RUTTING EVALUATION OF HOT MIX ASPHALT MIXTURES USING STATIC CREEP AND REPEATED LOAD TESTS

A Thesis

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Submitted By

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This is to certify that the

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Submitted by

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DEDICATED

TO

MY DEAR PARENTS,

MY WIFE AND DAUGHTER

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ABSTRACT

Permanent deformation of hot mix asphalt (HMA) mixtures is a complex phenomenon in which aggregate, asphalt, and aggregate asphalt interface properties govern overall performance. With passage of time, these properties as well as their relative influence changes as mixture starts to fail due to excessive permanent deformation (rutting). This research investigated the rutting susceptibility of various HMA mixtures subjected to static and repeated loading. Eight (08) HMA mixtures (four wearing and four base course) were selected including Superpave, asphalt institute manual series (MS), dense bituminous macadam (DBM) and national highway authority (NHA)'s class A & B gradations. Optimum bitumen content was determined using Marshall mix method and Superpave gyratory compactor (SGC) was used to fabricate specimens for performance testing. The Flow test (flow time and flow number test) at selected single effective temperature 54.4°C and stress level of 300 KPa was conducted using asphalt mixture performance tester (AMPT). For flow time test, specimen were subjected to static load while haversine repeated load is applied with a waveform of 0.1 second loading time followed by 0.9 seconds rest time for flow number test. Maximum allowed accumulated axial strain is 50,000 microstrains or test shall continue till 10,000 load cycles. The results were used to determine commencement of tertiary flow for selected HMA mixtures. The test results indicated that all mixtures experienced tertiary flow in flow number test whereas no mixtures reached the tertiary flow state in flow time test. Data smoothening technique (five point moving average method) is employed for removing the resonance in raw data obtained from AMPT software. Performance of mixtures were compared using flow number values, cycle number at which the 50,000 microstrains occurred in specimen and intercept obtained from regression analysis of total permanent strain. Observed accumulated axial strains at the time of termination were used for comparison of mixtures as tertiary phase is not exhibited in flow time tests. The analysis indicated that NHA-A among wearing course mixtures and DBM in base course mixtures found comparatively better resistance to rutting among tested mixtures. The findings of this study would facilitate the pavement engineers/ practitioners in selection of rut resistant wearing and base course mixtures. The results of this study (static creep and repeated load tests) can be correlated with other rutting evaluation tests (Asphalt pavement analyzer & Hamburg wheel tracker) to better characterize the rutting propensity of HMA mixtures in selection of appropriate material for hot climatic conditions of Pakistan.

Chapter 1

INTRODUCTION

1.1 Background

Transportation is basic need of every nation as it provides movement of goods and people. For the development of country, it is mandatory to have transportation infrastructure which serve as basis for socio-economic growth. Pakistan is one of the developing countries where social and economic opportunities are enhanced by providing good accessibility to markets, workplace and intercity roads. In general, pavements designed according to local specification and standards, yields economical and durable road which can serve to designed service life even after exposed to several distresses during its service life. The pavement structure serves the basic needs of people by providing daily commuting and long trips. Hence, this makes the road as an important asset of country as huge amount is incurred during its construction and maintenance.

In Pakistan, the total road network consists of more than 260,000 km and most of roads are flexible pavements. Flexible pavements when exposed to loading after its construction get associated with several distresses like rutting (permanent deformation), fatigue and thermal cracking, stripping and many more. These distresses forced pavement to premature failure as they deteriorate the structure with time and loading before completing the design life. If these distresses are not incorporated during the design phase of pavement, it’s very difficult for pavement to complete service life without undue deterioration. In such situations, maintenance and rehabilitation (M&R) becomes more frequent, which tends to increase the life cycle cost and pavement remains no more economical.

Most of the flexible pavements in Pakistan are experiencing rutting which is serious distress especially under high temperatures. In flexible pavements, rutting usually occurs as strains are accumulated in all layers which are under application of intense and continuous traffic loading. The final rut depth in pavement is due to cumulative of permanent strain which contribute to rut depth of various layers in flexible pavements. Permanent deformation is visible on the flexible pavements surface along the wheel path indicated by rut depth or depressions. The general schematics of rutting can be seen by figure 1.

Figure 1. 1 Schematic of rutting on flexible pavements

The depth and width of rut is mostly affected by various characteristics like thickness, material quality, vehicle load, and atmospheric conditions. Rutting is categorized into three types; vertical flow, lateral flow and mechanical deformation. Rutting in either of three mentioned type is major hindrance to traffic flow and cause safety, comfort issues and also affects the overall life cycle cost of pavement. In hot areas of Pakistan, pavement structure commonly experienced rutting in any of the form described above. Huge stresses in upper portion of hot mix asphalt (HMA) mixtures cause shear (flow deformation, which is primary mechanism of rutting. Temperature has significant effect on shear deformation. Experimentally, rutting in asphalt pavements is directly proportional to load cycle number and it goes upto 100 mm below the surface layer in asphalt pavements. The big rut depth can be termed as major structural failure and a safety issue as well for the road user. There are more chances of hydroplaning, splash and spray due to rutting. In Superior Performing Asphalt Pavements (Superpave) mix design procedures, rutting is described as one of serious distress. In order to reduce the probability of rutting in pavement during its service life, it is mandatory to select adequate material and mix design procedure which will subsequently yield durable and more economical mix design.

The current design procedure followed is AASHTO 1993 flexible pavement which is based on empirical method and does not cater the different environmental condition, load/ tyre pressures as exist in Pakistan. Hence, Mechanistic-Empirical Pavement Design Guide (M-EPDG) came to into practice developed by AASHTO for such conditions where as both models and empirical data may be used to forecast the pavement performance. The dynamic modulus is used as basic input parameter for newly flexible pavement design guide encompasses for material characterization. National Cooperative Highway Research Program (NCHRP) also recommend the use of Flow number and Flow time in order to completely understand the behavior of viscoelastic material like asphalt mixtures.

The "Flow Number" (Repeated load test) is defined as the cycle number at which tertiary flow zone starts on a cumulative permanent strain curve obtained during the test. Repeated load test captures fundamental properties of HMA mixture that correlates with rutting performance. This test conducted over a specific stress level in as well as at single effective temperature. The stress typically a haversine type of loading is applied with pattern of 0.1 seconds loading time being followed by 0.9 seconds dwell time. Flow time differs in loading pattern; static load is applied instead of repetitive load.

The “flow time” (Static creep) test has been recognized as one of the tests to measure the fundamental material properties of HMA mixtures related to rutting performance. The test aims at measuring the visco-elastic behavior of HMA mixtures under static stress level. For visco-elastic material it is more beneficial to use compliance term rather than modulus. The main advantage of its use is that compliance helps in segregation of time dependent and time independent components of strain response.

1.2 Problem Statement

Pavements are constructed for efficient communication at desired level of service and economical due to budgetary constraints. Pakistan has the total road network more than 260,000 km. Transportation infrastructure is funding handsome sum annually for this road network which including motorways as well as national highways. Although such huge amount is invested annually in order to construct, maintain and rehabilitate the pavements but still it is found abundantly that level of service achieved is not as desired because of distresses. Premature failure of recently constructed asphalt pavements is due to these distresses in shape of cracking and plastic or inelastic deformation. Permanent deformation (rutting) found most common distress on national roads which causes premature failure. This early failure of pavements results in extra burden over budget as well as safety hazard with increase in travel time and discomfort. These distresses may be due to empirical design approach for pavement designing, material selection and/ or higher loads than design loads. This leads to incorrect design and does not predict future performance. Hence, these distresses may be catered at design stage in order to ensure economical and safer pavement. It is need of hour to undertake study aimed at performance evaluation of HMA mixtures being use in nation-wide.

National Highway Authority (NHA) of Pakistan has carried out national research project entitled "Improvement of asphalt mix design technology for Pakistan". In this project, various selected hot mix asphalt mixtures are being investigated using a wide spectrum of performance tests are planned to conduct to characterize asphalt mixtures for fatigue and rutting. For evaluation of rutting resistance of selected mixtures Asphalt Pavement Analyzer (APA) and Hamburg Wheel Tracker are used. To further argument results obtained from these tests, there was a need to conduct flow number (repeated load) and flow time (static creep) tests. Both tests are capable of capturing fundamental properties of HMA (asphalt, aggregate and asphalt aggregate interface properties) and are being strong candidate tests for evaluation of rutting susceptibility of mixtures. It is envisaged that the output of present study using the protocols of simple performance tester (SPT) would facilitate the implementation of M-EPDG.

1.3 Objectives of the Study

Objectives of this research are:

- To evaluate rutting susceptibility of selected Hot Mix Asphalt mixtures by static creep and repeated load tests using Asphalt Mixture Performance Tester.
- To identify better indicator for rutting susceptibility based on the output parameters of flow time and flow number tests.

1.4 Scope of the Study

Current study is planned to achieve above mentioned objectives. Literature on static creep and repeated load tests were reviewed. Research patterns, findings and correlation were deeply studied. Testing was conducted at eight different gradations including four (04) asphaltic wearing course mixtures and four (04) asphaltic base course mixtures. This research as part of national research envisioning the use for whole country therefore the most common material source used nation-wide is opted for research i.e. Margalla (aggregate material source) and asphalt binder is penetration grade 60/70 of Attock refinery limited (ARL). Based on optimum bitumen content and volumetric properties determined using standard Marshall method, specimens were fabricated through superpave gyratory. Each mix is tested for flow time and flow number at static and repeated unconfined stress of 300 KPa respectively. Test is conducted at single effective temperature which is 54.4^{o}C and each specimen is pre-conditioned for two (02) hours. The table 1.1 shows the test matrix for research study.

Table 1. 1 Test Matrix for Flow Number and Flow Time Test

Gradation (ARL 60/70 & Margalla)	**Layer**	**Flow Number (FN), 54^{o}C, 300KPa**	**Flow Time (FT), 54^{o}C, 300KPa**
NHA - A	Wearing Course	12 specimens (triplicate of each gradation)	12 specimens (triplicate of each gradation)
NHA - B			
Superpave - A			
MS - 2			
NHA - A	Base Course	12 specimens (triplicate of each gradation)	12 specimens (triplicate of each gradation)
NHA - B			
Superpave - B			
DBM			

1.5 Organization of Thesis

This study is structured in five chapters. The first chapter consists of background of mixture, the problem statement, objectives and scope of the study. The chapter two consists of literature review which captures brief introduction of flow time and flow number tests, rutting, its types and mechanism, previous research findings, determination of the flow time and flow number, flow number prediction models and review of various past researches done over it. The chapter three describes the methodology of laboratory testing adopted for optimum calculation as well as performance testing, testing equipment, sample preparation and procedure. In fourth chapter results and analyses are presented, the results obtained are reported using plots and tables in this sequential order firstly flow number results then flow time results shown. These further sub-divided into sections for wearing layer and base layer. The fifth chapter compromised of the conclusion made on the basis of the current study results as well as recommendations for future research.

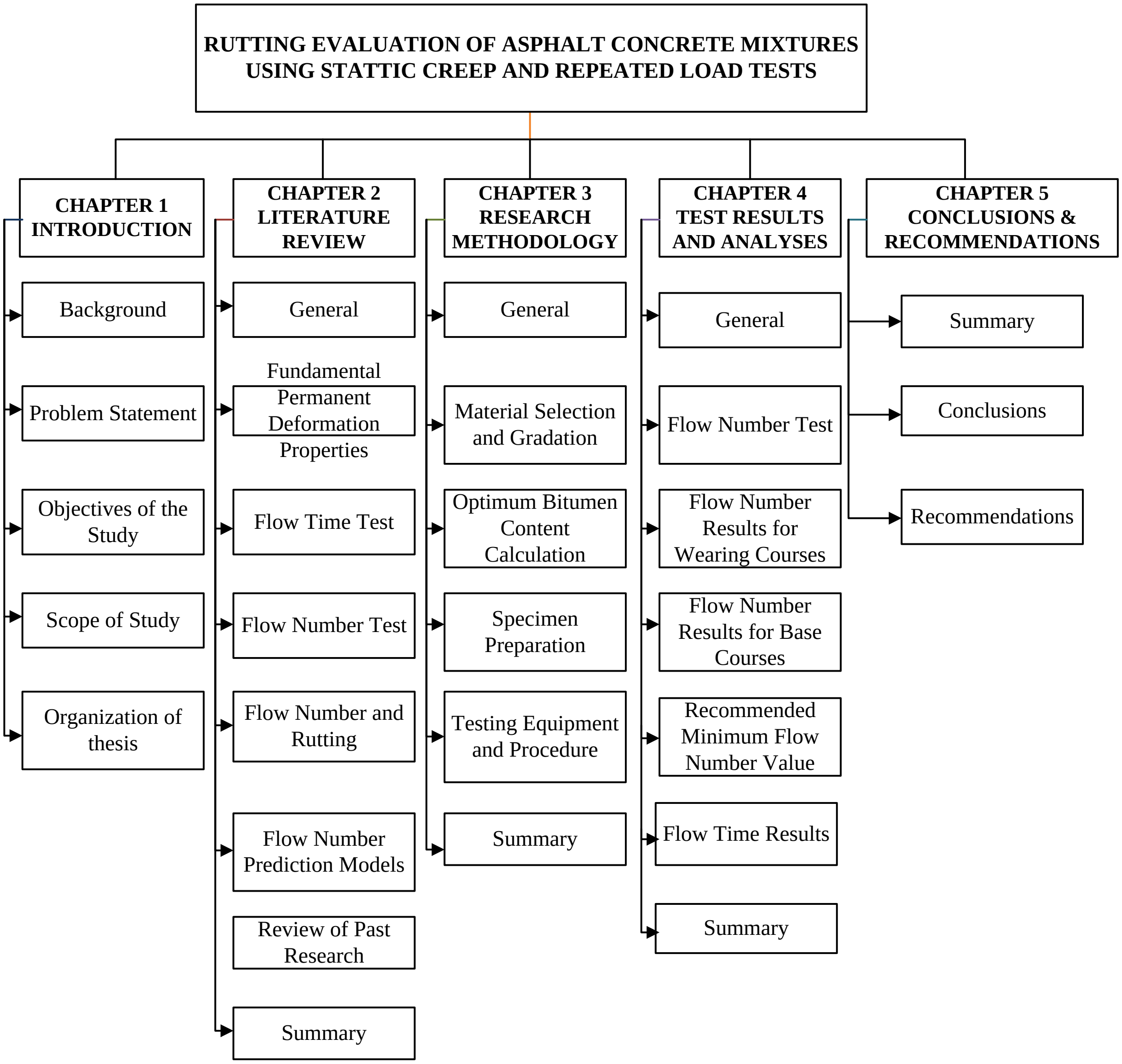

Figure 1.2 Organization of Thesis

Chapter 2

LITERATURE REVIEW

2.1 General

Hubbard Field Method was introduced for asphaltic mixtures during First World War and voids mineral aggregate (VMA) and field stability test were the main features introduced by this method. In 1930's the Marshall method and 1940's the Hveem's method were developed. These two volumetric properties based method tests were recognized internationally and adopted by the most of global highway/ road agencies. In Pakistan, Marshall test was adopted by provincial and federal departments and/ or authorities. In early 90's USA road authorities realizes need of alternate tests for pavements which resulted in shape of superpave mixture design and analysis system that was developed under the Strategic Highway Research Program (SHRP).

Superpave mix design method for HMA mixtures has three phases: materials selection, aggregate blending and volumetric analysis. Superpave Gyratory Compactor (SGC) was introduced for specimen compaction. And fourth phase programmed was to build guidelines for analyzing of mix characteristics as well as determination of performance potential. In USA, most highway agencies shifted to new volumetric mixture design method. The traditional Marshall and Hveem mixture design methods had associated strength tests. However, unlike the traditional Marshall and Hveem mix design method, the Superpave method does not have a performance evaluation to complement the volumetric mixture design. Some researchers and designers (Cominsky et al. 1998) have raised the question that whether the volumetric design method alone can provide a sufficient design over a full spectrum of loading conditions till the end of second millennium. To address this concern, a set of Asphalt Mixtures Performance Tests (AMPT) have been proposed and evaluated by the National Cooperative Highway Research Program (NCHRP) for estimating the mechanical performance of the mixtures (Witczak et al. 2002). These tests include the dynamic modulus test, flow number and flow time test. The latter both tests are used in this research and elaborated in this chapter.

2.2 Fundamental Permanent Deformation Properties

The distress identification manual for long-term pavement performance project defines rut as "a longitudinal surface depression in wheel path [that] may have associated transverse displacement." Nearly all flexible pavements are affected by rutting, some more and some less.

Permanent deformation produced in HMA layer is a combined effect of densification ($\Delta V \neq 0$) and shear deformation ($\Delta V = 0$) caused by repetitive load pattern of traffic. Large shear stress is experienced in upper portions of HMA pavement in over-compacted pavements leads to permanent deformation.

2.2.1 Types of Rutting

Rutting is classified into three types. These types are identified by their causes and specific layers associated with them are summarized below.

(a) Vertical Compression

Vertical compression is associated with material densification and a rut depth under or near the center of the wheel path is generated without producing humps on any side of rut. The densification occurred in materials is generally due to too much air voids or inadequate compaction after laying of HMA material, thus letting the material of layers to compress when exposed to traffic loading. This rut depth type frequently outcomes in low to moderately severe rutting level.

(b) Lateral Flow

Pavements layers of HMA mixture with poor shear strength or deficient in air voids are susceptible to lateral flow or displacement of materials. Low air voids ($\leq$ 3%) in HMA mixture after construction makes pavement on risk to lateral flow as low air voids asphalt are acting like a lubricant instead of binder in hot climatic conditions. And in these over-compacted asphaltic pavement layers are also susceptible to bleeding over pavement surface under heavy traffic loads. It is very difficult to predict this rutting type.

(c) Mechanical Deformation

Densification, the consolidation, and/or the lateral movement of the liberated materials under HMA surface is the third rutting type and also termed as the mechanical deformation. This rutting type caused by continuation in base layer, sub-base layer, and/or subgrade layer and often occurred in longitudinal cracking form over pavement's surface in highly stiff HMA mixture. Center of ruts of alongside of it is the most probable place where these longitudinal cracks can be found usually.

2.2.2 Mechanism of Rutting

Permanent or inelastic deformation occurred due to traffic loads in HMA layers results in surface distortion. Inelastic deformations also known as plastic deformations are those irrecoverable deformations retained in material after removal of load. When a pavement surface is exposed to traffic load, wearing layer and underneath pavement layers distort to extent which is proportional to modulus and thickness of individual layers at temperature and speed of loading. After removal of loads all deformation produced under load is not revocable thus leaving a residual value in one or more pavement layers. Residual deformations are accumulated under repeated traffic loads, thus accumulation results in increasing the permanent deformation amount and rutting severity.

The distortion mechanism specifically for rutting can be classified into two categories: (a) one-dimensional vertical inelastic deformation and (b) two-dimensional inelastic deformation. Densification occurs due to decrease in volume of material. Also it may be lateral or shear deformations contain plastic material flow associated with volume change or without change in volume.

(a) One-Dimensional Inelastic Deformations

Consolidation of unbound materials in asphalt and/or underneath pavement layers or over-densification in these layers leads to vertical inelastic deformation. Densification is a constant and slow but steady reduction of air voids under repeated traffic loads that happens in all pavement layers after their initial compaction. Due to vertical inelastic or plastic deformations under traffic loadings, the densification is occurred in pavement. Pavement layers are prone to a little extent of over-densification as compressive stresses under traffic loads and temperatures conditions are too high nearby surface. When temperature is higher, asphalt becomes softer causing asphaltic layers more susceptible to densification under traffic loads.

Another very less experienced rutting mechanism is consolidation of the underneath layers. The major causes of this type may be the fine grained materials and highly moisturized soils. Pressures applied by traffic loadings to the surface of pavement are transferred to underneath layers and the subgrade. The gradual process of consolidation process continues under traffic loads and depends on amount of fines and content of moisture existed in soil.

(b) Two-Dimensional Inelastic Deformations

Longitudinal distortion of HMA mixtures is produced by in-situ shear failure in mixture leads to over stressing mixture with high tire pressures. This type of rutting usually occurs in mixtures with low shear strength. Rutting caused by lateral flow is difficult to predict accurately with repeated load triaxial testing equipment, especially for the HMA mixture which is highly anisotropic.

Yoder and Witczak, (1980) defined shear deformation as plastic flow of pavement layers that occurs without change in volume. Shear deformation is repelled by shear modulus of material, “G*”. For viscoelastic and isotropic materials, the value of G* as well as elastic modulus affected by rate of load application and temperature. For the viscoelastic material length of loading time affects amount of deformation that happens in material. Therefore, deformations under same traffic loads will be less on high speed highways than on low speed highways.

