0	2.755E8	31.992	-2.453	7.497	-.945	.580
28.1	2.752E8	27.297	-2.457	7.529	-.952	.593
29.0	2.752E8	27.297	-2.457	7.529	-.952	.593
29.1	2.748E8	23.410	-2.459	7.554	-.958	.607
30.0	2.748E8	23.410	-2.459	7.554	-.958	.607
30.1	2.745E8	20.140	-2.461	7.574	-.963	.620
31.0	2.745E8	20.140	-2.461	7.574	-.963	.620
31.1	2.742E8	17.370	-2.463	7.590	-.969	.634
32.0	2.742E8	17.370	-2.463	7.590	-.969	.634
32.1	2.739E8	15.013	-2.464	7.605	-.973	.647
33.0	2.739E8	15.013	-2.464	7.605	-.973	.647
33.1	2.736E8	13.002	-2.465	7.618	-.978	.661

34.0	2.736E8	13.002	-2.465	7.618	-.978	.661
34.1	2.733E8	11.281	-2.465	7.631	-.982	.674
35.0	2.733E8	11.281	-2.465	7.631	-.982	.674
35.1	2.730E8	9.805	-2.466	7.643	-.987	.688
36.0	2.730E8	9.805	-2.466	7.643	-.987	.688
36.1	2.727E8	8.536	-2.466	7.654	-.991	.701
37.0	2.727E8	8.536	-2.466	7.654	-.991	.701
37.1	2.725E8	7.307	-2.467	7.666	-.996	.715
38.0	2.725E8	7.307	-2.467	7.666	-.996	.715
38.1	2.722E8	6.275	-2.467	7.678	-1.000	.730
39.0	2.722E8	6.275	-2.467	7.678	-1.000	.730
39.1	2.719E8	5.399	-2.468	7.690	-1.005	.744
40.0	2.719E8	5.399	-2.468	7.690	-1.005	.744
40.1	2.716E8	4.654	-2.468	7.702	-1.009	.758
41.0	2.716E8	4.654	-2.468	7.702	-1.009	.758
41.1	2.713E8	4.019	-2.469	7.713	-1.014	.772
42.0	2.713E8	4.019	-2.469	7.713	-1.014	.772
42.1	2.710E8	3.477	-2.469	7.725	-1.018	.786
43.0	2.710E8	3.477	-2.469	7.725	-1.018	.786
43.1	2.708E8	3.013	-2.470	7.736	-1.022	.800
44.0	2.708E8	3.013	-2.470	7.736	-1.022	.800
44.1	2.705E8	2.615	-2.470	7.747	-1.027	.813
45.0	2.705E8	2.615	-2.470	7.747	-1.027	.813
45.1	2.702E8	2.274	-2.471	7.758	-1.031	.827
46.0	2.702E8	2.274	-2.471	7.758	-1.031	.827
46.1	2.700E8	1.980	-2.471	7.768	-1.035	.840
47.0	2.700E8	1.980	-2.471	7.768	-1.035	.840
47.1	2.698E8	1.696	-2.472	7.780	-1.040	.854
48.0	2.698E8	1.696	-2.472	7.780	-1.040	.854
48.1	2.696E8	1.457	-2.472	7.792	-1.044	.869
49.0	2.696E8	1.457	-2.472	7.792	-1.044	.869
49.1	2.693E8	1.254	-2.473	7.803	-1.049	.883
50.0	2.693E8	1.254	-2.473	7.803	-1.049	.883
50.1	2.690E8	1.082	-2.473	7.815	-1.053	.897
51.0	2.690E8	1.082	-2.473	7.815	-1.053	.897
51.1	2.688E8	.935	-2.474	7.826	-1.057	.911
52.0	2.688E8	.935	-2.474	7.826	-1.057	.911
52.1	2.685E8	.809	-2.474	7.837	-1.062	.925

53.0	2.685E8	.809	-2.474	7.837	-1.062	.925
53.1	2.683E8	.701	-2.475	7.848	-1.066	.939
54.0	2.683E8	.701	-2.475	7.848	-1.066	.939
54.1	2.680E8	.609	-2.475	7.859	-1.070	.952
55.0	2.680E8	.609	-2.475	7.859	-1.070	.952
55.1	2.678E8	.530	-2.476	7.869	-1.074	.965
56.0	2.678E8	.530	-2.476	7.869	-1.074	.965
56.1	2.677E8	.454	-2.476	7.881	-1.079	.980
57.0	2.677E8	.454	-2.476	7.881	-1.079	.980
57.1	2.674E8	.390	-2.477	7.893	-1.083	.995
58.0	2.674E8	.390	-2.477	7.893	-1.083	.995
58.1	2.672E8	.336	-2.477	7.904	-1.087	1.009
59.0	2.672E8	.336	-2.477	7.904	-1.087	1.009
59.1	2.670E8	.290	-2.478	7.915	-1.092	1.023
60.0	2.670E8	.290	-2.478	7.915	-1.092	1.023
60.1	2.667E8	.251	-2.478	7.926	-1.096	1.037
61.0	2.667E8	.251	-2.478	7.926	-1.096	1.037
61.1	2.665E8	.217	-2.479	7.937	-1.100	1.051
62.0	2.665E8	.217	-2.479	7.937	-1.100	1.051
62.1	2.663E8	.188	-2.479	7.948	-1.105	1.064
63.0	2.663E8	.188	-2.479	7.948	-1.105	1.064
63.1	2.661E8	.164	-2.480	7.959	-1.109	1.078
64.0	2.661E8	.164	-2.480	7.959	-1.109	1.078
64.1	2.659E8	.142	-2.480	7.969	-1.113	1.091
65.0	2.659E8	.142	-2.480	7.969	-1.113	1.091
65.1	2.658E8	.122	-2.481	7.981	-1.117	1.106
66.0	2.658E8	.122	-2.481	7.981	-1.117	1.106
66.1	2.655E8	.105	-2.482	7.992	-1.122	1.120
67.0	2.655E8	.105	-2.482	7.992	-1.122	1.120
67.1	2.653E8	.090	-2.482	8.004	-1.126	1.135
68.0	2.653E8	.090	-2.482	8.004	-1.126	1.135
68.1	2.651E8	.078	-2.483	8.015	-1.130	1.149
69.0	2.651E8	.078	-2.483	8.015	-1.130	1.149
69.1	2.649E8	.067	-2.483	8.026	-1.134	1.163
70.0	2.649E8	.067	-2.483	8.026	-1.134	1.163
70.1	2.647E8	.058	-2.484	8.036	-1.139	1.176
71.0	2.647E8	.058	-2.484	8.036	-1.139	1.176
71.1	2.645E8	.051	-2.484	8.047	-1.143	1.190

72.0	2.645E8	.051	-2.484	8.047	-1.143	1.190
72.1	2.643E8	.044	-2.485	8.058	-1.147	1.204
73.0	2.643E8	.044	-2.485	8.058	-1.147	1.204
73.1	2.641E8	.038	-2.485	8.068	-1.151	1.217
74.0	2.641E8	.038	-2.485	8.068	-1.151	1.217
74.1	2.640E8	.033	-2.486	8.079	-1.155	1.231
75.0	2.640E8	.033	-2.486	8.079	-1.155	1.231
75.1	2.637E8	.031	-2.486	8.086	-1.158	1.239
76.0	2.637E8	.031	-2.486	8.086	-1.158	1.239
76.1	2.638E8	.026	-2.487	8.096	-1.162	1.253
76.2	2.636E8	.029	-2.487	8.089	-1.159	1.244
77.0	2.636E8	.029	-2.487	8.089	-1.159	1.244
77.1	2.635E8	.027	-2.487	8.096	-1.162	1.253
78.0	2.635E8	.027	-2.487	8.096	-1.162	1.253
78.1	2.634E8	.024	-2.487	8.103	-1.164	1.262
79.0	2.634E8	.024	-2.487	8.103	-1.164	1.262
79.1	2.633E8	.022	-2.488	8.110	-1.167	1.271
80.0	2.633E8	.022	-2.488	8.110	-1.167	1.271
80.1	2.632E8	.020	-2.488	8.117	-1.170	1.280
81.0	2.632E8	.020	-2.488	8.117	-1.170	1.280
81.1	2.631E8	.018	-2.488	8.124	-1.173	1.289
82.0	2.631E8	.018	-2.488	8.124	-1.173	1.289
82.1	2.629E8	.017	-2.489	8.131	-1.175	1.298
83.0	2.629E8	.017	-2.489	8.131	-1.175	1.298
83.1	2.628E8	.015	-2.489	8.138	-1.178	1.307
84.0	2.628E8	.015	-2.489	8.138	-1.178	1.307
84.1	2.627E8	.014	-2.489	8.145	-1.180	1.316
85.0	2.627E8	.014	-2.489	8.145	-1.180	1.316
85.1	2.626E8	.013	-2.490	8.151	-1.183	1.324
86.0	2.626E8	.013	-2.490	8.151	-1.183	1.324
86.1	2.625E8	.012	-2.490	8.158	-1.186	1.333
87.0	2.625E8	.012	-2.490	8.158	-1.186	1.333
87.1	2.629E8	.010	-2.491	8.171	-1.190	1.350
87.2	2.624E8	.011	-2.490	8.161	-1.187	1.336
88.0	2.624E8	.011	-2.490	8.161	-1.187	1.336
88.1	2.624E8	.010	-2.491	8.166	-1.189	1.343
89.0	2.624E8	.010	-2.491	8.166	-1.189	1.343
89.1	2.625E8	.009	-2.491	8.176	-1.192	1.356