2.2.3 Factors Affecting Rutting of HMA Mixtures

Permanent deformation of asphalt aggregate mixtures is a complex phenomenon where aggregate, asphalt, and aggregate asphalt interface properties control the overall performance. With the passage of time these properties and their relative influence altered till the mixture comes to the termination of its beneficial life period. HMA mixtures are time and temperature dependent material. Their behavior is strongly dependent of the rate, the time and the temperature and they shows different properties when these conditions changed. Thus exhibiting different properties while in tension and different behavior in compression. These different kind of factors which may affect inelastic or plastic deformation as well as effect of factors being changed are shown in Table 2.1

Table 2.1 Factors Affecting Rutting Of Asphalt Concrete Mixes (SHRP Report A-415)

Contributor	Factor	Change in Factor	Effect of Change Factor on Rutting Resistance
Aggregate	Surface Texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in maximum size	Increase
Binder	Stiffness[a]	Increase	Increase
Mix	Binder content	Increase	Decrease
	Air Void content[b]	Increase	Decrease
	VMA[c]	Increase	Decrease
	Method of compaction	___[d]	___[d]
Test or field Conditions	Temperature	Increase	Decrease
	State of stress/strain	Increase in tire contact pressure	Decrease
	Load repetitions	Increase	Decrease
	Water	Dry to wet	Decrease if mix is water sensitive

[a]Refers to stiffness at temperature at which rutting propensity is being determined. Modifiers may be utilized to increase stiffness at critical temperatures, thereby reducing rutting potential.

[b]When air void contents are less than about 3%, the rutting potential of mixes increases.

[c]It is argued that very low (i.e., less than 10%) voids in mineral aggregate (VMA) should be avoided.

[d]The method of compaction, whether laboratory or field, may influence the structure of the system and therefore the propensity for rutting.

Air voids also play an important role in altering properties of HMA pavement. When air voids are less the act as continuous slab and transferred loads longitudinally as well, thus enhances the rate of permanent deformation. It acted as a stiff material upon losing air voids and at high temperature it starts behaving a fluid under traffic loadings. With high content of air voids, the HMA pavements consolidate under traffic loadings thus leads to permanent deformation along wheel paths. Some mistures also susceptible to water, thus moisture would be the major factor for deterioration of pavement.

2.3 Flow Time Test

Flow time test also known as static creep test is one of the recognized tests to determine fundamental properties of HMA mixtures subjected to their rutting performance and recommended in NCHRP Project 9-19 by Witczak et al. (2002). Visco-elastic behavior of HMA mixtures under a static stress level can be measure by this test. Total compliance at any given point in time, D (t), can be calculated as ratio of measured strain ε_t to applied stress σ_0.

$$D(t) = \frac{\varepsilon_t}{\sigma_0} \qquad (2\text{-}1)$$

Compliance or D (t) is more useful to use for visco-elastic material than modulus because time dependent and time independent components of strain response can be separated using compliance. Witczak et al. (2002) reported that the compliance is the reciprocal of the modulus. Flow time test may be performed in laboratory under conditions of either confined or unconfined to get a strain response of material over time period. Flow time test helpful to understand the material's response by providing sufficient information about instantaneous elastic (recoverable) and plastic (irrecoverable) components as well as the viscoelastic and viscoplastic components. Typical relationship in between calculated total compliance and loading time is shown in Figure 2.1.

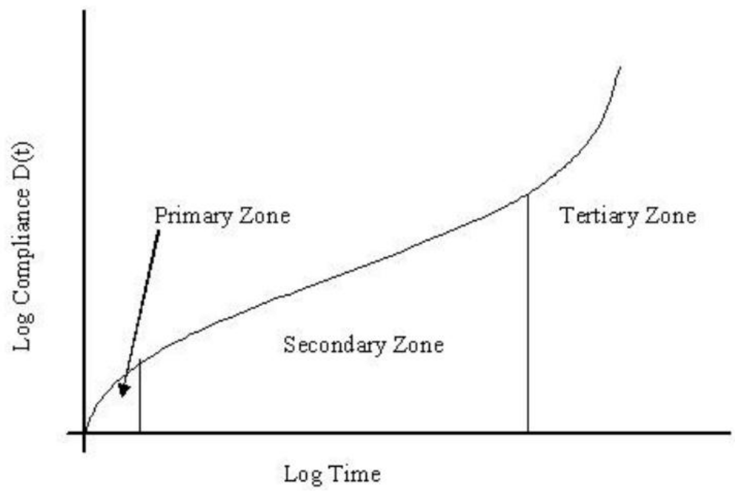

Figure 2.1 Compliance versus Time curve on log scale. (Witczak 2002)

As shown above in figure 2.1, total compliance can be distributed in three major zones:

1. **The primary zone**: Strain rate decreases with loading cycle,

2. **The secondary zone**: Strain rate is constant with load cycle, and

3. **The tertiary flow zone**: Strain rate again increases with load cycles.

Ideally, enormous increase in compliance generally exhibited at constant volume in tertiary flow zone. Flow time can be defined as the cycle number at where the commencement point of tertiary flow noted. It is found a very significant test parameter for evaluation the rutting resistance of an HMA mixture. Witczak et al., (2002) stated that the flow time can also be reported as a minimum value of rate of change of strain versus load cycle time plot on log-log scale. Mathematically, total compliance in secondary zone at any given time, D (t), as a power function can be expressed as follows:

$$D(t) = at^m \qquad (2\text{-}2)$$

Where,

t = Time in seconds, and

a, m = Materials regression parameters.

Regression parameters a and m are the compliance parameters and are general indicators for the behavior of inelastic deformation of the material. In general, higher the value of ‘a’ compliance value (D (t)) will be higher depicting that material is less susceptible to permanent deformation. On the other hand lower modulus value is associated with material having larger permanent deformation tendency. For a constant value of parameter a, an increase in slope parameter m means higher permanent deformation.

These regression constants are determined by total compliance versus time plots on a log to log scale up to secondary zone only (or up to the flow time cycle number). Power models are used generally to model secondary zone (linear phase) of creep compliance curve and is illustrated by figure 2.2.

The expression 2-2 rewritten on a log-log scale as:

$$\log D(t) = m \log(t) + \log(a), \qquad (2\text{-}3)$$

Where,

m= Slope of curve , and

a= Strain at N=1or Intercept.

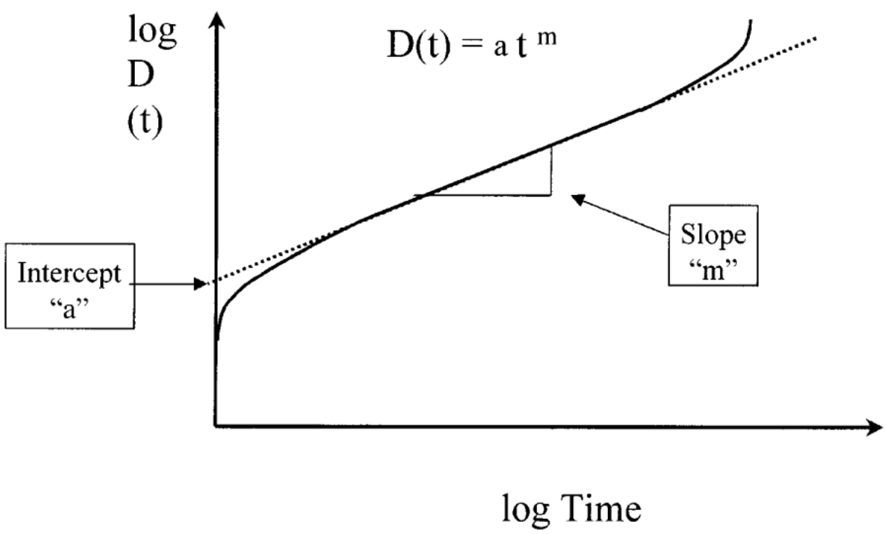

Figure 2. 2 Material's regression constant 'a' and 'm' (Witczak 2002)

Parameters flow time and regression parameters are targeted to obtain from the test for evaluation of rutting performance. In conjunction with this (flow time) test, other test conducted in this research is flow number test. Both tests are targeted to perform on same parameters.

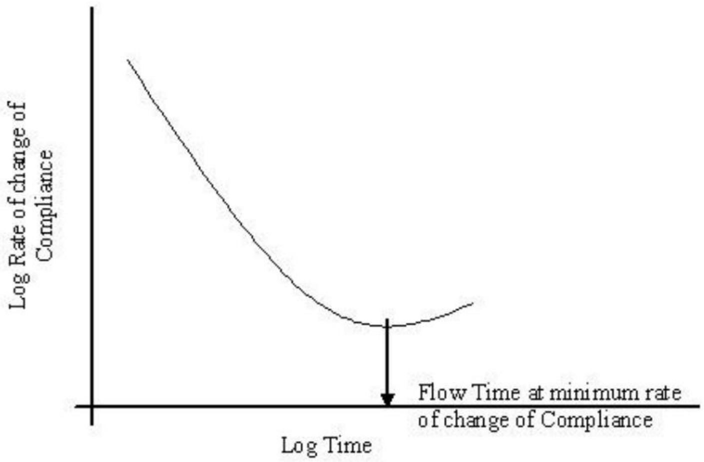

Figure 2.3 Rate of change of compliance versus time on log scale (Witczak 2002)

2.4 Flow Number

The repeated load test also called Flow number test is dynamic type of creep test where a haversine type of loading is applied with pattern of 0.1 seconds loading time and 0.9 seconds dwell time. Amit et al. (2005) with reference to Barksdale mentioned the rationale for selecting 10 Hz. Equivalent pulse time conversion for haversine loading at rate of 10 Hz frequency closely represents speed of 110 kmph speed.

As shown in Figure 2.4, the typical result between the measured permanent axial strain and load cycle is classified in three flow parts. In the primary phase, strain rate (slope of the permanent strain curve) reduces. During secondary phase, permanent strain rate is constant and in tertiary phase, permanent strain rate dramatically upturns. At low stress levels, the material may mainly exhibit primary and/or secondary permanent strain. In this case, the permanent strain rate may approach a value equal to zero as the total strain reaches a certain value. This also suggests that at this very low stress level the tertiary flow region may never appear within a reasonable amount of time. At higher stress levels, the occurrence of the constant secondary permanent strain rate phase will depend on the stress level applied.

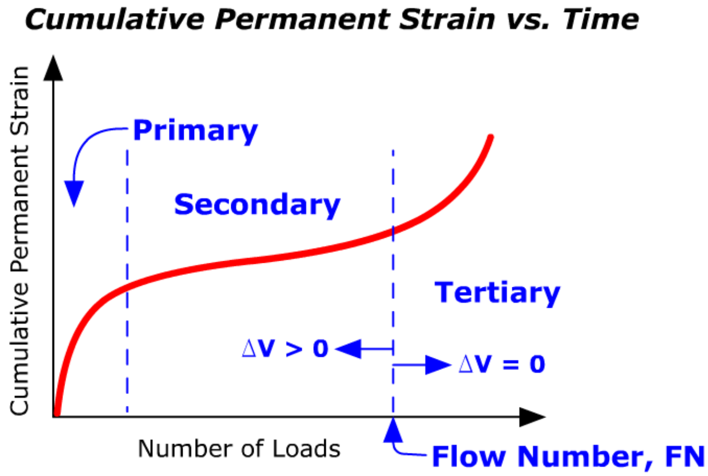

Figure 2. 4 Typical repeated load permanent deformation behavior of pavement material

The repeated load test has ability to evaluate fundamental properties of HMA mixtures which can correlate rutting performance. Specific stress level is applied in dynamic (repeated) pattern in flow number test. Typically, dynamic stress applied is in a waveform of haversine with a pattern of 0.1 second loading time followed by unloading or dwell time for 0.9 seconds. Witczak et.al (2002) recommended to conducting the flow number tests at single temperature and stressing level. All samples tested on 54.4 °C (130 F) temperature for uniform basis for comparison for this research and the temperature was selected based on earlier research work (Witczak et al. 2002).

For selection of test conditions (confined or unconfined) and selection of stress level, the limitation of equipment is also kept under view. The available equipment is limited to apply maximum stress level of 460 KPa for one hour time duration. Therefore, confined test is not possible to conduct. The stress level opted for testing was 300 KPa (43.5 Psi). Trial tests had been conducted on various samples before selection of this stress level to ensure that in a suitable time most of these specimens would reach tertiary flow.

Termination of test is selected as maximum 5% of accumulated axial strain. 5% strain is target termination because the finite element studies shows that the half (0.5) inch (12.5 mm) rutting is expected at 5% strain. The maximum value of load repetition is set at 10, 000 seconds. Terminations shall be occurred upon maximum limit of strain or cycles whichever comes first.

Permanent axial strain data obtained from results of flow number test can be plotted versus load cycle. Figure 2.5 shows typical data from flow number test.

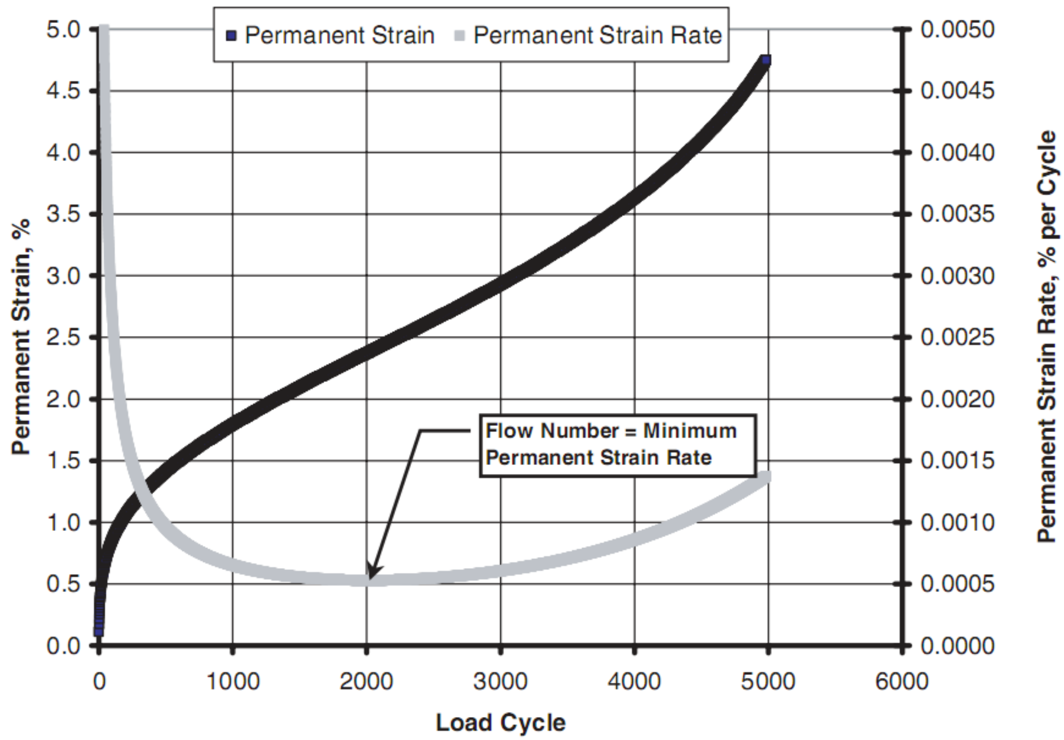

Figure 2. 5 Typical data from flow number test. (NCHRP Report 702)

The permanent axial strain as a power function driven by number of cycles can be written as:

$$\varepsilon_p = aN^b \tag{2-4}$$

Where,

ε_p = Permanent axial strain,

a , b = Regression coefficients,

N = Load cycles number.

On scale of log to log equation 2-4 can be written as,

$$\log \varepsilon_p = \log a + b \log N \tag{2-5}$$

Where,

log a = intercept of permanent axial strain versus number of load cycles on log to log plot,

b = slope of permanent strain versus number of load cycles on log to log plot.

The several parameters selected by Witczak et al. (2002) for evaluation of results obtained from the flow number test were intercept ‘a’ and slope ‘b’, resilient strain, resilient modulus, µ parameter, permanent strain, flow number value, and ratio of permanent to resilient strain. For current research study, parameters selected sufficient to fulfill the objectives of this study are;

- Flow number value
- Number of cycle at which test terminate.
- Slope, b

2.5 Flow number and rutting

Ideally, the huge increase in permanent strain generally exhibited at constant volume in tertiary flow zone. Flow number can be defined as postulated cycle when shear deformation under constant volume initiates indicating beginning of tertiary zone in the mixture. Practically, the flow number can be determined as the load cycle at which rate of the change of permanent strain reaches the minimum amount. Permanent deformation (rutting) of the flexible pavement is a combined effect of densification and shear deformation under repetitive loading. Witczak (2007) categorized rutting into three classes and termed them as one-dimensional densification or vertical compression, lateral flow and mechanical deformation. Factors affecting rutting vary since rutting is a complex phenomenon between aggregate, asphalt, and aggregate asphalt interface, and the properties of those component are changing with the change in time, loading and temperature.

Several testing methods have been proposed by Witczak et al. (2002) for evaluating the rutting resistance including repeated load test and creep load test. Witczak (2007) stated that the flow number test was found to be able to correlate with field rut depth as verified by field projects at MNRoad, Westrack and FHWA pavement testing facility. In NCHRP project 9-19, the relationship between the reduced flow number and field rut depth at a specific traffic level wa investigated. Temperature-reduced flow numbers were calculated with the following equation 2-6.

$$Log(F_{nr}) = \frac{\ln\left(\frac{\alpha}{\log(\sigma)-\delta}-1\right)-\beta}{\gamma} \tag{2-6}$$

Where,

σ = Applied stress,

tr = Ft or Fn at reference temperature,

δ = Minimum stress that will cause damage,

δ + α = Maximum stress that will cause instantaneous damage, and

β, γ = Parameters relating shape of sigmoidal function.

α will be a linear function of δ. The parameters in the equation were determined from a global temperature shifted master curve analysis.

Christensen (2008) proposed a resistivity/rutting equation which provides maximum allowed traffic in function of compaction, air voids and mixture composition based on regression data. Equation 2-7 is expressed as below.

$$TR = 9.85 \times 10^{-5} (PN_{eq}K_s)^{1.373} V_d^{1.5185} V_{IP}^{-1.4727} M \quad (2\text{-}7)$$

Where:

TR = Allowable traffic in ESALs up to an average rut depth of 7.2 millimeter (Confidence level=50 %)

= Allowable traffic in ESALs (million) up to a maximum rut depth of 12 millimeter (Confidence level=95 %)

P = Resistivity, s/nm

$= \frac{(\frac{|G^*|}{sin\delta})S_a^2 G_a^2}{49VMA^2}$

|G*|/sinδ = Estimated aged PG grading parameter at high temperatures, determined at 10 rad/s and at the yearly, 7-day average maximum pavement temperature at 20 mm below the pavement surface, as determined using LTPP Bind, Version 3.1 (units of Pa/s); aged value can be estimated by multiplying the RTFOT value by 4.0 for long-term projects (10 to 20 year design life), and by 2.5 for short term projects of 1 to 2 years.

S_a = Specific surface of aggregate in mixture, m^2/kg

≅ Sum of the percent passing the 75, 150 and 300 micron sieves, divided by 5.0

≅ 2.05 + (0.623 × percent passing the 75 micron sieve)

G_a= Bulk specific gravity (aggregate)

VMA= Design voids volume in mineral aggregate for HMA mixture,

Net = Design gyrations

K_s = Speed correction, $(v/70)^{0.8}$and v is average traffic speed in km/hr

V_d = Design volume of air void content, %

VIP = Volume (in-place) of air void content, %,

M= 7.13 for polymer-modified binders else 1.00.

2.6 Flow Number Prediction Models

Significant efforts have been made to establish testing method to evaluate the material properties of asphalt mixture design during last decade. These efforts targeted the behavior of in place or field performance of asphaltic pavements. Dynamic Modulus been focused by majority of these researchers and the predictive models based on material's dynamic modulus presented. However, some researchers (Witczak,1996; Bhasin, 2004) felt that supplementary test should be employed in combination with dynamic modulus for evaluation of rutting performance of HMA mixtures. The flow number has been proved to be an effective tool for rutting performance indicator.

Flow number test has the ability to provide information of material deformation concerning the three phases of flow zones associated with asphalt mix. Flow number is obtained from the repeated load test to determine resistance of HMA mixture to tertiary flow. In order to predict the flow number of asphalt mixture, some researchers have been proposed different prediction models to provide guidance on the understanding of flow characteristics.

Kaloush (2001) provided the first attempt in predicting the flow number of HMA mixture based on mixtures volumetric properties, binder type, and test temperature. The model used 135 unconfined laboratory FN tests and was presented as follows.

$$FN(432367000)T^{-2.215}Visc^{0.312}V_{beff}^{-2.604}V_d^{-.1525} \tag{2-8}$$

Where,

FN = Flow Number

T = Test Temperature, °F

Visc = Binder Viscosity at 70°F, 10^6 poise

V_{beff} = Effective Asphalt Content, % volume

V_a = Air Voids, %

Another study by Kvasnak et al. (2007) presented a flow number predictive equation based on 17 dense graded mixtures from the State of Wisconsin.

$$\log FN = 2.866 + 0.006313Gyr + 3.86Visc - .072VMA + 0.0282P_4 - .051P_{16} + 0.075P_{200} \quad (2\text{-}9)$$

In this model, the number of gyrations (Gyr) was found to be the most significant factor. The authors pointed out that the model limited to apply within data ranges used for the dense graded HMA mixes.