89.2	2.623E8	.010	-2.491	8.170	-1.190	1.348
90.0	2.623E8	.010	-2.491	8.170	-1.190	1.348
90.1	2.623E8	.009	-2.491	8.177	-1.193	1.357
91.0	2.623E8	.009	-2.491	8.177	-1.193	1.357
91.1	2.622E8	.008	-2.492	8.184	-1.196	1.367
92.0	2.622E8	.008	-2.492	8.184	-1.196	1.367
92.1	2.620E8	.007	-2.492	8.192	-1.198	1.376
93.0	2.620E8	.007	-2.492	8.192	-1.198	1.376
93.1	2.619E8	.007	-2.492	8.199	-1.201	1.386
94.0	2.619E8	.007	-2.492	8.199	-1.201	1.386
94.1	2.618E8	.006	-2.493	8.206	-1.204	1.395
95.0	2.618E8	.006	-2.493	8.206	-1.204	1.395
95.1	2.617E8	.006	-2.493	8.213	-1.207	1.404
96.0	2.617E8	.006	-2.493	8.213	-1.207	1.404
96.1	2.616E8	.005	-2.494	8.220	-1.209	1.413
97.0	2.616E8	.005	-2.494	8.220	-1.209	1.413
97.1	2.615E8	.005	-2.494	8.227	-1.212	1.422
98.0	2.615E8	.005	-2.494	8.227	-1.212	1.422
98.1	2.614E8	.004	-2.494	8.234	-1.215	1.431
99.0	2.614E8	.004	-2.494	8.234	-1.215	1.431
99.1	2.613E8	.004	-2.495	8.241	-1.217	1.440
100.0	2.613E8	.004	-2.495	8.241	-1.217	1.440
100.1	2.612E8	.003	-2.495	8.248	-1.220	1.449
101.0	2.612E8	.003	-2.495	8.248	-1.220	1.449
101.1	2.612E8	.003	-2.496	8.255	-1.223	1.459
102.0	2.612E8	.003	-2.496	8.255	-1.223	1.459
102.1	2.611E8	.003	-2.496	8.262	-1.226	1.468
103.0	2.611E8	.003	-2.496	8.262	-1.226	1.468
103.1	2.610E8	.003	-2.496	8.270	-1.229	1.478
104.0	2.610E8	.003	-2.496	8.270	-1.229	1.478
104.1	2.609E8	.002	-2.497	8.277	-1.231	1.487
105.0	2.609E8	.002	-2.497	8.277	-1.231	1.487
105.1	2.608E8	.002	-2.497	8.284	-1.234	1.497
106.0	2.608E8	.002	-2.497	8.284	-1.234	1.497
106.1	2.607E8	.002	-2.498	8.291	-1.237	1.506
107.0	2.607E8	.002	-2.498	8.291	-1.237	1.506
107.1	2.606E8	.002	-2.498	8.298	-1.239	1.515
108.0	2.606E8	.002	-2.498	8.298	-1.239	1.515