Kaloush et al. (2010) proposed an equation to predicted flow number as following.

$$\log FN = 2.174 + 0.649LogV_1 + 0.101P_{200} + 18.465Logp + 0.0140R_{04} - 0.084V_a - 18.901logq - 0.872R_{34} + 0.182q - 0.193p - 0.871log \quad (2\text{-}10)$$

Where,

V_1 = Viscosity at testing temperature,

V_a = Air voids level,

T = Temperature,

%P200, %R04 and %R34 = Three variables related with the gradation of the mix,

p = shear stress and

q = normal stress

Christensen (2008) applied numerous statistical techniques to correlate flow number with complex modulus, applied stress level and air void content. The proposed model based on data regression is;

$$N_f = 4.96 \times 10^{-4} \beta_1 |E^*|^{2.478} \sigma^{-0.009VTM - 0.187|E^-|} \quad (2\text{-}11)$$

Where,

N_f = Flow number value

β_i = Indicator variable, adjusting regression constant for i^{th} projects/sections

|E*| = Complex modulus (lb/in^2) at 10 Hz and same temperature as flow number test

VTM = Volume of air voids (in test specimen), %

σ = Deviator stress, lb/in^2

2.7 A Review of Past Researches

Amit et al. (2003) conduct a research using nine HMA mixtures which were obtained from state Departmental of Transportation has varying degrees of reported field performance. They aslo tested three laboratory prepared mixtures. All mixtures were characterized using flow number, flow time and dynamic modulus tests conducted at Asphalt Mixture Performance Tester (AMPT) and they used Asphalt Performance Analyzer (APA) being a torture test to mixtures characterization. They concluded that slope of flow time (creep load) and flow number (repeated load) value showed the closest correlations with the APA's rut depth. But, the APA's rut depth and the flow time slope correlation had been much superior to the between APA's rut depth and flow number.

Bonaquist et al. (2004) concluded the results of the environmental conditioning system to SPT integration effort showed that flow time and flow number testings needed to be modified or conducted in a different testing sequence before they can be used as a replacement to the resilient modulus test in Environmental Conditioning System. Moreover, the results of dynamic modulus test showed the ranking similar to the expected field performance.

Bahia et al. (2005) managed to use gradations of two diverse types, for their research, for aggregates from Wisconsin of four different sources. Optimum asphalt contents used in their research varied from 4.3% to 6.2%. In order to validate the chosen measure it needed to be compared to a performance test, so they choose the uniaxial repeated creep test, a performance test recommended in NCHRP 9-19 project. The measure that was achieved from the Superpave Gyratory Compactor (SGC) is the Traffic Force Index (TFI) and the Traffic Densification Index (TDI). The output obtained from the uniaxial repeated creep test was the flow number, which clearly indicated the tertiary creep failure of asphalt mixtures. The correlation between the Traffic Force Index and the Flow Number yielded a coefficient of determination (R^2) of 81% which indicated a significant relationship between asphalt mixtures resistance to permanent deformation and the Traffic Force Index. Hence, using Traffic Force Index as an indication of asphalt mixture mechanical stability can help to propose recommended minimum limits for mixture stability as a function of expected traffic levels.

Mohammad et al. (2005) evaluated six plant-produced HMA mixtures through four laboratory tests that are flow number (FN), Hamburg-type loaded wheel tracking, frequency sweep at constant height, and dynamic modulus |E*| tests. They concluded that the ranking order of asphalt mixtures obtained from the flow number test results was quite coherent with the use in field of those mixtures considered in their study. In addition, a pair of a-value and b-value obtained from the permanent strain repetitions curve correlated well with the flow number results. Such parameters complemented the analysis of a flow number test, especially when the tertiary flow zone was not reached in a test which was one of the most important finding persistent to the topic. The flow number values shows fairly good correlation with Hamburg rut depths, indicating both parameters were found quite sensitive to rutting characteristics for the mixtures evaluated.

Mohammad et al. (2006) concise their results of thirteen (13) plant produced asphaltic mixtures. They investigated these HMA mixtures using four laboratory tests including flow number (FN) and flow time (FT) alongwith Hamburg-Type Loaded Wheel Tracking test and dynamic modulus |E*| test. The concluded that the average ranking of the rutting resistance parameters from the flow time, flow number and dynamic modulus test were able to differentiate between mixtures based on their design traffic. In addition, all the parameters had a comparable ranking for the mixes.

Kaloush et al. (2010) used Ninety four HMA mixtures and a total of 1759 Flow Number test results. They developed a flow number predictive model which is described previous section of flow number prediction models. Their final model's statistics had an R^2 of 0.62 with s_e/s_y of 0.60, which are considered to be fair statistical measures of model accuracy, considering the wide range of each variable. Variables included in their final model are viscosity at testing temperature (V_1), temperature, air voids level, $\%P_{200}$, $\%R_{04}$ and $\%R_{34}$ and the shear and normal stresses (p and q) that are incorporated in model with arithmetic as well as logarithmic terms. Researchers further quoted that their final model is valid to wide range of temperatures, stress conditions and mix types. It is also important to mention here that the variability within replicates used in their research was relatively high.

Miljković and Radenberg (2011) reported that permanent deformation in asphalt layers which manifestation on pavement surface is named rutting represents one of the most significant distresses of asphalt pavements and depending on the level, it can be a huge inconvenience for traffic safety, driving comfort, and overall pavement life-cycle. Depending on the cause and the layer permanent deformation predominantly occurs, rutting may be classified into three basic types: one-dimensional or vertical compaction, lateral flow or plastic movement, and mechanical deformation. Mixture permanent deformation susceptibility is equally dependent on component materials and their relative content as on test i.e. performance conditions. As an addition to Superpave mixture volumetric design Simple Performance Tests (SPT) were recommended. The objective of these tests is acquiring a better insight asphalt mixtures performance. They cover the determination of dynamic modulus, Flow Number test (repeated load permanent deformation test), and Flow Time (static load permanent deformation test).

Shen et al. (2012) measured the dynamic modulus and flow number of seven plant produced mixes from Washington State used in pavements. On basis of experimental findings they recommended Hirsch Model and a modified flow number prediction model conventional dense graded asphalt mixtures for Washington State. They found impact of air voids is significant on both dynamic modulus and flow numbers. The higher air voids, the lower dynamic modulus and flow number will be. They locally calibrated a flow number prediction model for Washington State which correlates flow number with volumetric properties, binder type, and testing temperature of mix. They achieved reasonable prediction results for locally conventional mixes (PG 70-28, PG 64-28 and PG 64-22 binder mixes). Moreover, model is not applicable for highly polymer modified mix.

2.8 Summary

This chapter consists of Superpave brief introduction and then importance of flow time and flow number value in performance testing. Flow time is static creep load test used to measure the fundamental properties of HMA related to rutting performance. The main advantage is that compliance allows for the separation of the time-independent and time-dependent components of the strain response. Three zones of total compliance, primary, secondary and tertiary are defined with the help of figure.

Flow number test is briefly described alongwith the selected parameters of test supported with the rationale and justification of selection of those parameters. Axial stress 300 KPa, test temperature 54.4 °C under unconfined stress conditions. Loading of one second is applied in haversine waveform with 0.1 second load time with 0.9 second rest period. Termination of test is set at either achieving of 5% microstrains in axial strain or upon completion of 10,000 cycles whichever comes first. At the end section, literature review of previous studies is given in brief form with their findings.

Chapter 3

RESEARCH METHODOLOGY

3.1 General

In current chapter the material selection, gradations, asphalt mixtures, specimen preparation, laboratory apparatus and testing methodology are discussed. Hot Mix Asphalt (HMA) mixture specimens were prepared. Eight different HMA mixtures were prepared in laboratory, four (04) asphaltic wearing courses (AWC) and another same number for asphaltic base course (ABC) which are subjected to repeated and static loadings.

Optimum bitumen content used for these mixtures, calculated using marshal mix design is elaborated in subsequent sections. MS-2 manual is used for determining volumetric properties; flow, stability, VMA, VFA and AV. By using the optimum binder content calculated by Marshall mix method, both wearing and base course mixture specimens were fabricated through Superpave gyratory compactor (SGC). Gradation charts and specimen preparation as well as conditioning is also discussed in subsequent portions of this chapter. Asphalt mixture performance tester (AMPT), old name simple performance tester (SPT) was the equipment used for performance evaluation. Static creep (flow time) and repeated load (flow number) tests were performed on specimens prepared for above stated mixtures using AMPT also discussed in this chapter.

Figure 3.1 illustrates the research methodology. In the first step, the material was selected, the gradations was finalized and then the optimum bitumen content was calculated for these gradations using the Marshal Mix design method. This included the determination of the volumetric properties, flow and stability measures which served as the foundation for the performance testing. Gyratory specimens were later prepared at the optimum bitumen content, cored and sawed for the performance testing. Then testing was performed on the prepared specimens at the AMPT. Before subjected to loading, the samples were pre-conditioned heating for the two (02) hours at the testing temperature. Data noise was removed from the test results obtained and the smoothened data was used for the further analyses.

3.2 Material Selection and Gradations

As this study is a component of national research project, so it was envisaged the use for whole

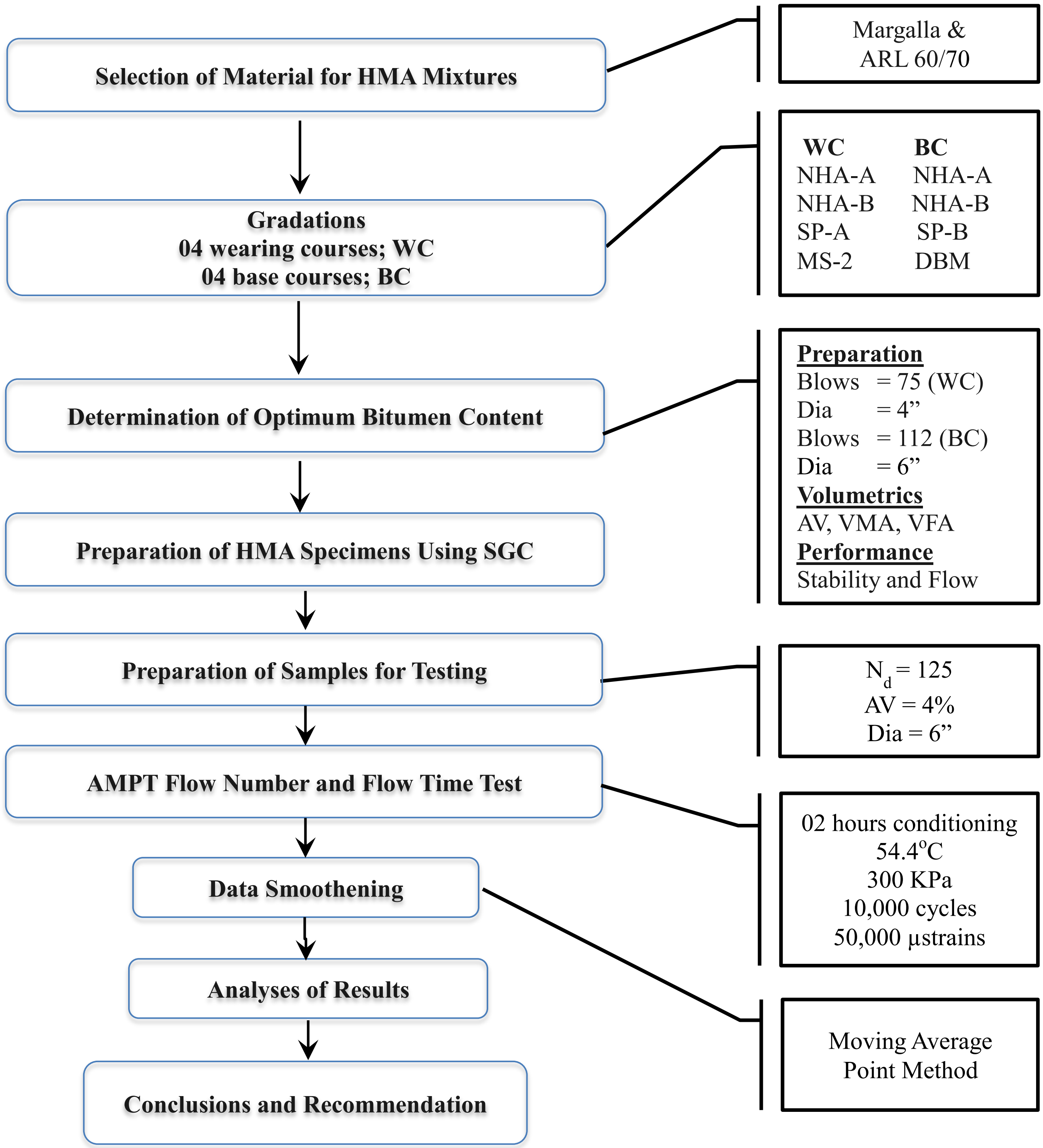

Figure 3. 1 Research methodology

country, thus the most common material source used the nation-wide is opted for the research i.e. Margalla (aggregate material source) and the asphalt binder is penetration grade 60/70 of the Attock refinery limited (ARL).

The proportion of aggregate in HMA gradation is significant factor for proper design. Therefore, four different gradations were used for AWC as well as for BC mixes. The gradations selected for AWC were: two classes of NHA gradation A & B, Superpave Class A-1 (termed as SP-A) and Asphalt Institute MS-2 and for the ABC mixes: two classes of NHA gradation A & B, Superpave Class A-2 (termed as SP-B) and Dense Bituminous Macadam (DBM). Table 3.1 contains accumulative passing content in percentage from each sieve against gradations. The cumulative percentage passing was used to calculate accumulative retained by subtracting former from 100. Individual percentage retained on each sieve was then found by subtracting the consecutive percentages in the table. Finally the weights for each size were computed using these percentages.

Table 3.1 Gradations-Wearing and Base Course Mixtures

Sieve Size	Asphaltic Wearing Course Gradations				Asphaltic Base Course Gradations			
	Accumulative Percentage Passing (%)				Accumulative Percentage Passing (%)			
	NHA-A	**NHA-B**	**SP-A**	**MS-2**	**NHA-A**	**NHA-B**	**SP-B**	**DBM**
37.5 mm	100	100	100	100	95.0	100	100	100
25.4 mm	100	100	100	100	77.0	82.5	95.0	95.0
19 mm	95.0	100	100	100	65.5	72.5	85.0	83.0
12.5 mm	76.0	82.0	94.0	95.0	52.5	62.5	60.0	70.0
9.0 mm	63.0	70.0	87.0	82.0	44.0	52.5	47.0	63.0
6.4 mm	51.5	59.0	74.0	69.0	37.0	44.0	35.0	57.0
4.75 mm	42.5	50.0	65.0	59.0	31.5	37.5	30.0	52.0
2.36 mm	29.0	30.0	37.0	43.0	22.5	25.0	20.0	39.0
1.18 mm	20.0	20.0	21.0	30.0	15.5	18.0	15.0	28.0
0.6 mm	13.0	15.0	14.0	20.0	10.5	13.5	12.0	20.0
0.3 mm	8.5	10.0	9.0	13.0	7.0	10.0	8.0	14.0
0.15 mm	6.0	7.0	7.0	8.5	5.5	7.0	6.0	9.0
0.075 mm	5.0	5.0	5.0	6.0	4.5	4.5	4.0	5.5
Pan	0	0	0	0	0.0	0	0	0

Using table 3.1, wearing and base course mixtures' gradation charts are prepared. Figure 3.2 shows curves for wearing course mix gradations and sieve size raised to power 0.45 is at X-.

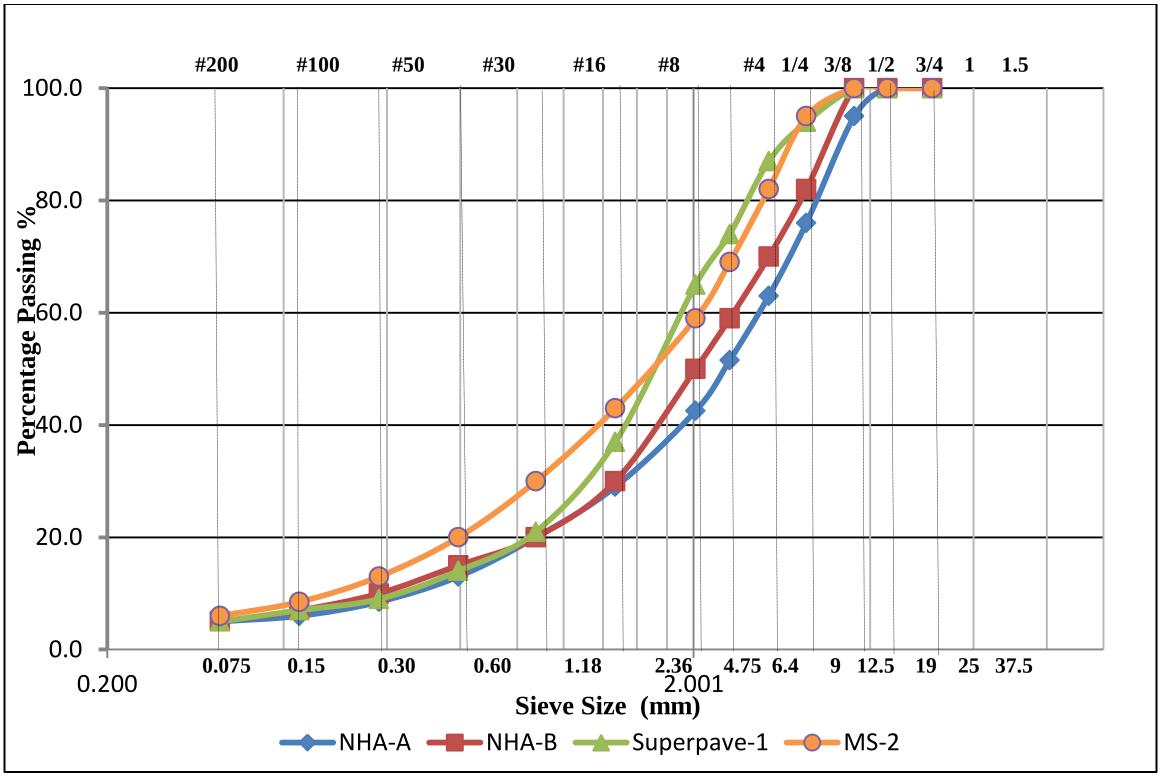

Figure 3. 2 Asphalt Wearing Course Mixtures - 0.45 Power Gradation Chart

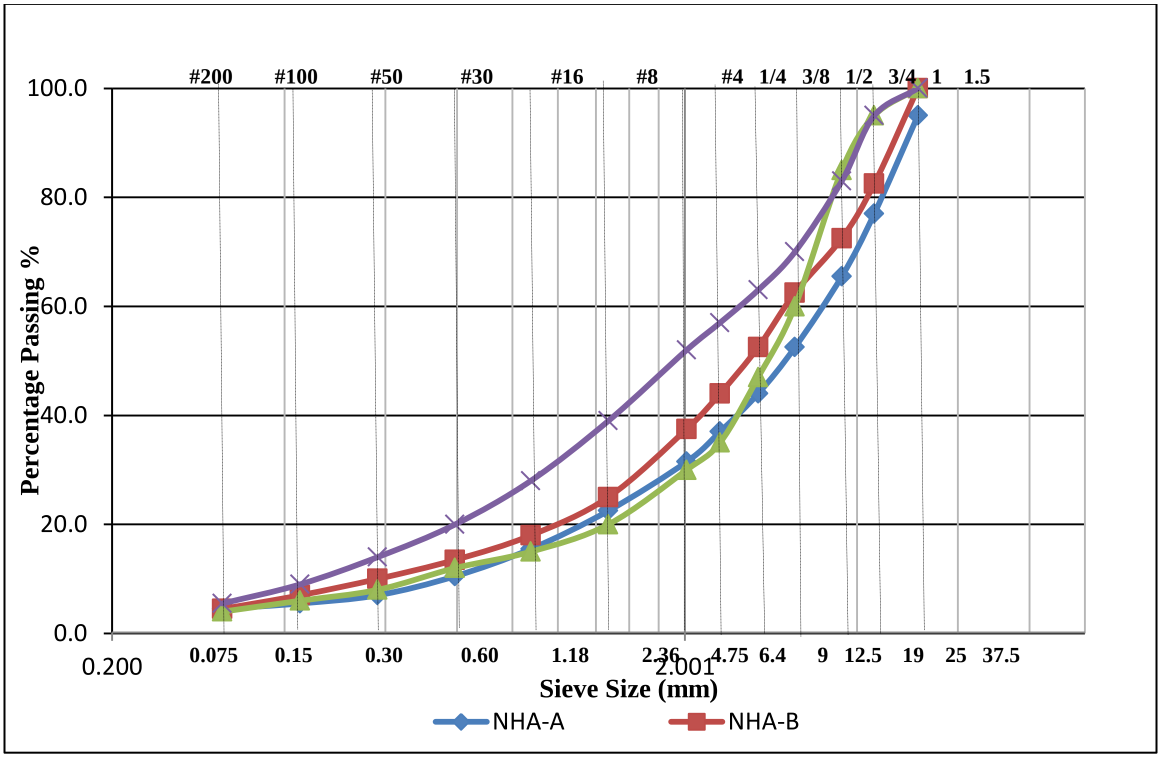

Figure 3. 3 Asphalt Base Course Mixtures - 0.45 Power Gradation Chart

axis whereas percentage passing is shown at Y-axis. Figures 3.3 is the curve generated for base course mixtures with the help of above given gradation table. These charts (shown in figure 3.2 and 3.3) could be used for calculating the percentage of the missing sieves.

3.3 Optimum Asphalt Content Determination

Optimum asphalt content calculation is the first stage to performance testing and volumetric properties were obtained through marshall mix design procedure. Following paragraphs explain the procedure.