108.1	2.605E8	.002	-2.498	8.305	-1.242	1.524
109.0	2.605E8	.002	-2.498	8.305	-1.242	1.524
109.1	2.604E8	.001	-2.499	8.312	-1.245	1.533
110.0	2.604E8	.001	-2.499	8.312	-1.245	1.533
110.1	2.603E8	.001	-2.499	8.319	-1.247	1.542
111.0	2.603E8	.001	-2.499	8.319	-1.247	1.542
111.1	2.602E8	.001	-2.500	8.326	-1.250	1.551
112.0	2.602E8	.001	-2.500	8.326	-1.250	1.551
112.1	2.601E8	.001	-2.500	8.333	-1.253	1.560
113.0	2.601E8	.001	-2.500	8.333	-1.253	1.560
113.1	2.601E8	.001	-2.500	8.340	-1.255	1.570
114.0	2.601E8	.001	-2.500	8.340	-1.255	1.570
114.1	2.600E8	.001	-2.501	8.347	-1.258	1.579
115.0	2.600E8	.001	-2.501	8.347	-1.258	1.579
115.1	2.599E8	.001	-2.501	8.355	-1.261	1.589
116.0	2.599E8	.001	-2.501	8.355	-1.261	1.589
116.1	2.598E8	.001	-2.502	8.362	-1.264	1.598
117.0	2.598E8	.001	-2.502	8.362	-1.264	1.598
117.1	2.597E8	.001	-2.502	8.369	-1.267	1.608
118.0	2.597E8	.001	-2.502	8.369	-1.267	1.608
118.1	2.596E8	.001	-2.503	8.376	-1.269	1.617
119.0	2.596E8	.001	-2.503	8.376	-1.269	1.617
119.1	2.595E8	.001	-2.503	8.383	-1.272	1.626
120.0	2.595E8	.001	-2.503	8.383	-1.272	1.626
120.1	2.595E8	.001	-2.503	8.390	-1.275	1.635
121.0	2.595E8	.001	-2.503	8.390	-1.275	1.635
121.1	2.594E8	.000	-2.504	8.397	-1.277	1.644
122.0	2.594E8	.000	-2.504	8.397	-1.277	1.644
122.1	2.593E8	.000	-2.504	8.404	-1.280	1.653
123.0	2.593E8	.000	-2.504	8.404	-1.280	1.653
123.1	2.592E8	.000	-2.505	8.410	-1.282	1.662
124.0	2.592E8	.000	-2.505	8.410	-1.282	1.662
124.1	2.592E8	.000	-2.505	8.417	-1.285	1.671
125.0	2.592E8	.000	-2.505	8.417	-1.285	1.671
125.1	2.591E8	.000	-2.505	8.424	-1.288	1.681
126.0	2.591E8	.000	-2.505	8.424	-1.288	1.681
126.1	2.590E8	.000	-2.506	8.432	-1.291	1.690
127.0	2.590E8	.000	-2.506	8.432	-1.291	1.690

127.1	2.589E8	.000	-2.506	8.439	-1.293	1.700
128.0	2.589E8	.000	-2.506	8.439	-1.293	1.700
128.1	2.588E8	.000	-2.507	8.446	-1.296	1.709
129.0	2.588E8	.000	-2.507	8.446	-1.296	1.709
129.1	2.588E8	.000	-2.507	8.453	-1.299	1.719
130.0	2.588E8	.000	-2.507	8.453	-1.299	1.719
130.1	2.587E8	.000	-2.508	8.460	-1.302	1.728
131.0	2.587E8	.000	-2.508	8.460	-1.302	1.728
131.1	2.586E8	.000	-2.508	8.467	-1.304	1.737
132.0	2.586E8	.000	-2.508	8.467	-1.304	1.737
132.1	2.585E8	.000	-2.509	8.474	-1.307	1.746
133.0	2.585E8	.000	-2.509	8.474	-1.307	1.746
133.1	2.585E8	.000	-2.509	8.481	-1.309	1.755
134.0	2.585E8	.000	-2.509	8.481	-1.309	1.755
134.1	2.584E8	.000	-2.509	8.488	-1.312	1.764
135.0	2.584E8	.000	-2.509	8.488	-1.312	1.764
135.1	2.583E8	.000	-2.510	8.494	-1.315	1.773
136.0	2.583E8	.000	-2.510	8.494	-1.315	1.773
136.1	2.583E8	.000	-2.510	8.501	-1.317	1.782
137.0	2.583E8	.000	-2.510	8.501	-1.317	1.782
137.1	2.582E8	9.945E-5	-2.511	8.508	-1.320	1.792
138.0	2.582E8	9.945E-5	-2.511	8.508	-1.320	1.792
138.1	2.581E8	9.001E-5	-2.511	8.516	-1.323	1.801
139.0	2.581E8	9.001E-5	-2.511	8.516	-1.323	1.801
139.1	2.581E8	8.155E-5	-2.512	8.523	-1.325	1.811
140.0	2.581E8	8.155E-5	-2.512	8.523	-1.325	1.811
140.1	2.580E8	7.396E-5	-2.512	8.530	-1.328	1.820
141.0	2.580E8	7.396E-5	-2.512	8.530	-1.328	1.820
141.1	2.579E8	6.715E-5	-2.512	8.537	-1.331	1.830
142.0	2.579E8	6.715E-5	-2.512	8.537	-1.331	1.830
142.1	2.579E8	6.102E-5	-2.513	8.544	-1.334	1.839
143.0	2.579E8	6.102E-5	-2.513	8.544	-1.334	1.839
143.1	2.578E8	5.550E-5	-2.513	8.551	-1.336	1.848
144.0	2.578E8	5.550E-5	-2.513	8.551	-1.336	1.848
144.1	2.577E8	5.053E-5	-2.514	8.558	-1.339	1.857
145.0	2.577E8	5.053E-5	-2.514	8.558	-1.339	1.857
145.1	2.577E8	4.605E-5	-2.514	8.565	-1.341	1.866
146.0	2.577E8	4.605E-5	-2.514	8.565	-1.341	1.866

146.1	2.576E8	4.200E-5	-2.515	8.571	-1.344	1.875
147.0	2.576E8	4.200E-5	-2.515	8.571	-1.344	1.875
147.1	2.575E8	3.834E-5	-2.515	8.578	-1.346	1.884
148.0	2.575E8	3.834E-5	-2.515	8.578	-1.346	1.884
148.1	2.575E8	3.465E-5	-2.516	8.585	-1.349	1.894
149.0	2.575E8	3.465E-5	-2.516	8.585	-1.349	1.894
149.1	2.574E8	3.137E-5	-2.516	8.592	-1.352	1.903
150.0	2.574E8	3.137E-5	-2.516	8.592	-1.352	1.903
150.1	2.574E8	2.842E-5	-2.517	8.600	-1.355	1.913
151.0	2.574E8	2.842E-5	-2.517	8.600	-1.355	1.913
151.1	2.573E8	2.578E-5	-2.517	8.607	-1.357	1.922
152.0	2.573E8	2.578E-5	-2.517	8.607	-1.357	1.922
152.1	2.572E8	2.341E-5	-2.517	8.614	-1.360	1.932
153.0	2.572E8	2.341E-5	-2.517	8.614	-1.360	1.932
153.1	2.572E8	2.128E-5	-2.518	8.621	-1.363	1.941
154.0	2.572E8	2.128E-5	-2.518	8.621	-1.363	1.941
154.1	2.571E8	1.936E-5	-2.518	8.628	-1.365	1.950
155.0	2.571E8	1.936E-5	-2.518	8.628	-1.365	1.950
155.1	2.571E8	1.763E-5	-2.519	8.635	-1.368	1.959
156.0	2.571E8	1.763E-5	-2.519	8.635	-1.368	1.959
156.1	2.570E8	1.607E-5	-2.519	8.641	-1.371	1.968
157.0	2.570E8	1.607E-5	-2.519	8.641	-1.371	1.968
157.1	2.570E8	1.466E-5	-2.520	8.648	-1.373	1.977
158.0	2.570E8	1.466E-5	-2.520	8.648	-1.373	1.977
158.1	2.569E8	1.338E-5	-2.520	8.655	-1.376	1.986
159.0	2.569E8	1.338E-5	-2.520	8.655	-1.376	1.986
159.1	2.569E8	1.210E-5	-2.521	8.662	-1.378	1.996
160.0	2.569E8	1.210E-5	-2.521	8.662	-1.378	1.996
160.1	2.568E8	1.095E-5	-2.521	8.669	-1.381	2.005
161.0	2.568E8	1.095E-5	-2.521	8.669	-1.381	2.005
161.1	2.567E8	9.924E-6	-2.522	8.676	-1.384	2.015
162.0	2.567E8	9.924E-6	-2.522	8.676	-1.384	2.015
162.1	2.567E8	9.002E-6	-2.522	8.683	-1.387	2.024
163.0	2.567E8	9.002E-6	-2.522	8.683	-1.387	2.024
163.1	2.566E8	8.175E-6	-2.523	8.690	-1.389	2.034
164.0	2.566E8	8.175E-6	-2.523	8.690	-1.389	2.034
164.1	2.566E8	7.432E-6	-2.523	8.697	-1.392	2.043
165.0	2.566E8	7.432E-6	-2.523	8.697	-1.392	2.043