3.3.1 Specimen Preparation and Testing

ASTM D6929 procedure, Standard Practice for the Preparation of Specimens using Marshall Apparatus, was used to prepare HMA mixes for AWC and ABC. Duplicate specimens were prepared per gradation type and tested accordingly. Standard marshall method (4" sample) was used for wearing course and modified marshall method (6" sample) was used for base course mixtures. Then prepared samples were tested with the help of marshall apparatus.

3.3.2 Material characterization

Gradation and bitumen quantity has quite significant impact on performance of any hot mix asphalt mixture. Volumetrics and performance properties determined using the results obtained from marshall testing are shown in tables 3.2 to 3.5.

Volumetric properties of the mixtures determined were Air voids (V_a), Voids filled asphalt (VFA), Voids filled with mineral aggregate (VMA), Bulk specific gravity (G_{mb})and the theoretical maximum specific gravity (G_{mm}). ASTM D2041 and ASTM D2726 were used for determination of theoretical maximum specific gravity (G_{mm}) and Bulk specific gravity respectively. Performance parameters flow and stability were calculated using ASTM D6927-06.

Table 3.2 Volumetrics - Wearing Course

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

Table 3. 3 Job Mix Formula - Wearing Course (Ali, 2014)

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

Volumetric properties of wearing course mixtures are shown in table 3.2 and in table 3.3 Job Mix Formulae (JMF) of wearing course mixtures are shown. NHA-A and NHA-B mixes have coarser gradations whereas SP-A and MS-2 are mixtures with high content of fines. Variation in gradation from coarser to finer impacts on optimum bitumen content required. Surface area for coarser gradation is less than finer ones, so higher optimum bitumen quantity is understandable for fine gradations. G_{mm}, G_{mb}, Flow and stability are also shown in table 3.3 with optimums and air voids. Results obtained satisfied the minimum criteria given in MS-2 manual for Marshall mix design.

Table 3. 4 Volumetrics - Base Course

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

Volumetric properties of base course mixtures are presented in table 3.4 and 3.5. Low optimum asphalt content is required for base course gradation than wearing mixtures. And it is well justified by difference in surface areas of these two different types of mixture. Same is the fact behind the difference in optimums within base course gradations, the coarser one requires lower binder content than the finer gradation lower side and quantity vary as per surface areas of their particle. Coarser the gradation, larger the particle size and lower the surface area thus optimum bitumen content required shall be less. All properties of base course mixtures also lie within specified criteria.

Table 3. 5 Job Mix Formula - Base Course (Ali, 2014)

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

3.4 Specimen Preparation

Based on optimum asphalt content and volumetric properties calculated using standard Marshall method, the specimens were prepared through Superpave gyratory compactor (SGC). Specimen specifications, preparation and procedure are same for performance testing of flow number, flow time and dynamic modulus specimens. Dynamic modulus test is a non-destructive testing and same specimen can be used for flow point test after tested for dynamic modulus. Mentioning again that this research is a component of national level research project and a number of tests are also part of this project. Being a part of national project Dynamic Modulus test had been performed by my colleague using same equipment. Researchers have scope of work with dynamic modulus test with one performance test of flow number or flow time can adopt same specimen practice to avoid wastage of time, efforts and resources. But for current study, flow number (repeated load) and flow time (static creep) both tests were included in study scope, so specimen tested for dynamic modulus were not sufficient both tests. So, it was decided to prepare all specimen fresh in order to avoid any possible error within replicates. Same standard was opted for specimen preparation, ASTM D6925-09 “Standard Practice for Preparation of Bituminous Mixture Specimens for Dynamic Modulus Testing”. Figure 3.4 shows a few of fresh prepared specimens. Specimen type and name was written on papers laid under each specimen. After the specimen cooled down in room temperature, each specimen name shifted over them with white marker. Size of specimens compacted at SGC are not same and neither aspect ratio. The oversized specimens prepared at SGC were 165 mm to 170 mm in height and 150mm in dia. For performance testing, required specimen size is 150mm height and 100mm dia. Besides to obtain proper aspect ratio in specimens (1:1.5 :: dia: height), these oversize specimens were prepared because specimen compacted at SGC has high air voids near surface which removed in coring and cutting.

Figure 3.4 Specimen prepared from Gyratory compactor

Cutting also provides a cushion to obtain smooth surfaces and remove parallelism. Parallelism is necessary to remove in a specimen for avoiding eccentric loading, ultimately gives underestimated performance evaluation. Each specimen was labeled on top as well as sides. To avoid time waste during core process, each specimen priory labeled on top carefully with precaution to readable after being reduced to 100 mm. Figure 3.5 shows specimens cored to targeted diameter alongwith wasted rings. Figure 3.6 shows the samples after trimmed form both edges and ready for testing.

Triplicate specimens were prepared for each mixture of wearing as well as base course and tested. Total forty eight specimens were prepared, twenty four for wearing course and same number of base course mixtures. Flow time and flow number testing was conducted on separate triplicates of each mixture.

Figure 3. 5 Gyratory prepared specimen cored with waste rings.

Figure 3. 6 Cored and trimmed SGC samples

3.5 Testing Equipment

Apparatus used in flow time and flow number performance tests is asphalt mix performance tester (AMPT) has also been known as Simple Performance Tester (SPT) in research work conducted earlier. Figure 3.7 shows AMPT machine used in this research. AMPT is being used internationally by Transportation agencies to develop necessary inputs for structural design of asphaltic pavements. Results obtained can be used for quality assurance and to predict asphaltic mixture's in-service performance quality. AMPT is a fully integrated asphaltic mixture testing machine with high performance hydraulic actuator. This machine is equipped with built in air cooling hydraulic pump, refrigeration and heating unit. An air driven compressor for confining pressure system is also a notable feature of machine. This equipment has integrated triaxial cell and environmental chamber with built in control unit featured with digital control. Testing machine has its own data acquisition and processing system. This testing machine is capable of application of compacted cyclic loading to asphalt mixture specimen over a wide range of temperatures as well as frequencies. This machine can assess asphalt mixture properties to evaluate potential performance. A salient feature of equipment is its own software and built in test modules for each test type (flow number, flow time, etc.) which are installed in computer system attached to it. Applied or testing parameters can be observed during the test alongwith respected deflections and strains at real time basis on monitor screen. Data recorded on computer hard drive is also accessible after test and can be exported in Microsoft excel file format.

Figure 3.7 Asphalt mixture performance tester.

3.6 Testing Parameters and Procedure

Each specimen is pre-conditioned at testing temperature for two (02) hours just prior to performance testing. Recommended time duration for pre-conditioning is shown in Table 3.6. After completion of pre-conditioning time, specimen is subjected to selected stress level. All tests are performed at 54.4 °C and 300 KPa stress level as recommended of conducting test at single temperature and stress level in earlier research work (Witczak et al. 2002).

Repeated load and static creep tests conducted at effective temperature and selected single stress level as per standards and specifications. Effective Temperature is defined as a single test temperature at which an amount of permanent deformation would exhibit equivalent to that measured by considering each season separately throughout the year. Pakistan lies in warm climatic countries and rutting is deformation related to high temperature, so high temperature is targeted for performance evaluation.

For selection of test conditions (confined or unconfined) and selection of stress level, the limitation of equipment is also kept under view. The available equipment is limited to apply maximum stress level of 460 KPa for one hour time duration. Therefore, confined test is not possible to conduct. The stress level opted for testing was 300 KPa (43.5 Psi). Trial tests had been conducted on various samples before selection of this stress level to ensure that in a suitable time most of these specimens would reach tertiary flow.

Termination of test is selected as maximum 5% of accumulated axial strain. 5% strain is target termination because the finite element studies shows that the half (0.5) inch (12.5 mm) rutting is expected at 5% strain. The maximum value of load repetition is set at 10, 000 seconds. Terminations shall be occurred upon maximum limit of strain or cycles whichever comes first.

Table 3. 6 Recommended Equilibrium Times (Witczak, 2002)

Specimen Test Temperature, °C (°F)	Time, hours
25 (77)	0.5
30 (86)	1.0
37.8 (100)	1.5
>54.4 (130)	2.0

Flow number test differs in stress application from flow time test. As in static loading is applied in flow time test and dynamic or repeated load is applied in flow number test in haversine wavelength form. A haversine type of loading is applied with pattern of 0.1 seconds loading followed by 0.9 seconds dwell period. Equivalent pulse time conversion for haversine loading at rate of 10 Hz frequency closely represents speed of 110 kmph, posted speed for heavy traffic on national highways.

The selected input parameters are inserted in testing equipment (AMPT). The test input parameters were entered in input module of software equipped with AMPT machine. Input parameters were project name, operator name, file name, posttest remarks, specimen information (specimen identification, conditioning, remarks, dimensions i.e. dia and height), test parameters (temperature, contact stress, confining stress) and duration of test (maximum number of cycles to terminate or maximum strain % achieved to terminate). And most importantly an option to select test run whether on flow number test mode or flow time test mode. Upper and lower friction reducer is also applied in between the sample and plates. When the specimen is placed inside AMPT chamber to avoid eccentric loading, specimen is centered visually within load actuator. After ensuring everything in test setup is alright and as desired, test is started and then test is watched till termination. Axial deformation was recorded against every load cycle using AMPT Flow, the software module of equipment. Figure 3.8 shows the sample condition after being tested for Flow number.

Figure 3. 8 Condition of samples after successful completion of FN test

3.7 Summary

Research methodology adopted for this research containing selection of gradations and asphaltic mixtures are report. Specimen preparation, equipment and laboratory test performed have been discussed herein detail. Total eight (08) mixtures were prepared in which half was wearing and other half was base course mixtures. Three replicates of these eight mixes were prepared for flow number test and another same number of mixes were prepared for flow time test. Source of aggregate is Margalla and binder source is ARL 60/70. Maximum Nominal aggregate size of wearing course is 19.0 and 12.5mm. For base course mixtures, is nominal maximum aggregate size is 37.5 mm and 25 mm.

Marshall mix design is used for mix design of gradation. Optimum asphalt content for each mixture is calculated using standard ASTM procedures which were calculation of flow, stability, Bulk specific gravity and theoretical maximum specific gravity. Similar procedure is repeated every time for each and every mixture. In this chapter volumetric properties are also shown in tabular form. Specimens are prepared at Superpave Gyratory compactor. After cross verifying the voids in prepared specimens these oversized specimens were cored then trimmed to get 100mm diameter into 150mm height sample Brief introduction of testing equipment, AMPT is given.

Flow time test procedure as well as flow time test procedure is briefly described used to conduct test. All tests are performed at 54.4 °C and 300 KPa stress level as recommended in earlier researches. The stress applied statically in flow time test whereas in repeated pattern for flow number test. The input fields and their parameters are also reported. Figures of samples after SGC preparation, cored sample with waste ring, trimmed sample are also shown in this chapter. Figures of samples before and after test are also presented.

Chapter 4

TEST RESULTS AND ANALYSES

4.1 General

This chapter includes the detailed analyses of data obtained from the experimental test results. Repeated load tests and static creep tests are conducted on wearing and base course mixtures prepared in laboratory according to test matrix shown in chapter 3. Triplicates specimen of each mixture are tested as per test procedure described in previous chapter. Flow number and Flow time results obtained from AMPT is firstly exported to excel data sheets from AMPT software file using APMT software named as AMPT Flow. Then data in these excel sheets are further used for analysis. Data smoothening technique is employed for removing error in order to obtain correct values of flow time and flow number. Five point moving average method is used for removing the resonance in raw data obtained from AMPT. Strain in microstrains against each cycle is reported by AMPT software, is used for obtaining strain rate. Using this strain rate graphs are plotted for calculating the corrected flow number value. Results obtained are presented hereafter with graphs and tables in a comprehensive form under flow number and flow time section headings.

4.2 Flow Number Test

Flow number test is conducted on mixtures at selected single effective temperature 54.4°C and unconfined single stress level of 300 KPa. The stress and temperature values are selected to capture the primary, secondary and tertiary phases of deformation of all mixtures within a reasonable time period. Haversine repeated load is applied with a waveform of 0.1 second loading time followed by 0.9 seconds rest period. Maximum allowed accumulated axial strain is 5% or test shall continue until 10,000 repeated load cycles.

Test specimens were conditioned for two (02) hours at effective test temperature. Before start of test input parameters were entered in input module of software equipped with AMPT machine. Input parameters were project name, operator name, file name, post-test remarks, specimen information (specimen identification, conditioning, remarks, dimensions i.e. diameter and height), test parameters (temperature, axial load, contact stress, confining stress) and duration of test (maximum number of cycles to terminate and maximum strain value achieved to terminate) and most importantly kind of test i.e. flow number test or flow time test. The test continued till the sample failed in tertiary zone or reached ten thousand (10,000) cycles. Tertiary phase of deformation is observed in all mixtures tested for flow number and test on all mixes were terminated before 10,000 cycles at their maximum allowed strain limit i.e. 50,000 miscrostrains. For flow number test, the parameters used for analysis are flow number value, cycle number at test termination and the slope intercept 'a'.

All specimens exhibit tertiary flow, so it is necessary to apply data smoothening on obtained test data. As the results of AMPT software determines the misrepresentative value of flow number and any understanding or decisions taken on basis of false value leads to wrong determination of sample characteristics and properties of flow.

4.2.1 Data Smoothening

As explained in chapter 2, the values shown by AMPT software are not the true representative of tertiary flow. Use of these false values may lead to incorrect design, so corrective measures are applied provided in literature to obtain correct values. AMPT software records the strain in microstrains against each cycle in its file format. Software also computes and reports the flow number value. Flow number value shown on software keep changing till the termination occur either set at maximum cycles reached or desired strain level (microstrain) occurred. Flow number given by equipment software is not the actual representation of flow number value. Therefore, corrective treatment is applied to obtain true values. Correction method in NCHRP report 513 by Bonaquist et al. (2003) is employed to find out actual flow number value (termed as corrected values in this research).

Using axial strain recorded in microstrains against each cycle by AMPT software, strain rate is calculated against each cycle. Strain rate against a designated cycle is obtained by half of difference of adjacent cycles. Then smoothening of strain rate moving average at five intervals is used. Figure 4.1 shows smoothened data after applying smoothening technique of moving average at five points. The coefficient of determination (R^2) of best fit line of smoothened data is also shown alongwith a fourth order polynomial equation. As the Flow number is the start point of tertiary deformation zone. The flow number can be reported as the lowest value point in relationship of rate of change of compliance to loading time. The plotted trend is too flat at bottom to obtain minimum value, plot is shown in appendix. Therefore, the relationship is plotted on log-log scale. In order to confirm flow number value visible as lowest on curve, the equation is solved by putting y as zero as Witczak et al, 2007 stated that theoretically flow number is cycle number corresponding to a rate of change of permanent strain equal to zero. Results obtained are smoothened as described above method and used for further analysis purpose.

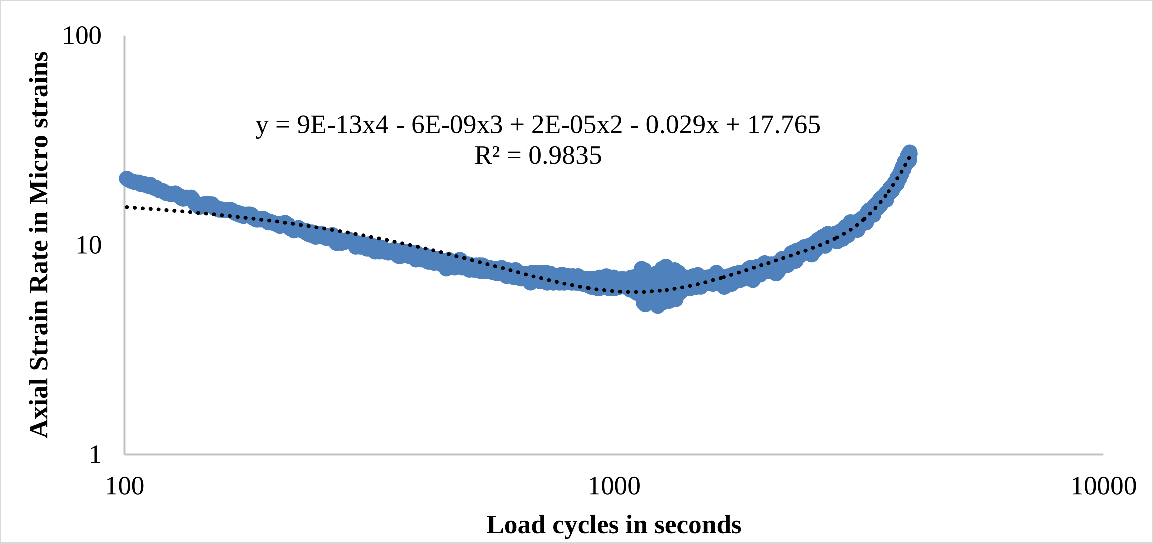

Figure 4. 1 Raw data obtained from AMPT software after smoothening.

4.3 Flow Number Results for Wearing Course Mixes

Flow number tests have been performed on wearing course mixes prepared and test conducted as per methodology detailed described in chapter 3. The results obtained after removal of any possible kind of error are presented in subsequent part of this section. Triplicate specimens for each mix were prepared and tested accordingly.

There are three phases of the accumulated strain versus time plot namely primary, secondary and tertiary. In the primary phase, the strain rate (slope of the permanent strain curve) decreases; in the secondary phase, the permanent strain rate is constant and in the tertiary phase the permanent strain rate dramatically increases. Figure 4.2 shows the accumulated strain is plotted against time for wearing course mixes and three phases of curve.

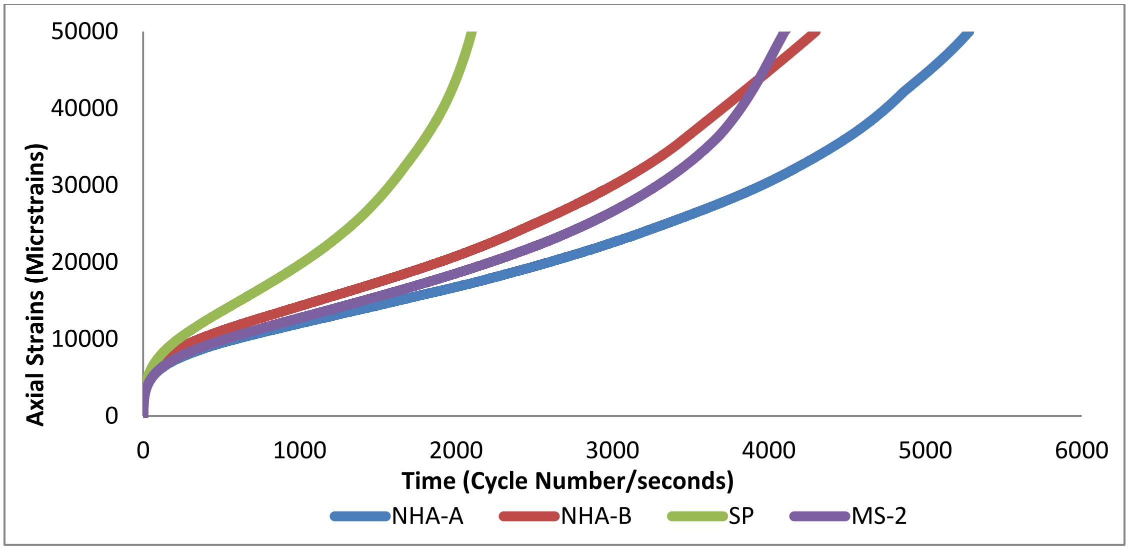

Figure 4. 2 Accumulated strain is plotted against time - wearing course mixes.

NHA-A has highest values of load cycles at all phases among the tested gradations which indicates that it takes more load repetition to achieve above mentioned three phases with respect to all mixtures tested. SP-A performed least among all as all three phases reached earliest depicting minimum load cycle values for all phases. In secondary phase of plot, the mixture's performance shall be ranked among the basis of longest and mildest secondary phase. NHA-A has longest and mildest phase among all mixtures depicting highest performance of blend under repetitive loading. NHA-B and MS-2 almost performed same in secondary zone with slight difference of microstrains values. SP-A had performed least against repetitive loading in secondary zone. The curve slope is steepest and the secondary phase starts earliest and also ended earliest. The cycle at which the third phase (tertiary zone) started is termed as flow number value. Figure 4.3 shows NHA-A has the maximum value for the end of secondary and start of tertiary phase. Table 4.2 presents the exact value of flow number, obtained from AMPT software as well as the corrected values after applying smoothening. The highest performance shall be of mix having highest value of cycle at target terminated strain i.e. 5%. NHA-A has highest value for termination, following NHA-B, MS-2 and the least value observed is for SP-A wearing mixture. As reported in chapter two, the 5% strain is target termination because the finite element studies shows that the half (0.5) inch (12.5 mm) rutting is expected at 5% strain. After applying the data smoothening, the shift in flow number value is shown in Figure 4.3.

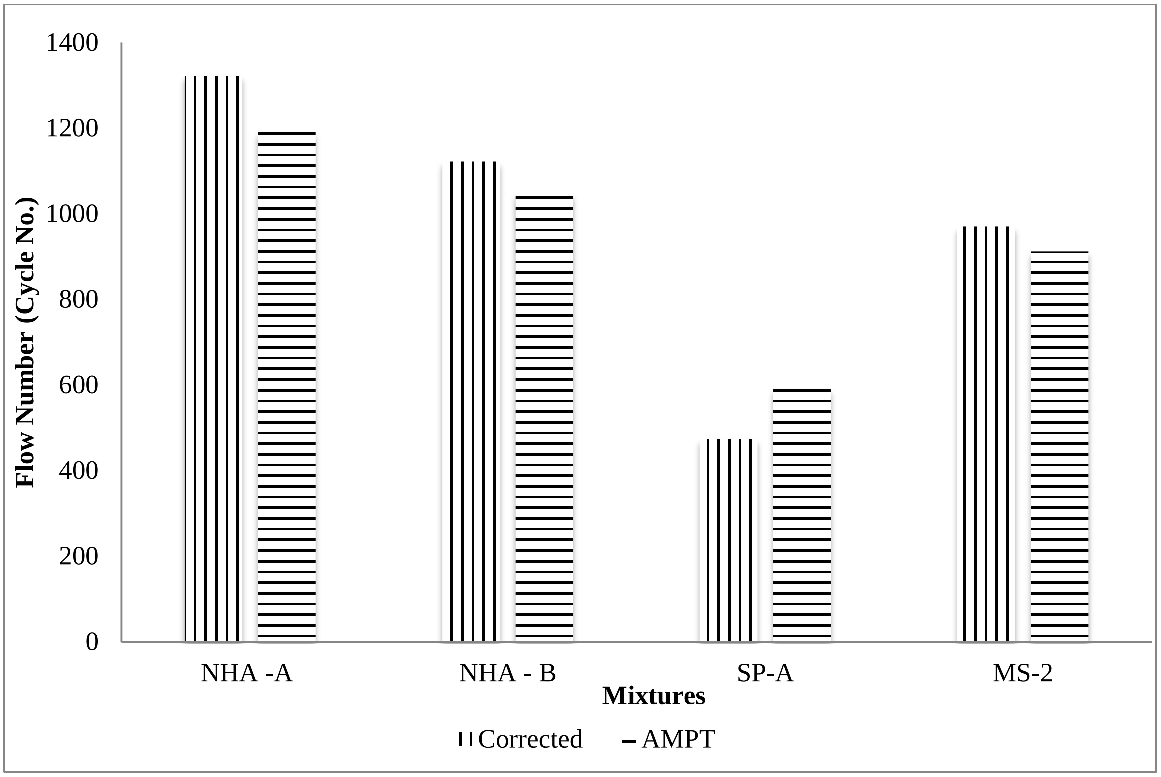

Figure 4. 3 Comparison of corrected flow number value with AMPT flow number values

Witczak et al. (2007) investigate the effect of mix and loading variables on three material strain parameters at flow point. Three parameters investigated were total compliance at flow ($D(t)_f$) for static creep flow time test, plastic strain at flow number (ϵ_{pf}) for repeated load flow time test and ratio of plastic to resilient strain at flow number (ϵ_{pf}/ϵ_r)for repeated load flow time test. Table 4.1 shows the summary of their findings for lab blends under unconfined stress as;

Table 4.1 Factors Affecting Strain at Flow for Lab Blends. (Witczak et al. 2007)

Factors	ϵ_{pf}	ϵ_{pf}/ϵ_r	$(D(t)_f)$
Confinement Level	Y	Y	Y
Temperature	N	Y	N
Mix Type	Y	Y	Y
Binder Type	Y	Y	Y
Binder Content	Y	N	Y
Air Voids	Y	Y	Y

Where, Y= effect is significant and N= effect is not significant

NHA-A is the coarser mix, having least amount of binder content with design air voids and has the highest performance among wearing mixtures. It is inferred from the corrected values of flow number shown in figure 4.3. NHA-B performs second under design stress and temperature, MS-2 is ranked third among wearing course mixes and SP-A performs least and it can justified as mix having high asphalt content will be perform badly. Although MS-2 is finer than SP-A but MS-2 mix has relatively high coarser part which yields its better performance under repeated loads than mix SP-A.

In figure 4.4, comparison of accumulated strain in microstrain is plotted against flow number of wearing mixtures. Mixes shall not be compared against accumulated strain at their flow number cycles because of difference in cycle number (time). For comparison purpose; accumulated strains at target termination strain value against mix type is recommended. In case termination occurred at number of cycles instead of strain then an intermediate cycle, say two thousand (2000) can be used. NHA-A has slightly high value of strain at flow number point than MS-2 mix, the reason is difference of flow number cycle. In case of MS-2, tertiary phase started at 352 seconds earlier than the NHA-A while for another three hundred and fifty two (352) seconds, NHA-A wearing mix has taken successfully repetitive loading till its secondary phase ended and tertiary phase started. Similarly, SP-A has slightly low value than NHA-B but the time difference of starting of tertiary zone in this case is six hundred and forty eight (648) seconds.

Tertiary flow is occurred in all mixtures of wearing course in current research, so the termination cycles at same strain level i.e. 5% is plotted against mix type in figure 4.5. NHA-A has undergone highest number of cycles to achieve target termination of strain, hence, NHA-A is more rut resistance than all other mixtures. The wearing course mixes designated NHA-B is second highly rut resistance mix then MS-2 and least rut resistant mix is SP-A.

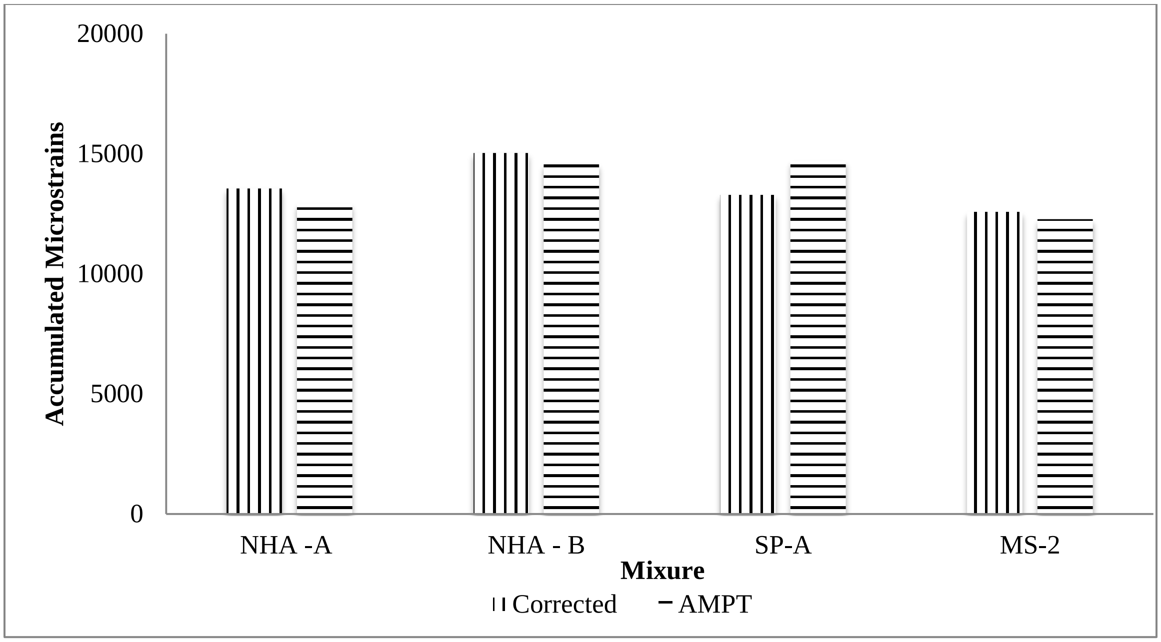

Figure 4. 4 Accumulated strains at Flow number cycle - Wearing course mixtures

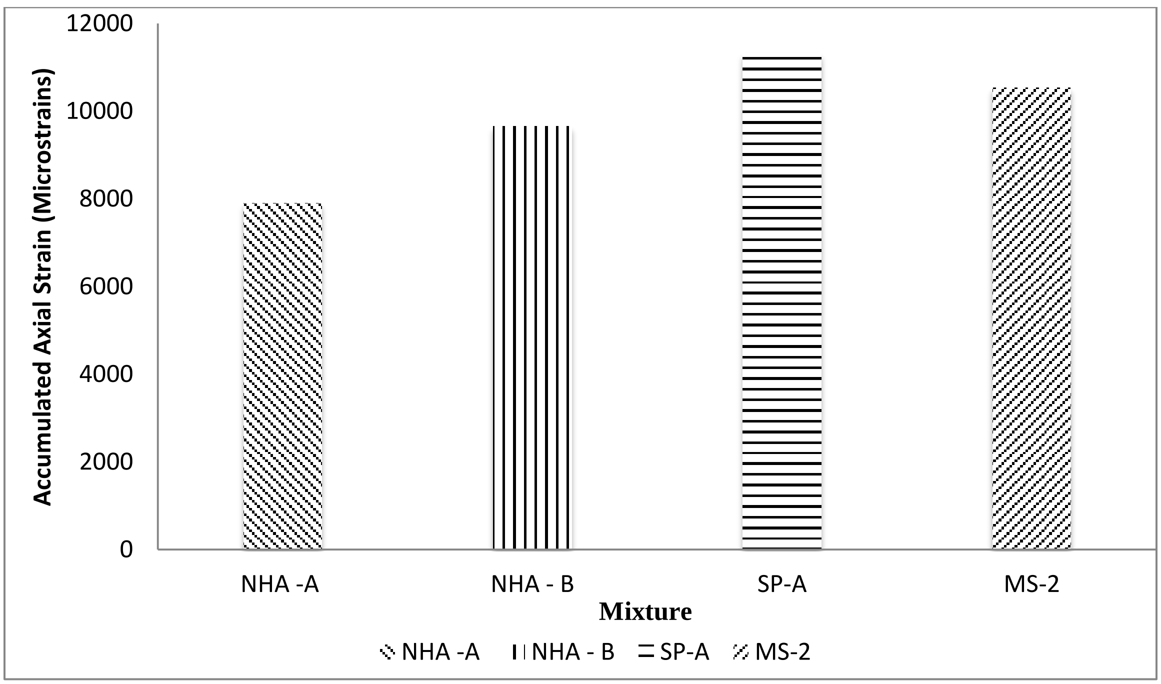

Figure 4. 5 Total number of cycles at termination by strain - Wearing course mixtures

A comprehensive summary of results obtained for flow number for wearing course mixtures is presented in table 4.2.

Table 4. 2 Wearing layer mixtures-Comprehensive Result Summary of Flow Number Test

Mix	FN Value (Seconds)		Acc. Strain @ FN (microstrains)		At Termination		COV (%)
	Corrected	AMPT	Corrected	AMPT	Acc. Strain	Cycles	
NHA -A	1322	1191	13552	12928	50004	5282	5.49
NHA - B	1122	1047	15031	14571	50007	4300	5.93
SP-A	474	591	13296	14698	50060	2102	11.01
MS-2	970	912	12586	12277	50036	4102	6.48

Ranking is made on the basis of corrected flow number value. Values mentioned under heading of AMPT are those obtained from AMPT software. “Corrected” ones are those obtained from the graphs plotted after removal of resonance in raw data as described in previous section. Values reported under ‘AMPT’ accumulated strain at flow number are those reported by software against its reported flow number. The accumulated strain values against corrected flow number in datasheet are reported under corrected accumulated strain values at flow number cycle. Strain rate in SP-A mix observed very high. Although the slight shift may lead to remarkable difference and there is difference in corrected versus AMPT reported values are significantly high revealing the significance of correction.

The flow number value and number of cycles taken by mix before termination of test at achieving 5% accumulated strain is also significant factors to detect mixture performance is better against rutting. Mixtures if ranked on basis of number of cycles at 5% accumulated strain then again these would have same position. Beside these two factors, Witczak et al. (2002) also determined regression coefficients intercept ‘a’ and slope ‘b’ for investigation of flow number in NCHRP report 465. Regression coefficients can be obtained from secondary zone of the log of compliance to log of time plot. Witczak et al. (2002) reported that regression constant ignores the tertiary zone of material deformability and are dependent on the material-test conditions. In order to obtain these two parameters, total permanent strain against number of load cycles is plotted for all mixtures. These plots should neglect the strain values after the flow number, as flow number is the start of tertiary phase and these two parameters ignores the tertiary zone, so for obtaining the correct value, one should restrict the strain values till the secondary phase. Then the line on the part of curve having the linear portion most is plotted. The regression best fit line gives the value of ‘a’ and ‘b’. These regression coefficients are general indicator of inelastic deformation behavior of asphaltic material. Witczak et al. (2002) reported that higher the value of ‘a’, higher the permanent deformation.The flow number is recorded where the minimum slope occurs. Table 4.3 shows the value of intercept ‘a’ and slope ’b’ for the wearing mixes.

Table 4. 3 Regression Coefficients ‘a’ and ‘b’ - Wearing Course Mixtures.

Mix	Slope 'b'	Intercept 'a'
NHA-A	6.352	5765
NHA-B	8.104	6554
SP-A	18.307	5380
MS-2	8.111	5380

SP-A has the largest value of intercept ‘a’ as it can be seen in above table; it should have the largest permanent deformation. For wearing mix, NHA-A has the least value of intercept shows that it is more rut resistance than all other mixtures. Ranking will not be changed if done on basis of intercept value ‘a’. As mentioned earlier slope parameter ‘b’ reflects deformation in case of constant value of slope intercept ‘a’. As ‘a’ values in Table 4.3 are not constant, so ‘b’ cannot be used for reflection of deformation against observed flow number test results.

4.4 Flow Number Results for Base Course Mixtures

Triplicate specimens of four different mixtures for base course are prepared and tested for repeated load test (flow number test). There are three phases of the accumulated strain versus time plot. Figure 4.6 shows these phases of permanent deformation of tested base course mixtures. Data smoothening techniques is applied on results obtained on all testes base course specimens. Accumulated strains against load cycles are plotted of each mixture in figure shown below. The minimum value reported corresponding to the flow number cycle is known as flow number value. The strain rate plot versus loading times is developed in order to obtain minimum value as shown in appendix but these generates plots give flat curves and minimum value is not possible to obtain. Therefore, strain rate is plotted against load time on log to log scale.

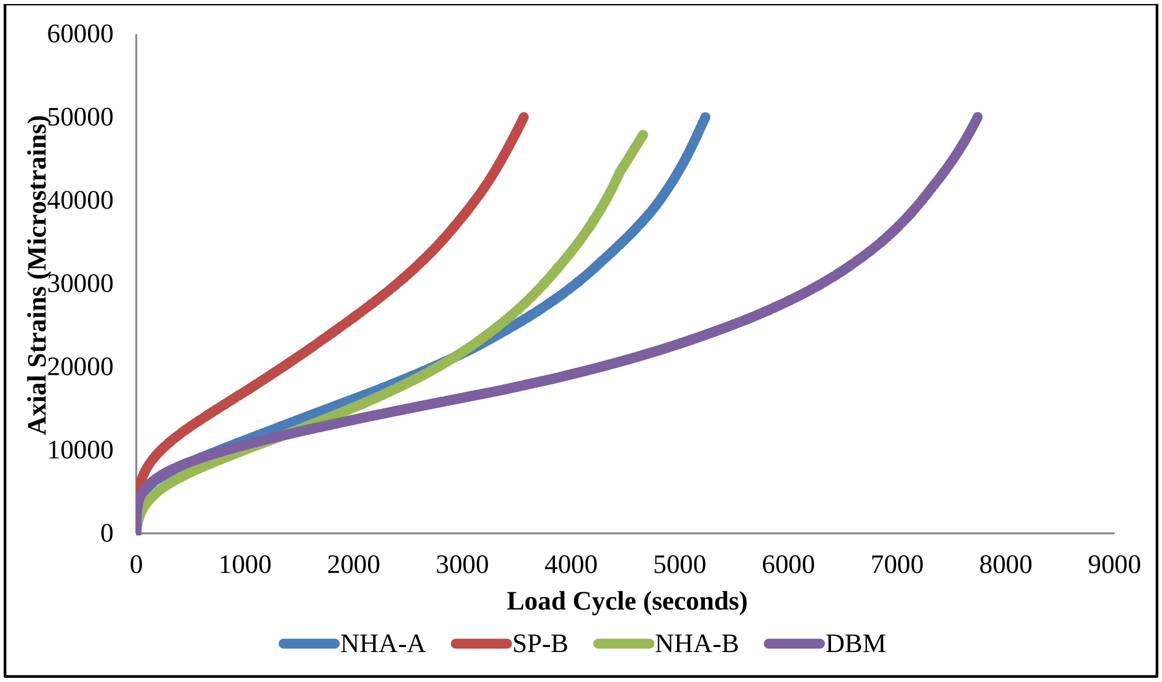

Figure 4. 6 Plot of Accumulated strain versus time - base course mixes.

Primary phase termination of NHA-B is at highest value, NHA-A & DBM both mixes primary phase ended after NHA-B. SP-B's primary phase ends quickly and secondary phase started as primary zones ended. It is worth mentioning here that the secondary phase plays an important role in determination of flow number value. DBM has longest secondary phase with largest straight portion. It shows the flow number value should be very high and it is depicted from the figure 4.7. NHA-A performance is at second highest after DBM mix then NHA-B performed and SP-B has least performance under repetitive load.

Tertiary flow is observed in all mixtures, so smoothening will be applied on all mixtures as described in detail in previous sections of this chapter. The smoothened data values are used for further investigation of base course rut susceptibility. Figure 4.7 shows the bar chart comparison of flow number values obtained from AMPT software and corrected values after data smoothening.

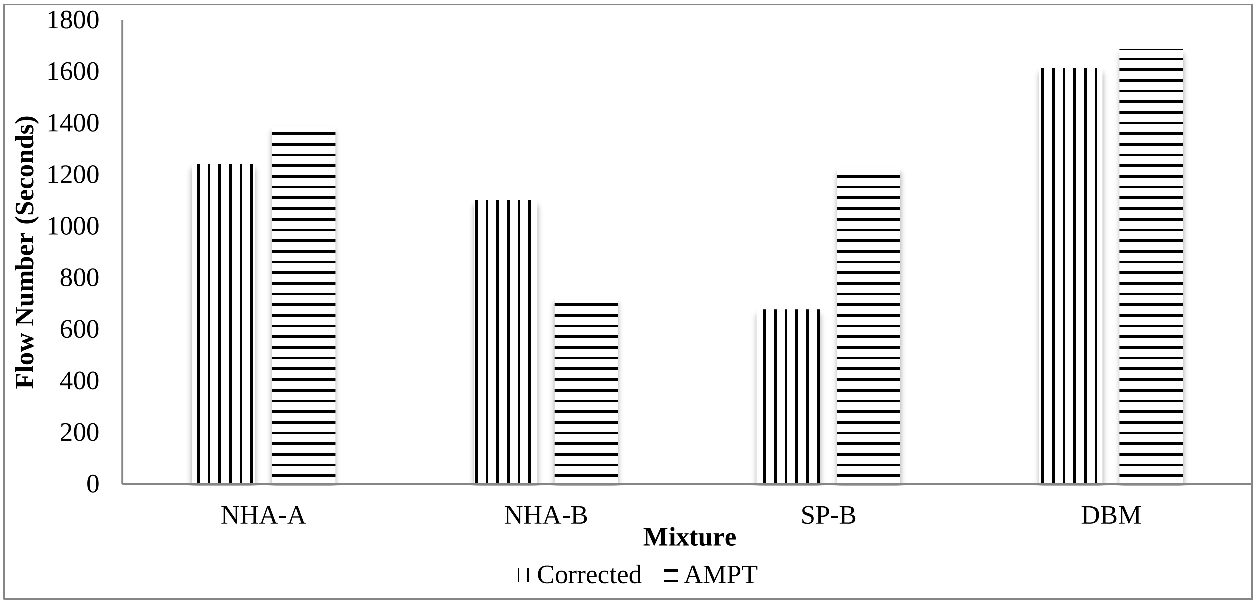

Figure 4. 7 Comparison of corrected flow number value with AMPT flow number values

Variation between reported AMPT and corrected flow number values in base course mixtures results are observed more than in wearing mixtures. Corrected values of DBM base mix is highest, so ranked first among base course mixtures, whereas NHA-A is ranked second and then the value of NHA-B and least value for flow number is of SP-B mix. As mentioned in table 4.2, mix type is also a significant factor which affects the flow number value. Moreover the asphalt content in base mixtures is less than wearing mixtures.