165.1	2.565E8	6.762E-6	-2.523	8.704	-1.394	2.052
166.0	2.565E8	6.762E-6	-2.523	8.704	-1.394	2.052
166.1	2.565E8	6.159E-6	-2.524	8.711	-1.397	2.061
167.0	2.565E8	6.159E-6	-2.524	8.711	-1.397	2.061
167.1	2.564E8	5.615E-6	-2.524	8.718	-1.400	2.070
168.0	2.564E8	5.615E-6	-2.524	8.718	-1.400	2.070
168.1	2.564E8	5.124E-6	-2.525	8.724	-1.402	2.079
169.0	2.564E8	5.124E-6	-2.525	8.724	-1.402	2.079
169.1	2.563E8	4.681E-6	-2.525	8.731	-1.405	2.088
170.0	2.563E8	4.681E-6	-2.525	8.731	-1.405	2.088
170.1	2.563E8	4.230E-6	-2.526	8.738	-1.407	2.098
171.0	2.563E8	4.230E-6	-2.526	8.738	-1.407	2.098
171.1	2.562E8	3.830E-6	-2.526	8.745	-1.410	2.107
172.0	2.562E8	3.830E-6	-2.526	8.745	-1.410	2.107
172.1	2.562E8	3.471E-6	-2.527	8.753	-1.413	2.117
173.0	2.562E8	3.471E-6	-2.527	8.753	-1.413	2.117
173.1	2.561E8	3.149E-6	-2.527	8.760	-1.416	2.126
174.0	2.561E8	3.149E-6	-2.527	8.760	-1.416	2.126
174.1	2.561E8	2.860E-6	-2.528	8.767	-1.418	2.136
175.0	2.561E8	2.860E-6	-2.528	8.767	-1.418	2.136
175.1	2.560E8	2.601E-6	-2.528	8.774	-1.421	2.145
176.0	2.560E8	2.601E-6	-2.528	8.774	-1.421	2.145
176.1	2.560E8	2.367E-6	-2.529	8.780	-1.423	2.154
177.0	2.560E8	2.367E-6	-2.529	8.780	-1.423	2.154
177.1	2.559E8	2.156E-6	-2.529	8.787	-1.426	2.163
178.0	2.559E8	2.156E-6	-2.529	8.787	-1.426	2.163
178.1	2.559E8	1.966E-6	-2.530	8.794	-1.428	2.172
179.0	2.559E8	1.966E-6	-2.530	8.794	-1.428	2.172
179.1	2.558E8	1.795E-6	-2.530	8.800	-1.431	2.181
180.0	2.558E8	1.795E-6	-2.530	8.800	-1.431	2.181
180.1	2.558E8	1.640E-6	-2.530	8.807	-1.433	2.190
181.0	2.558E8	1.640E-6	-2.530	8.807	-1.433	2.190
181.1	2.558E8	1.482E-6	-2.531	8.814	-1.436	2.199
182.0	2.558E8	1.482E-6	-2.531	8.814	-1.436	2.199
182.1	2.557E8	1.342E-6	-2.531	8.821	-1.439	2.209
183.0	2.557E8	1.342E-6	-2.531	8.821	-1.439	2.209
183.1	2.557E8	1.216E-6	-2.532	8.829	-1.442	2.219
184.0	2.557E8	1.216E-6	-2.532	8.829	-1.442	2.219

184.1	2.556E8	1.104E-6	-2.532	8.836	-1.444	2.228
185.0	2.556E8	1.104E-6	-2.532	8.836	-1.444	2.228
185.1	2.556E8	1.003E-6	-2.533	8.843	-1.447	2.237
186.0	2.556E8	1.003E-6	-2.533	8.843	-1.447	2.237
186.1	2.555E8	9.117E-7	-2.533	8.850	-1.450	2.247
187.0	2.555E8	9.117E-7	-2.533	8.850	-1.450	2.247
187.1	2.555E8	8.299E-7	-2.534	8.856	-1.452	2.256
188.0	2.555E8	8.299E-7	-2.534	8.856	-1.452	2.256
188.1	2.555E8	7.562E-7	-2.534	8.863	-1.455	2.265
189.0	2.555E8	7.562E-7	-2.534	8.863	-1.455	2.265
189.1	2.554E8	6.898E-7	-2.535	8.870	-1.457	2.274
190.0	2.554E8	6.898E-7	-2.535	8.870	-1.457	2.274
190.1	2.554E8	6.298E-7	-2.535	8.876	-1.460	2.283
191.0	2.554E8	6.298E-7	-2.535	8.876	-1.460	2.283
191.1	2.554E8	5.693E-7	-2.536	8.884	-1.462	2.292
192.0	2.554E8	5.693E-7	-2.536	8.884	-1.462	2.292
192.1	2.553E8	5.155E-7	-2.536	8.891	-1.465	2.302
193.0	2.553E8	5.155E-7	-2.536	8.891	-1.465	2.302
193.1	2.553E8	4.673E-7	-2.537	8.898	-1.468	2.312
194.0	2.553E8	4.673E-7	-2.537	8.898	-1.468	2.312
194.1	2.552E8	4.240E-7	-2.537	8.905	-1.470	2.321
195.0	2.552E8	4.240E-7	-2.537	8.905	-1.470	2.321
195.1	2.552E8	3.852E-7	-2.538	8.912	-1.473	2.330
196.0	2.552E8	3.852E-7	-2.538	8.912	-1.473	2.330
196.1	2.551E8	3.504E-7	-2.538	8.919	-1.476	2.340
197.0	2.551E8	3.504E-7	-2.538	8.919	-1.476	2.340
197.1	2.551E8	3.190E-7	-2.539	8.926	-1.478	2.349
198.0	2.551E8	3.190E-7	-2.539	8.926	-1.478	2.349
198.1	2.551E8	2.907E-7	-2.539	8.932	-1.481	2.358
199.0	2.551E8	2.907E-7	-2.539	8.932	-1.481	2.358
199.1	2.550E8	2.653E-7	-2.540	8.939	-1.483	2.367
200.0	2.550E8	2.653E-7	-2.540	8.939	-1.483	2.367
200.1	2.550E8	2.423E-7	-2.540	8.946	-1.486	2.376
201.0	2.550E8	2.423E-7	-2.540	8.946	-1.486	2.376
201.1	2.550E8	2.190E-7	-2.541	8.953	-1.488	2.385
202.0	2.550E8	2.190E-7	-2.541	8.953	-1.488	2.385
202.1	2.549E8	2.088E-7	-2.541	8.957	-1.490	2.390
203.0	2.549E8	2.088E-7	-2.541	8.957	-1.490	2.390