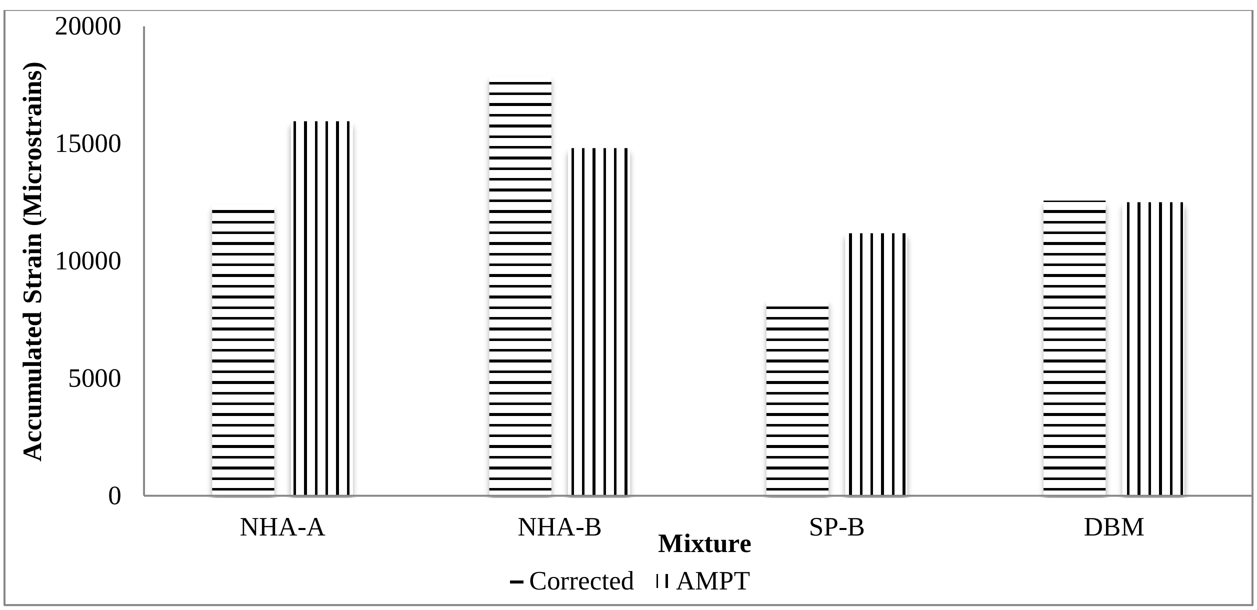

Figure 4. 8 Comparison of corrected and AMPT accumulated strain values at flow no. cycle

Accumulated axial strain (microstrains) at flow number cycle reported by AMPT software and value calculated after smoothening is presented in figure 4.8. Although the flow number value of base course mixtures ranked the mixtures but for confirmation a comparison of flow number cycle at 5% axial strain (microstrains) i.e. at termination of test is presented in figure 4.9.

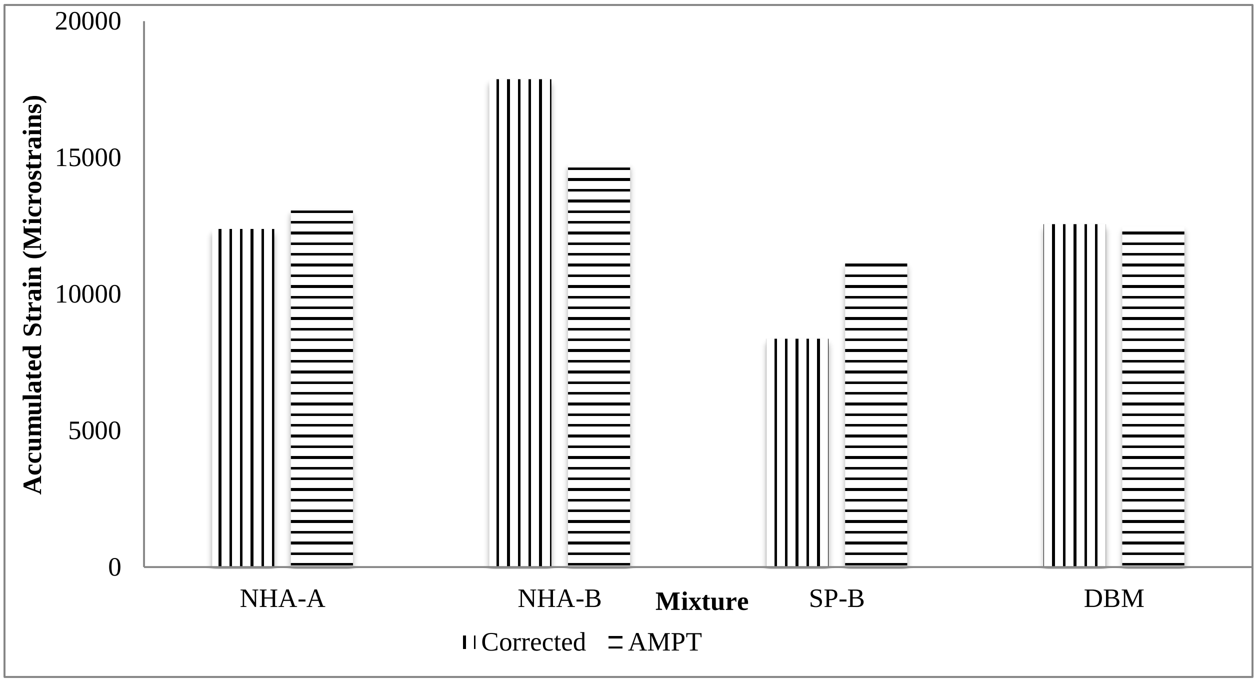

Figure 4. 9 Total number of cycles at termination by strain - Base course mixtures

The comprehensive summary of base course mixtures result is presented in in table 4.4.

Table 4. 4 Base Course Mixtures-Comprehensive Result Summary of Flow Number Test

Mix	FN Value (Seconds)		Acc. Strain @ FN (microstrains)		At Termination		COV (%)
	Corrected	AMPT	Corrected	AMPT	Acc. Strain	Cycles	
NHA-A	1242	1388	12387	13114	50002	5236	4.52
NHA-B	1101	726	17877	14805	50011	4766	13.19
SP-B	678	1230	8372	11186	50004	3565	7.65
DBM	1613	1687	12572	12498	50023	6372	5.90

Ranking is made on basis of average flow number value of mixtures. ‘AMPT’ flow number values are those obtained from AMPT software and values calculated after data smoothening termed as ‘corrected’. Similarly the values presented in accumulated strain at flow number, the values reported by AMPT software against its recorded flow number cycle by itself are presented here as ‘AMPT’ and the ‘corrected’ ones are those against the corrected flow number cycle.

Regression constants intercept ‘a’ and slope ‘b’ were also obtained after plotting total strain versus number of cycles (as shown in table 4.5) in order to check the resistance to plastic deformation of mixtures. It is shown that the intercept value for SP-B is largest, hence, this mix is most susceptible to rutting and the lowest value is observed for DBM mix depicting that this mixture is more rut resistance among tested base mixtures.

Table 4. 5 Regression Coefficients ‘a’ and ‘b’ - Base Course Mixtures

Mix	Slope 'b'	Intercept 'a'
NHA-A	6.217	5093
NHA-B	7.0729	3365
SP-B	12.952	6370
DBM	5.1723	5273

4.5 Recommended Minimum Flow Number Value

Mixtures are being ranked as per their relative performance to determine whether the flow number values of these mixtures are acceptable or not, this section developed. Bonaquist et al. (2011) mentioned the recommendation of NCHRP 9-33 in given tabular form for the minimum flow number criteria against traffic level.

Table 4. 6 Recommended Minimum Flow Number Values in NCHRP 9-33

Traffic Level (Million ESALs)	Minimum Flow Number (Cycle)
<3	-
3 to <10	50
10 to <30	190
≥30	740

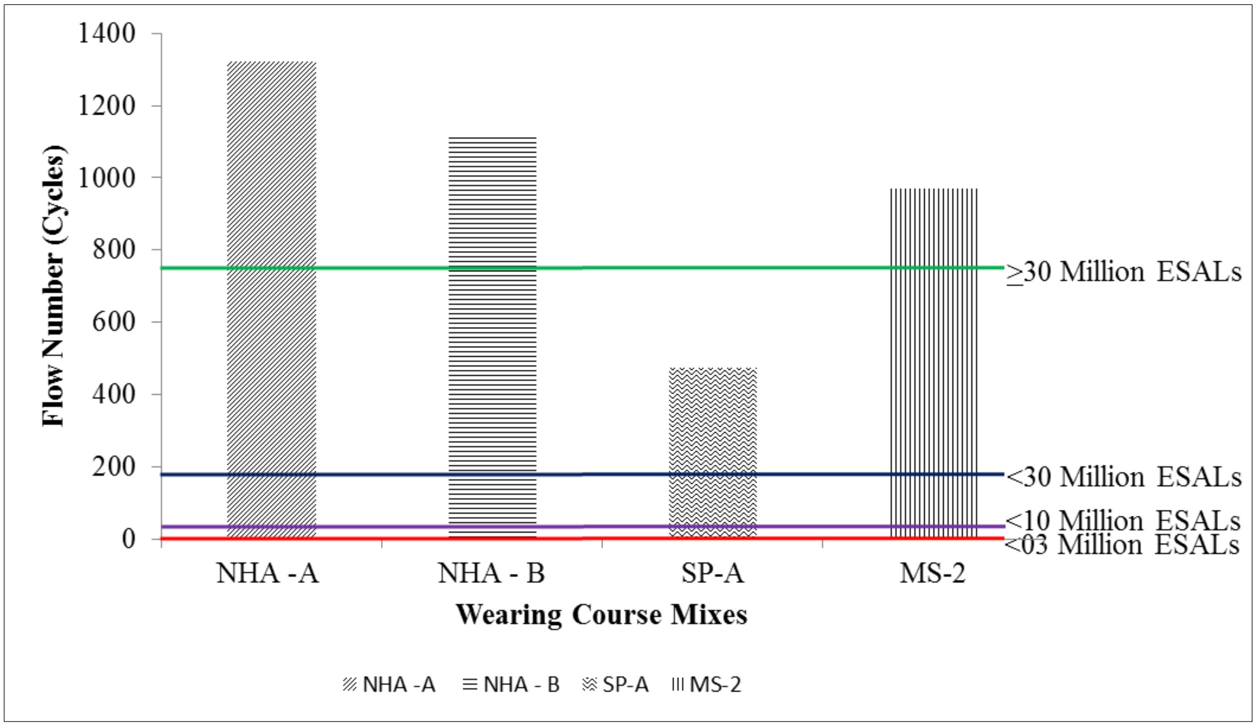

Figure 4.10 Flow Number Values with Traffic Level-Wearing Course Mixtures

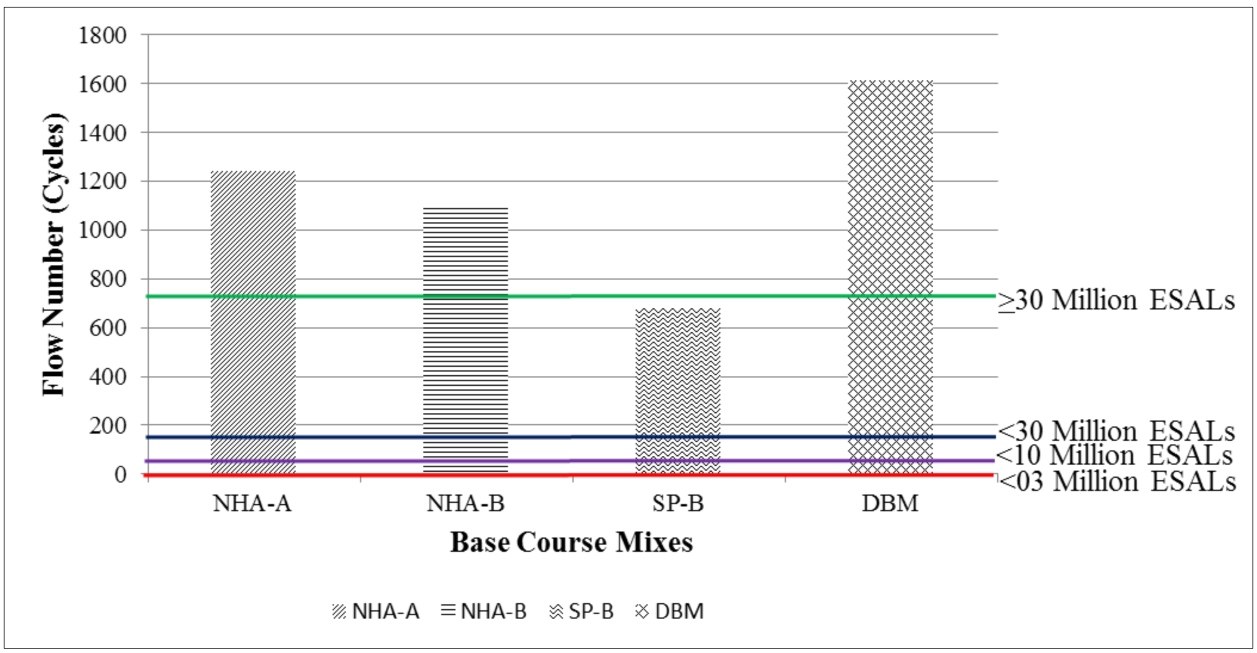

Figure 4.11 Flow Number Values with Traffic Level-Base Course Mixtures

For wearing mixtures, NHA-A, NHA-B and MS-2 crossed each category of traffic level. For traffic level of ≥30 Million ESALs, SP-A is not recommended in the light of above criteria.

For base course mixtures, SP-B is not recommended for traffic level ≥30Million ESALs. Remaining all mixtures can be considered as an option for all traffic levels.

4.6 Flow Time Results

Flow time or static creep test was conducted on triplicate specimens of each mixture at a static stress level of 300 KPa and single effective temperature 54.4°C. The stress and temperature are same as used in flow number test. The results obtained from flow time tests shows that no mixture yields the tertiary phase of deformation. Hence, data smoothening is not applied and data obtained from AMPT software is used for further analysis. As mentioned, the tertiary phase of deformation is not observed in any mixture, the analysis is restricted to the comparison of accumulated strain only. Table 4.7 shows the flow time results for wearing course mixtures.

Wearing			**Base**		
Mixtures	**Cycles**	**Acc. Strain**	**Mixes**	**Cycles**	**Acc. Strain**
NHA -A	> 10000	7894	NHA-A	> 10000	7831
NHA - B	> 10000	9658	NHA-B	> 10000	9337
SP-A	> 10000	11319	SP-B	> 10000	10286
MS-2	> 10000	10530	DBM	> 10000	5769

Table 4. 7 Accumulated strain values at termination

Flow time value for all mixtures is greater than or equal to ten thousand seconds as tertiary flow is not exhibited. Figure 4.10 is the plot showing a comparison of accumulated strain at termination.

Base course mixtures are tested for flow time test with same parameter and procedure as of wearing course mixtures. The results obtained are presented in table 4.7 and in figure 4.11. At intermediate cycles, the same performance trend is observed but with minimum differences among the mixtures accumulated strain. As we moved towards the maximum number of cycle, strain rate increases but the ranking trend remained same. So, the accumulated axial strain is tabulated as well as plotted against maximum number of cycle just to show some significant difference of strain values of mixtures with each other.

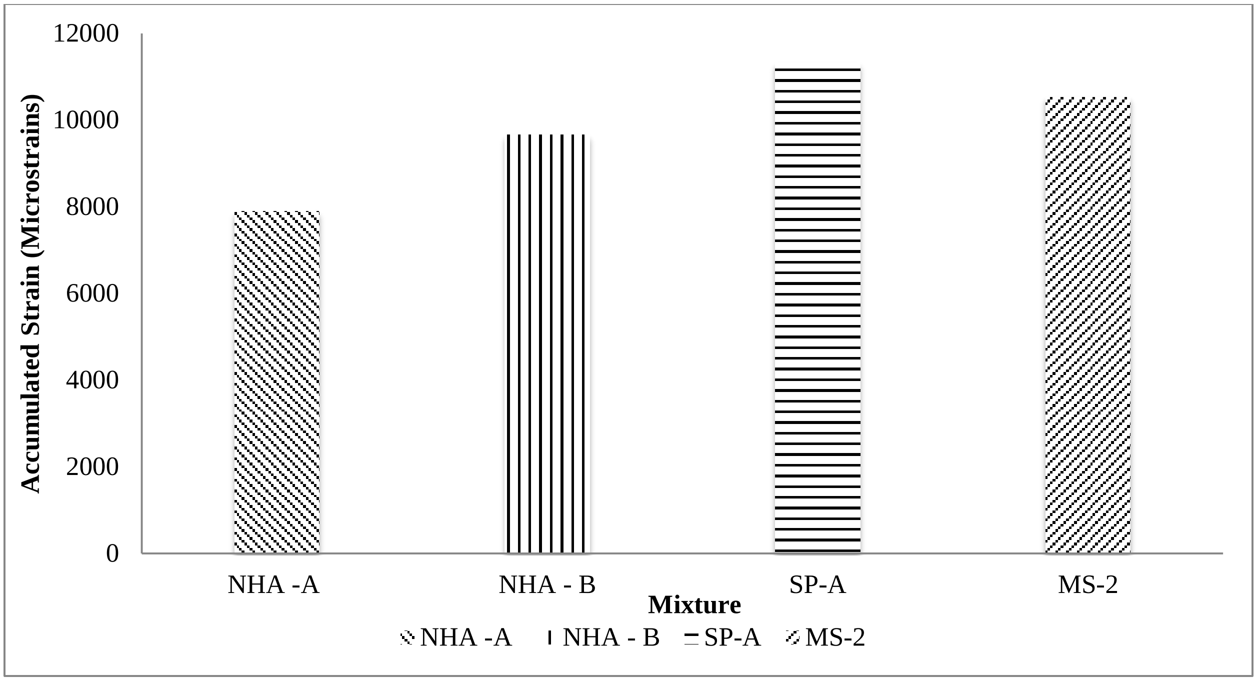

Figure 4. 10 Accumulated strain values at same cycle number 10,000.

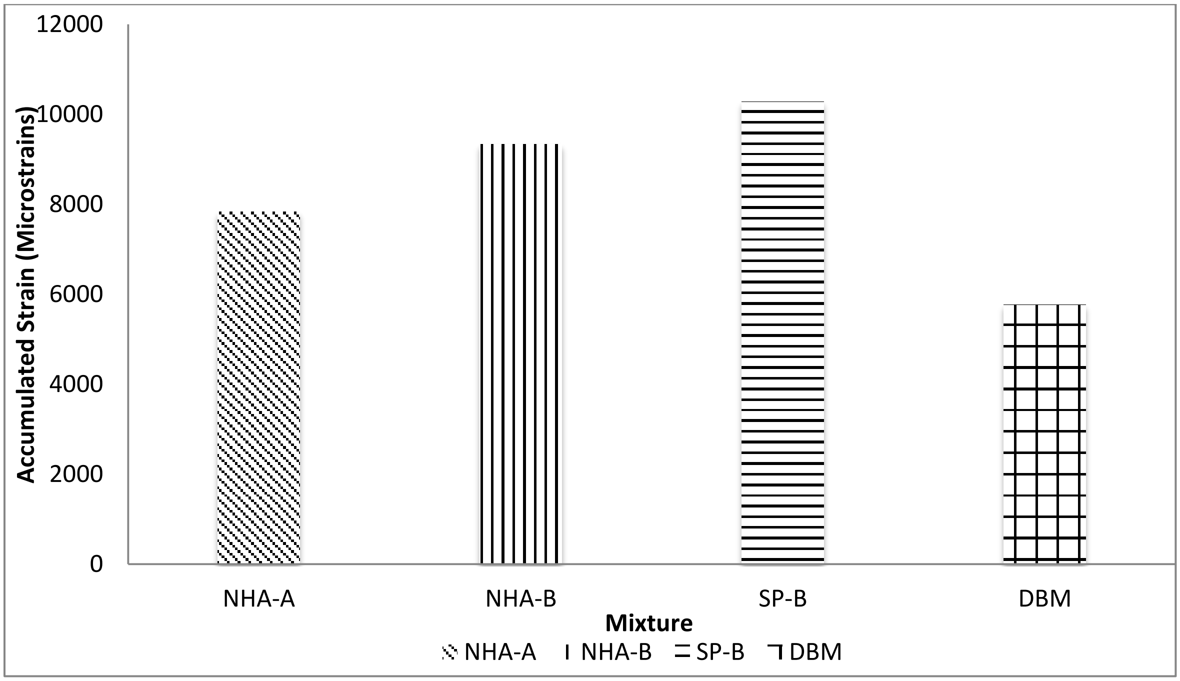

Table 4.11 Accumulated strain values at termination - Base course.

4.7 Summary

Smoothening is applied to the test results exhibited tertiary zone only. Specimens tested for flow number value experienced tertiary flow of deformation so flow number results are smoothened. On the other hand, flow time test results don't exhibit tertiary deformation so data smoothening is not applied for flow time results. Variation observed in flow number values of AMPT reported data and corrected values. For flow number test, flow number values are reported supporting with the regression analysis and cycle number comparison at highest & same level of axial strain i-e 5%. Total permanent strain plotted against number of cycles gives the regression constants, 'a' intercept and 'b' slope. Both values are reported but only intercept value 'a' is interpreted. Tertiary flow is not occurred in flow time tests, so the analysis is limited to comparison of accumulated axial strain observed at the time of termination, hence intermediate cycle can be selected. As the trend is same at all intermediate cycles, so for better visualization of plots, accumulated strain at highest cycle number is used for comparison. The analysis indicated that NHA-A wearing course mix and DBM base course mix had relatively better resistance to rutting among tested mixtures. Models for individual mixtures for wearing and base course as well combined models for wearing and base course mixtures in developed.

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Repeated load and static creep tests were conducted on eight mixures, four wearing and four base courses. Specimens were prepared using superpave gyratory compactor, cores extracted and then sawed to obtain 150mm high and 100 mm diameter specimen. These specimen are tested in asphalt mixture performance tester to investigate the performance of mixes for rutting susceptibility using repeated load tests and static creep tests. Total six replicates are tested, three for flow number (repeated load) and three for flow time (static creep) tests under single effective test temperature 54.4 ^{o}C (130 F) and at single stress level of 300 KPa (43.5 psi) with confining pressure kept at zero. Conditioning is done for 02 hours of all specimens at test temperature before start of test.

Results obtained from these test runs are scrutinized for possible errors. Smoothening technique is applied to specimens tested for flow number value experienced tertiary flow of deformation. On the other hand, flow time test results don't exhibit tertiary deformation, so, data smoothening is not applied for flow time results. For analysis, flow number test has more potential as tertiary flow is exhibited than the flow time results in which the tertiary flow is not observed.

After removal of data resonance, flow number values were reported using separate plots and tables. Performance of mixture was compared using the cycle number when tertiary flow starts. For flow number test results, mixtures were also compared for cycle number at the strain level of 5% i.e. the termination value or maximum value of strain. Regression analysis of total permanent strain versus number of cycles gives the regression constants, 'a' intercept and 'b' slope. Both values are reported but only intercept value 'a' can be used. Slope 'b' can only be used if plots yield same intercept 'a' values.

Tertiary flow was not observed in flow time tests, so the analysis was restricted to comparison of observed accumulated axial strain at the time of termination. As the performance trend based on accumulated strain was observed same at all intermediate cycles, so for enhanced visualization of plots, comparison of accumulated strain at maximum cycle number was used.

5.2 Conclusions

Results obtained from flow number tests showed that performance of NHA-A is highest amongst wearing course mixtures. For wearing course mixture, in analysis of ‘flow number values’ at tertiary flow , NHA-A is observed highest depicting the tertiary phase of deformation exhibited at highest number of cycle. For better field correlation, if number of cycle is assumed as vehicle count then NHA-A has the ability to cater the most vehicle counts than other tested wearing course mixtures. In second analysis, flow number cycle at the termination of test, again NHA-A takes more number of cycles than any other tested wearing course mixture. In third and last analysis, NHA-A has the lowest intercept value ‘a’ of regression analysis of plot of permanent strain versus number of cycle. NHA-A has the lowest value of intercept ‘a’ shows that the mixture has highest resistance to rutting. On the other hand, SP-A observed at last rank among wearing course mixtures in all three analysis of flow number test results. The wearing course mixtures are ranked on basis of their performance shown by all three analysis as; NHA-A>NHA-B> MS-2 >SP-A. SP-A is not recommended for traffic level with $\geq$30Million ESALs.

For base course mixtures, same kind of analyses was made as done for wearing course mixtures. Results showed that performance of DBM mix is consistently highest amongst base course mixtures in all comparisons. Flow number values at start of third phase of deformation shows that DBM mix has highest value indicating that tertiary phase of deformation experienced at highest number of cycle. When flow number cycle at the termination of test was compared, again DBM mix takes more number of cycles than any other tested base course mixture. In third and last analysis, DMB mix has the lowest intercept value ‘a’ of regression analysis of plot of permanent strain versus number of cycle. The lowest value of intercept ‘a’ is associated with mixture having higher rutting resistance. On the other hand, SP-B continuously observed at last rank among base course mixtures in all three analysis of flow number test results. The base course mixtures are ranked on basis of their comparison of performances as; DBM>NHA-A>NHA-B> SP-B. SP-B is not recommended for traffic level with $\geq$30Million ESALs.

Tertiary flow was not experienced for flow time tests which limit analyses to comparison of accumulated strain at same cycle number. This comparison of flow time values complimented the results of flow time tests. Accumulated strain comparison at maximum cycle’s number shows ranking of mixtures. For Wearing course mixtures as NHA-A>NHA-B> MS-2 >SP-A and for base course mixtures as DBM>NHA-A>NHA-B> SP-B.

5.3.1 Contribution to State-of-the-Practice

Current study is being a part of national research study carried out by Pakistan's National Highway Authority (NHA) in collaboration with NUST. The title of this research is 'Improvement of asphalt mix design technology of Pakistan'. Current research study examines the performance attributes of selected specimens against rutting susceptibility. The findings of this study would facilitate the pavement engineers/ practitioners in selection of rut resistant wearing and base course mixtures, as the rutting is the most serious distress observed in pavements of Pakistan. Moreover, selected stress level is kept higher to cater higher load experienced at national highways. Flow number test can be used in job mix formula (JMF) to ensure adequate rutting resistance. Moreover, flow number tests completed in reasonable time frame and gives good analysis spectrum. So, it is recommended to employ flow number test for performance testing of job mix formulae along with other tests before approval. The results of this study (flow number and flow time tests) can be correlated with other rutting evaluation tests (Asphalt pavement analyzer & Hamburg wheel tracker) to better characterize the rutting propensity of HMA mixtures.

5.4 Recommendations

This study focuses on examination of performance of mixtures against rutting using AMPT. Other performance tests like Asphalt pavement analyzer, Hamburg wheel tracker and indirect tensile strength should be carried out on same mixtures to fully capture the characteristics of these mixtures. As mentioned earlier, this is the part of a bigger study and dynamic modulus tests have been conducted on same mixtures. A short comparative study can be done by conducting the flow number test on these samples using same parameters in current study.

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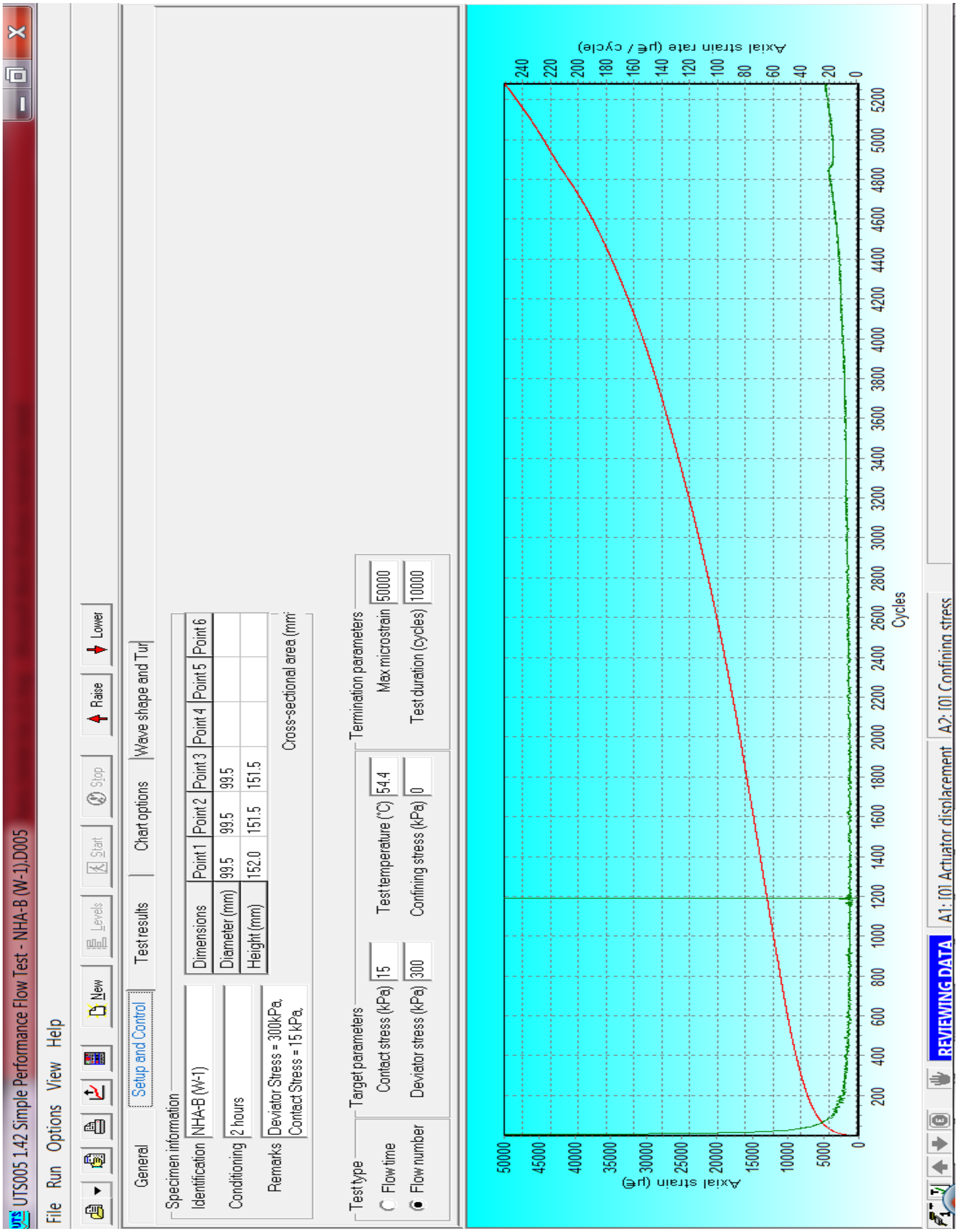
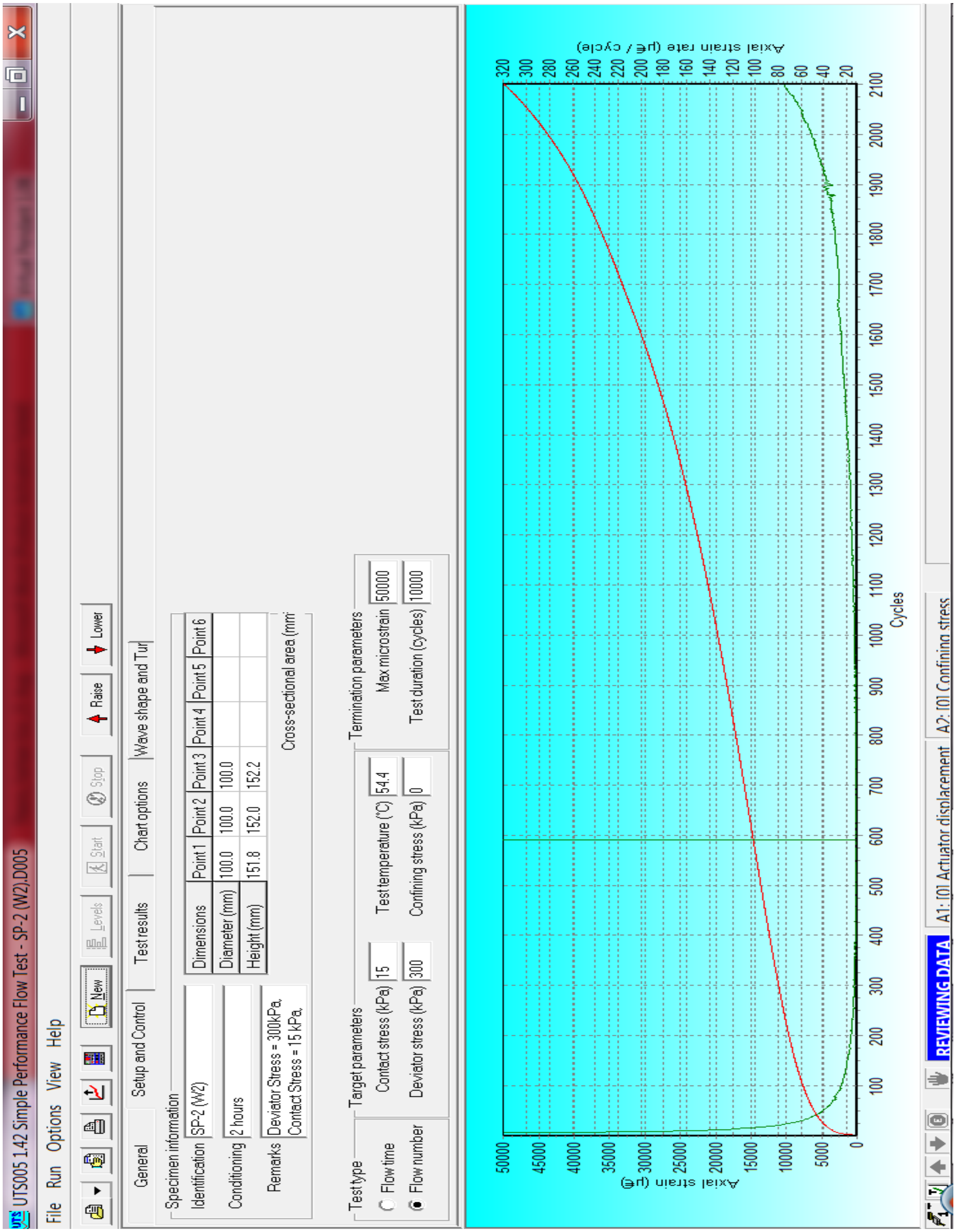
APPENDICES

APPENDIX-I: AMPT FLOW NUMBER TEST RESULT

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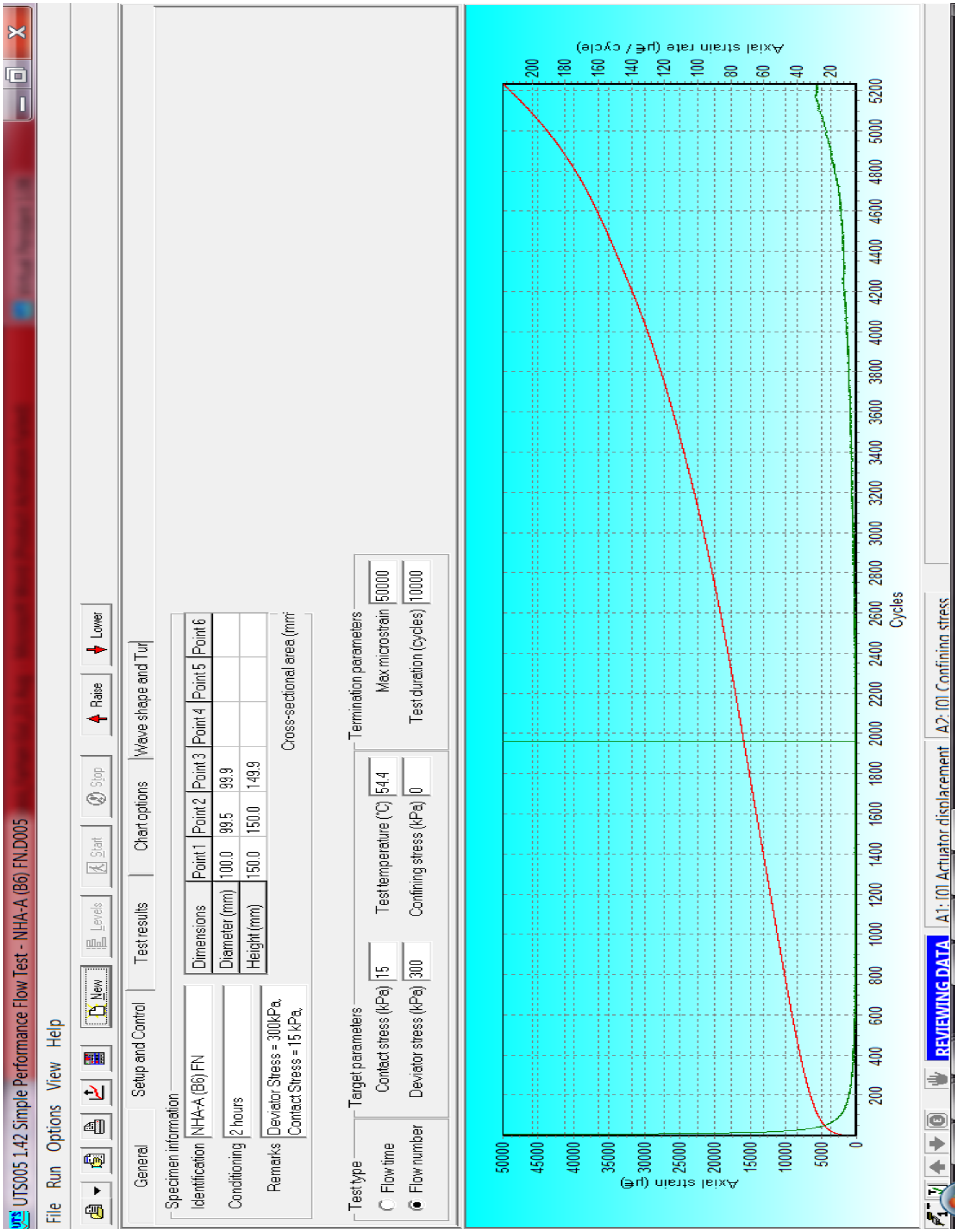
File Run Options View Help
New
Levels
Start
Stop
Raise
Lower
General
Setup and Control
Test results
Chart options
Wave shape and Tur
Specimen information
Identification SP-2 (W2)
Conditioning 2 hours
Remarks Deviator Stress = 300kPa, Contact Stress = 15 kPa,
Dimensions Point 1 Point 2 Point 3 Point 4 Point 5 Point 6
Diameter (mm) 100.0 100.0 100.0
Height (mm) 151.8 152.0 152.2
Cross-sectional area (mm
Test type
Flow time
Flow number
Target parameters
Contact stress (kPa) 15
Deviator stress (kPa) 300
Test temperature (°C) 54.4
Confining stress (kPa) 0
Termination parameters
Max microstrain 50000
Test duration (cycles) 10000
Axial strain (µε)
Axial strain rate (µε / cycle)
Cycles
REVIEWING DATA
A1: [0] Actuator displacement
A2: [0] Confining stress