203.1	2.549E8	1.888E-7	-2.542	8.964	-1.493	2.400
203.2	2.549E8	2.020E-7	-2.541	8.959	-1.491	2.394
204.0	2.549E8	2.020E-7	-2.541	8.959	-1.491	2.394
204.1	2.549E8	1.888E-7	-2.542	8.964	-1.493	2.400
205.0	2.549E8	1.888E-7	-2.542	8.964	-1.493	2.400
205.1	2.549E8	1.767E-7	-2.542	8.969	-1.494	2.406
206.0	2.549E8	1.767E-7	-2.542	8.969	-1.494	2.406
206.1	2.548E8	1.654E-7	-2.542	8.973	-1.496	2.413
207.0	2.548E8	1.654E-7	-2.542	8.973	-1.496	2.413
207.1	2.548E8	1.550E-7	-2.543	8.978	-1.498	2.419
208.0	2.548E8	1.550E-7	-2.543	8.978	-1.498	2.419
208.1	2.548E8	1.452E-7	-2.543	8.983	-1.500	2.425
209.0	2.548E8	1.452E-7	-2.543	8.983	-1.500	2.425
209.1	2.548E8	1.362E-7	-2.543	8.987	-1.502	2.432
210.0	2.548E8	1.362E-7	-2.543	8.987	-1.502	2.432
210.1	2.547E8	1.278E-7	-2.544	8.992	-1.503	2.438
211.0	2.547E8	1.278E-7	-2.544	8.992	-1.503	2.438
211.1	2.547E8	1.200E-7	-2.544	8.997	-1.505	2.444
212.0	2.547E8	1.200E-7	-2.544	8.997	-1.505	2.444
212.1	2.547E8	1.127E-7	-2.544	9.001	-1.507	2.450
213.0	2.547E8	1.127E-7	-2.544	9.001	-1.507	2.450
213.1	2.547E8	1.059E-7	-2.545	9.006	-1.508	2.456
214.0	2.547E8	1.059E-7	-2.545	9.006	-1.508	2.456
214.1	2.547E8	9.952E-8	-2.545	9.010	-1.510	2.462
215.0	2.547E8	9.952E-8	-2.545	9.010	-1.510	2.462
215.1	2.546E8	9.359E-8	-2.545	9.015	-1.512	2.468
216.0	2.546E8	9.359E-8	-2.545	9.015	-1.512	2.468
216.1	2.546E8	8.806E-8	-2.546	9.019	-1.513	2.474
217.0	2.546E8	8.806E-8	-2.546	9.019	-1.513	2.474
217.1	2.546E8	8.229E-8	-2.546	9.024	-1.515	2.481
218.0	2.546E8	8.229E-8	-2.546	9.024	-1.515	2.481
218.1	2.546E8	7.696E-8	-2.546	9.029	-1.517	2.487
219.0	2.546E8	7.696E-8	-2.546	9.029	-1.517	2.487
219.1	2.545E8	7.201E-8	-2.547	9.034	-1.519	2.494
220.0	2.545E8	7.201E-8	-2.547	9.034	-1.519	2.494
220.1	2.545E8	6.741E-8	-2.547	9.038	-1.521	2.500
221.0	2.545E8	6.741E-8	-2.547	9.038	-1.521	2.500
221.1	2.545E8	6.314E-8	-2.547	9.043	-1.522	2.507

222.0	2.545E8	6.314E-8	-2.547	9.043	-1.522	2.507
222.1	2.545E8	5.918E-8	-2.548	9.048	-1.524	2.513
223.0	2.545E8	5.918E-8	-2.548	9.048	-1.524	2.513
223.1	2.545E8	5.549E-8	-2.548	9.053	-1.526	2.519
224.0	2.545E8	5.549E-8	-2.548	9.053	-1.526	2.519
224.1	2.544E8	5.206E-8	-2.549	9.057	-1.528	2.525
225.0	2.544E8	5.206E-8	-2.549	9.057	-1.528	2.525
225.1	2.544E8	4.886E-8	-2.549	9.062	-1.529	2.531
226.0	2.544E8	4.886E-8	-2.549	9.062	-1.529	2.531
226.1	2.544E8	4.589E-8	-2.549	9.066	-1.531	2.538
227.0	2.544E8	4.589E-8	-2.549	9.066	-1.531	2.538
227.1	2.544E8	4.312E-8	-2.550	9.071	-1.533	2.544
228.0	2.544E8	4.312E-8	-2.550	9.071	-1.533	2.544
228.1	2.544E8	4.053E-8	-2.550	9.075	-1.534	2.550
229.0	2.544E8	4.053E-8	-2.550	9.075	-1.534	2.550
229.1	2.543E8	3.812E-8	-2.550	9.080	-1.536	2.556
230.0	2.543E8	3.812E-8	-2.550	9.080	-1.536	2.556
230.1	2.543E8	3.587E-8	-2.551	9.084	-1.538	2.562
231.0	2.543E8	3.587E-8	-2.551	9.084	-1.538	2.562
231.1	2.543E8	3.351E-8	-2.551	9.089	-1.540	2.568
232.0	2.543E8	3.351E-8	-2.551	9.089	-1.540	2.568
232.1	2.543E8	3.134E-8	-2.551	9.094	-1.541	2.575
233.0	2.543E8	3.134E-8	-2.551	9.094	-1.541	2.575
233.1	2.543E8	2.933E-8	-2.552	9.099	-1.543	2.581
234.0	2.543E8	2.933E-8	-2.552	9.099	-1.543	2.581
234.1	2.543E8	2.746E-8	-2.552	9.103	-1.545	2.588
235.0	2.543E8	2.746E-8	-2.552	9.103	-1.545	2.588
235.1	2.542E8	2.572E-8	-2.552	9.108	-1.547	2.594
236.0	2.542E8	2.572E-8	-2.552	9.108	-1.547	2.594
236.1	2.542E8	2.411E-8	-2.553	9.113	-1.549	2.600
237.0	2.542E8	2.411E-8	-2.553	9.113	-1.549	2.600
237.1	2.542E8	2.261E-8	-2.553	9.118	-1.550	2.607
238.0	2.542E8	2.261E-8	-2.553	9.118	-1.550	2.607
238.1	2.542E8	2.121E-8	-2.553	9.122	-1.552	2.613
239.0	2.542E8	2.121E-8	-2.553	9.122	-1.552	2.613
239.1	2.542E8	1.991E-8	-2.554	9.127	-1.554	2.619
240.0	2.542E8	1.991E-8	-2.554	9.127	-1.554	2.619
240.1	2.541E8	1.870E-8	-2.554	9.131	-1.555	2.625

241.0	2.541E8	1.870E-8	-2.554	9.131	-1.555	2.625
245.1	2.541E8	1.367E-8	-2.556	9.154	-1.564	2.655

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 500 model evaluations and 245 derivative evaluations because it reached the limit for the number of iterations.

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	1.367E-8	.000	-2.308E-7	2.581E-7
	b	-2.556	.105	-2.763	-2.348
	c	9.154	.738	7.691	10.617
	d	-1.564	.242	-2.043	-1.085
	e	2.655	.816	1.038	4.273

Correlations of Parameter Estimates

	a	b	c	d	e
a	1.000	.293	-.821	.916	-.998
b	.293	1.000	-.592	.459	-.295
c	-.821	-.592	1.000	-.810	.792
d	.916	.459	-.810	1.000	-.913
e	-.998	-.295	.792	-.913	1.000

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2.464E9	5	4.929E8
Residual	2.541E8	111	2288863.241
Uncorrected Total	2.719E9	116	
Corrected Total	1.766E9	115	

Dependent variable: Nf

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .856.