UTS005 1.42 Simple Performance Flow Test - NHA-A (B6) FN.D005
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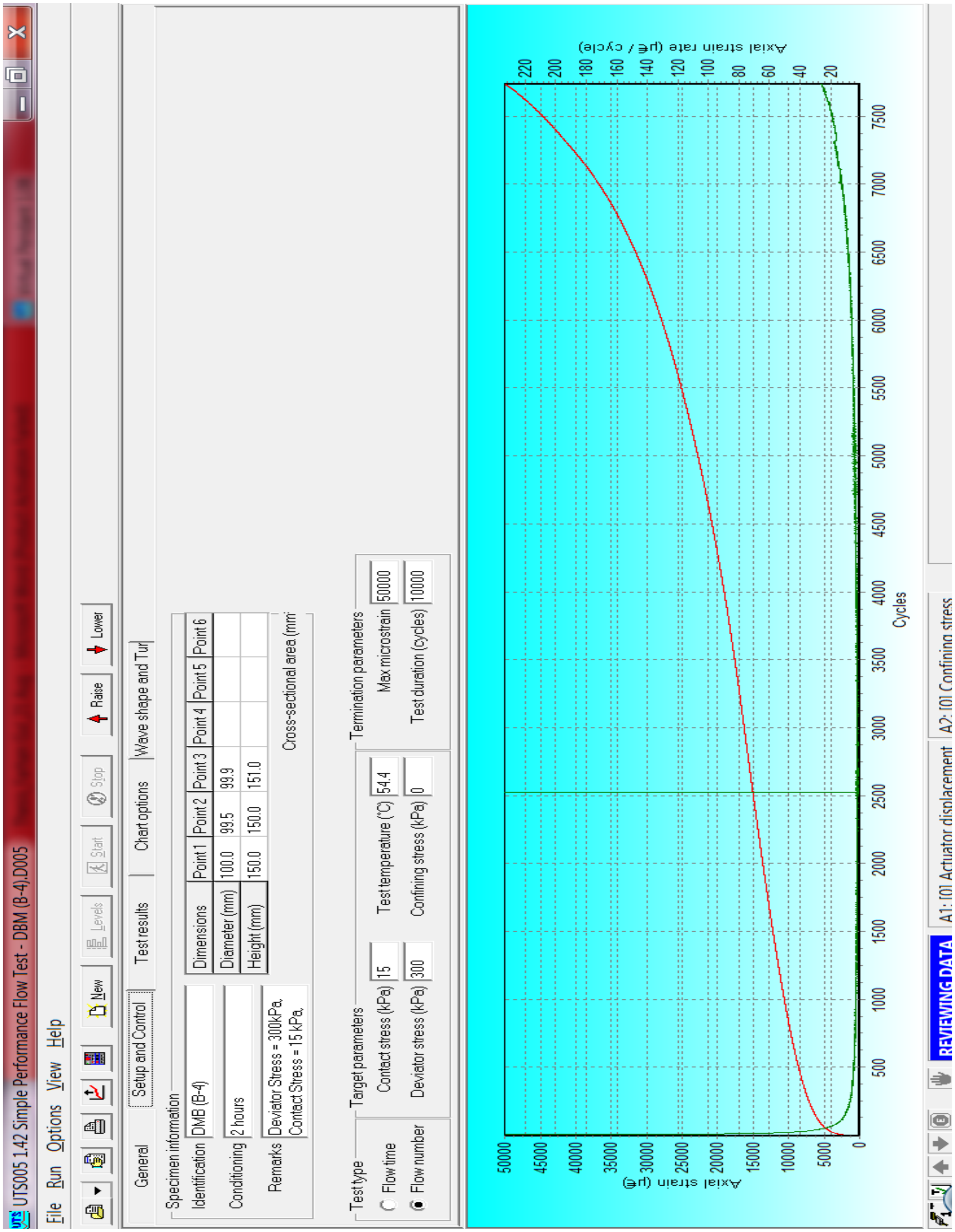
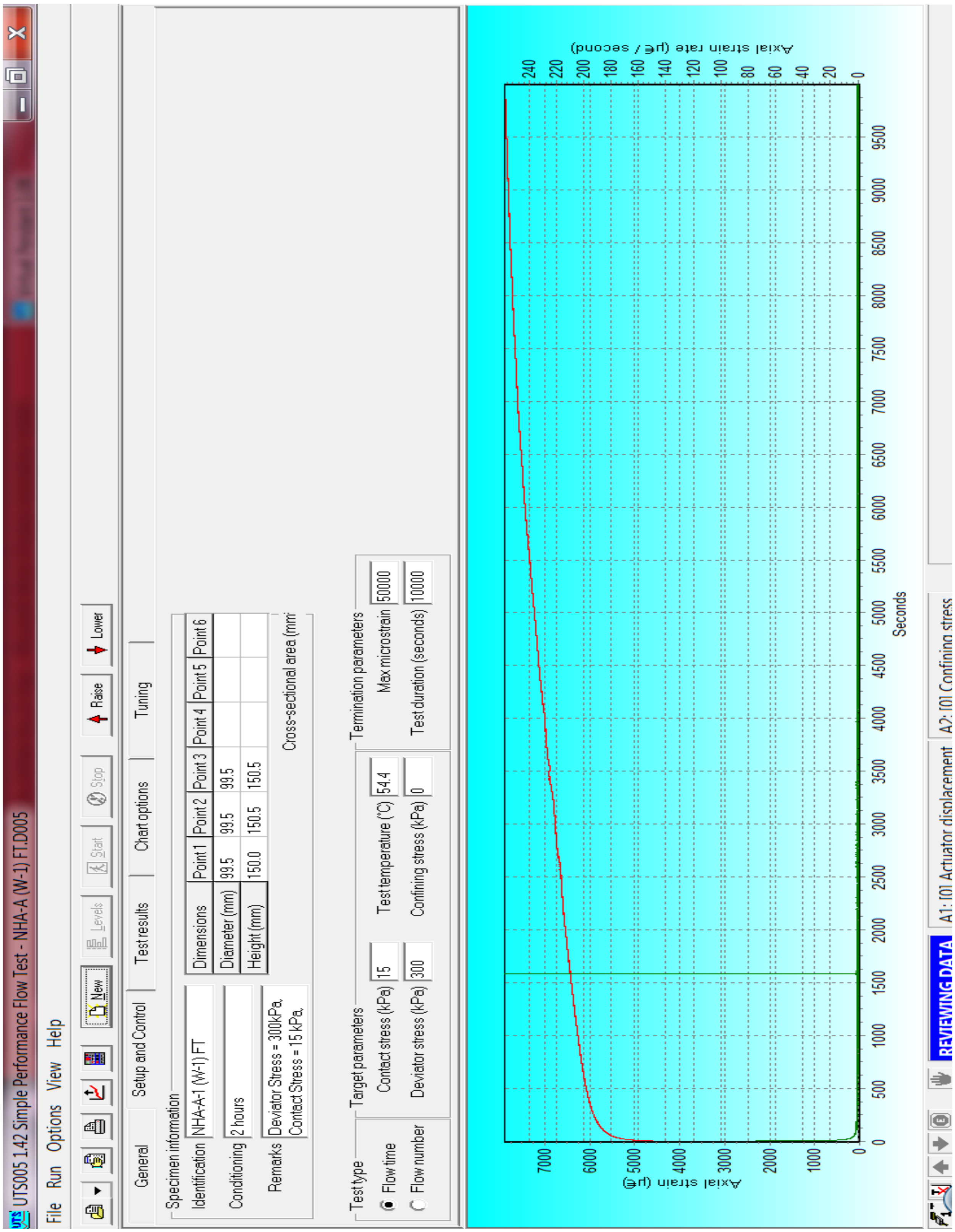
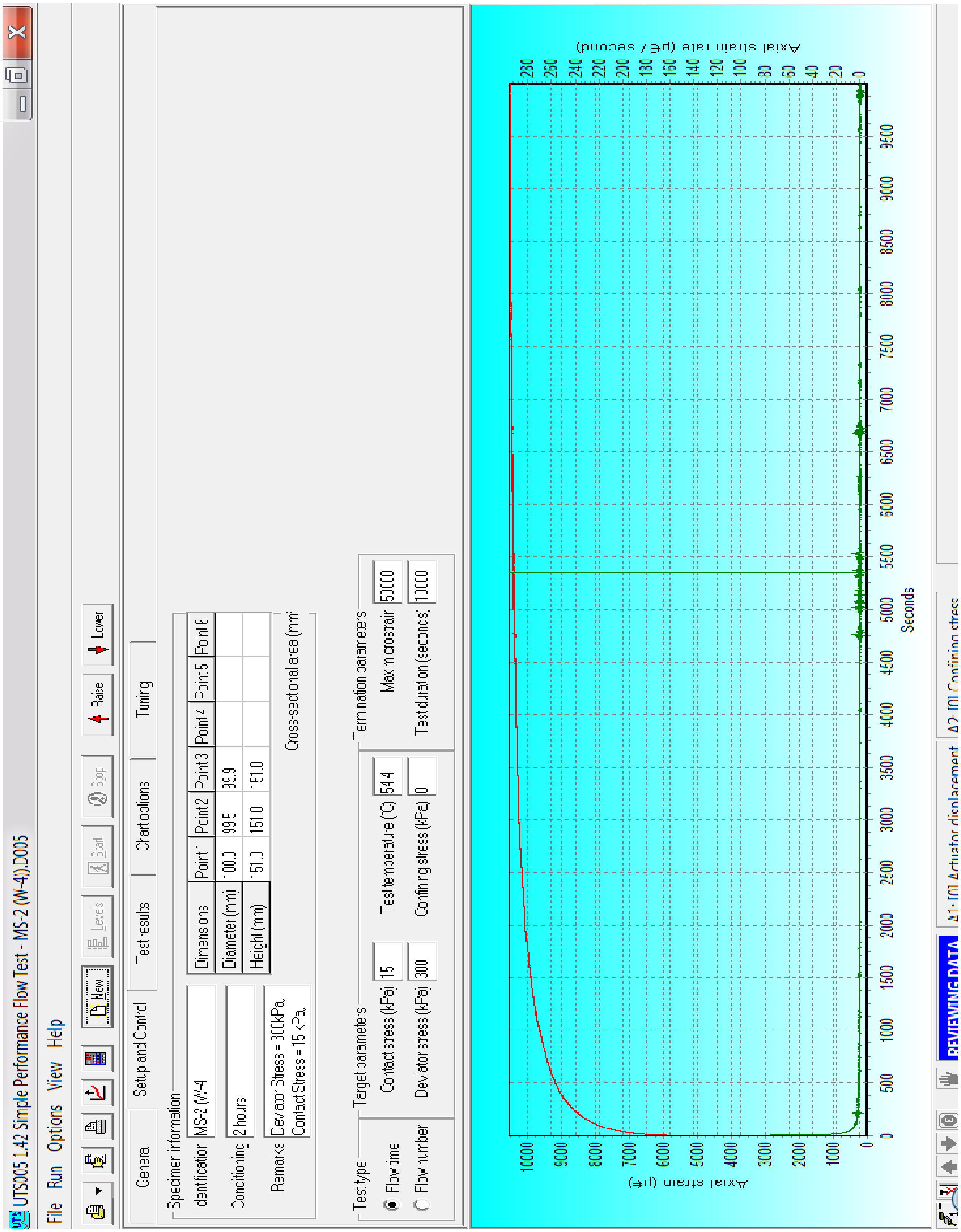
New
Levels
Start
Stop
Raise
Lower
General
Setup and Control
Test results
Chart options
Wave shape and Tur
Specimen information
Identification NHA-A (B6) FN
Conditioning 2 hours
Remarks Deviator Stress = 300kPa, Contact Stress = 15 kPa,
Dimensions Point 1 Point 2 Point 3 Point 4 Point 5 Point 6
Diameter (mm) 100.0 99.5 99.9
Height (mm) 150.0 150.0 149.9
Cross-sectional area (mm
Test type
Flow time
Flow number
Target parameters
Contact stress (kPa) 15
Deviator stress (kPa) 300
Test temperature (°C) 54.4
Confining stress (kPa) 0
Termination parameters
Max microstrain 50000
Test duration (cycles) 10000
Axial strain (µε)
Axial strain rate (µε / cycle)
Cycles
REVIEWING DATA
A1: [0] Actuator displacement
A2: [0] Confining stress



UTS005 1.42 Simple Performance Flow Test - DBM (B-4).D005
File Run Options View Help
New
Levels
Start
Stop
Raise
Lower
General
Setup and Control
Test results
Chart options
Wave shape and Tur
Specimen information
Identification DMB (B-4)
Conditioning 2 hours
Remarks Deviator Stress = 300kPa, Contact Stress = 15 kPa,
Dimensions Point 1 Point 2 Point 3 Point 4 Point 5 Point 6
Diameter (mm) 100.0 99.5 99.9
Height (mm) 150.0 150.0 151.0
Cross-sectional area (mm
Test type
Flow time
Flow number
Target parameters
Contact stress (kPa) 15
Deviator stress (kPa) 300
Test temperature (°C) 54.4
Confining stress (kPa) 0
Termination parameters
Max microstrain 50000
Test duration (cycles) 10000
Axial strain (µε)
Axial strain rate (µε / cycle)
Cycles
REVIEWING DATA
A1: [0] Actuator displacement
A2: [0] Confining stress

APPENDIX-II: AMPT FLOW TIME TEST RESULT




UTS005 1.42 Simple Performance Flow Test - MS-2 (W-4)).D005
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New
Levels
Start
Stop
Raise
Lower
General
Setup and Control
Test results
Chart options
Tuning
Specimen information
Identification MS-2 (W-4
Conditioning 2 hours
Remarks Deviator Stress = 300kPa, Contact Stress = 15 kPa,
Dimensions Point 1 Point 2 Point 3 Point 4 Point 5 Point 6
Diameter (mm) 100.0 99.5 99.9
Height (mm) 151.0 151.0 151.0
Cross-sectional area (mm
Test type
Flow time
Flow number
Target parameters
Contact stress (kPa) 15
Deviator stress (kPa) 300
Test temperature (°C) 54.4
Confining stress (kPa) 0
Termination parameters
Max microstrain 50000
Test duration (seconds) 10000
Axial strain (µε)
Axial strain rate (µε / second)
Seconds
REVIEWING DATA
A1: [0] Actuator displacement
A2: [0] Confining stress

APPENDIX-III: REGRESSION CO-EFFICIENTS ‘a’ & ‘b’ - WC

WEARING COURSE MIXTURES - ACCUMULATIVE AXIAL STRAIN VERSUS LOAD CYCLE PLOTS ON LOG-LOG SCALE

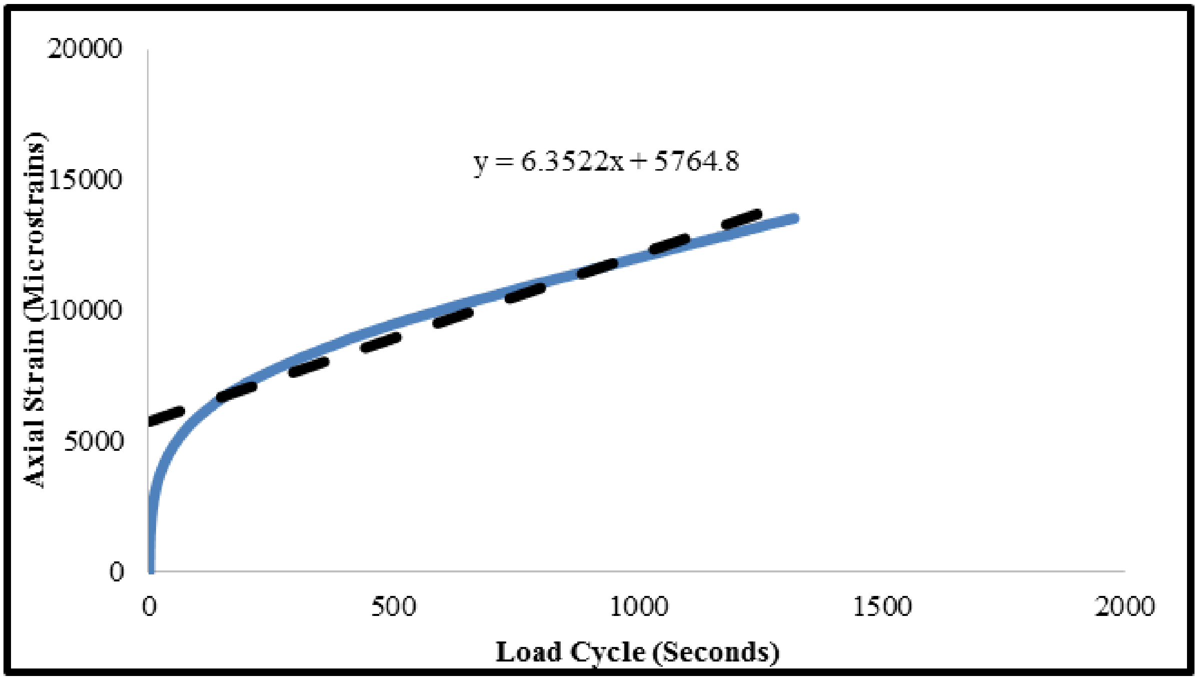

Figure 1 NHA-A Mixture

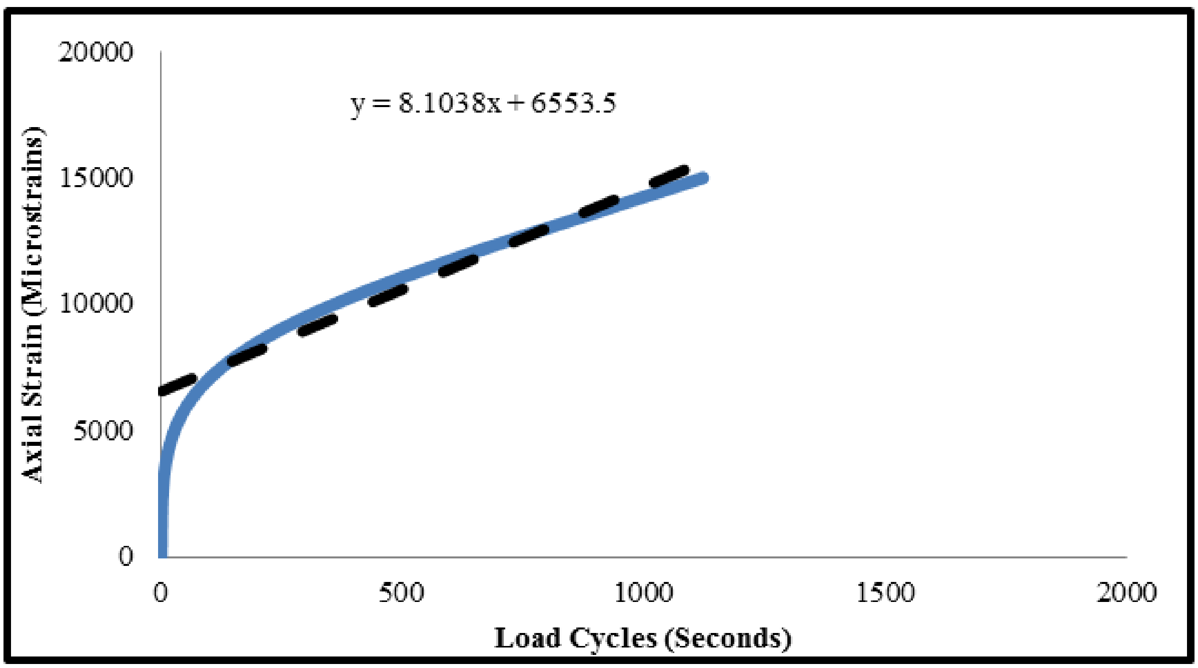

Figure 2 NHA-B Mixture

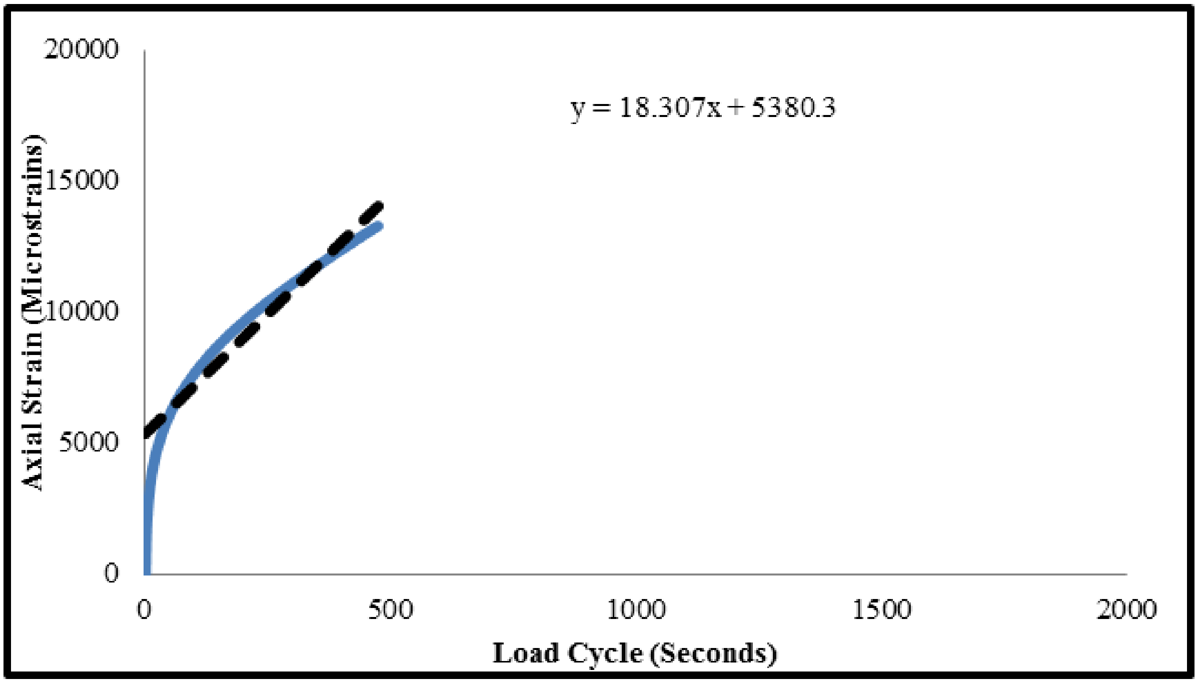

Figure 3 SP-A Mixture

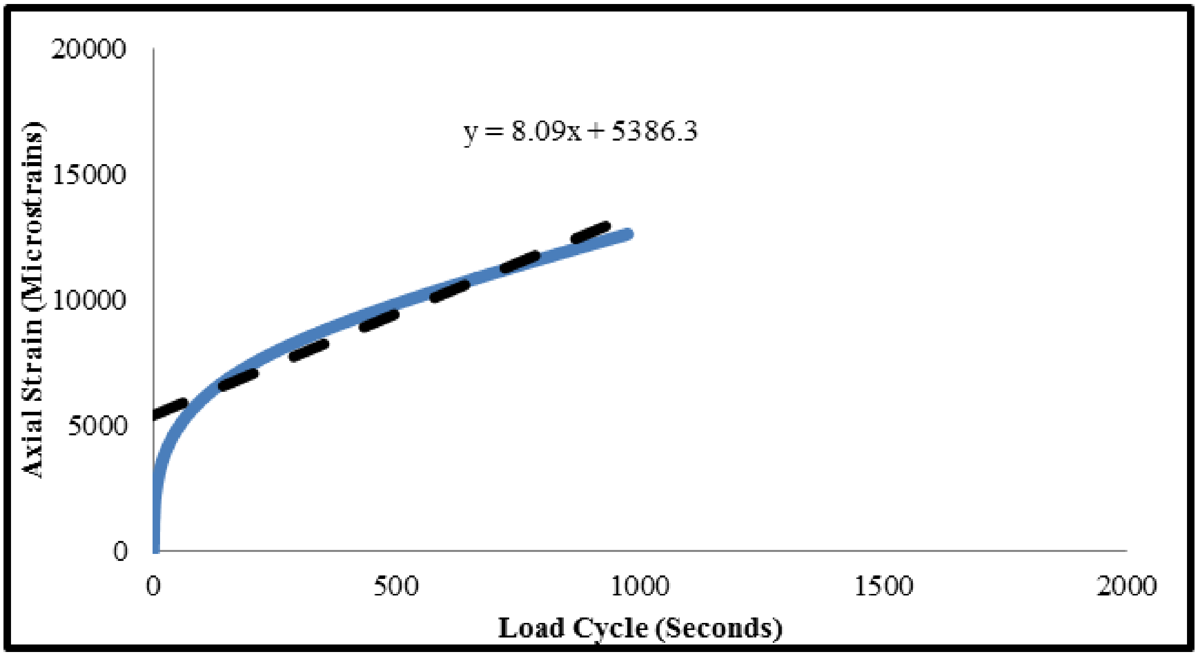

Figure 4 MS-2 Mixture

Where,

Generic Form of equation generated for plotted linear line is: $y = a + bx$

APPENDIX-IV: REGRESSION CO-EFFICIENTS ‘a’ & ‘b’ - BC

BASE COURSE MIXTURES - ACCUMULATIVE AXIAL STRAIN VERSUS LOAD CYCLE PLOTS ON LOG-LOG SCALE

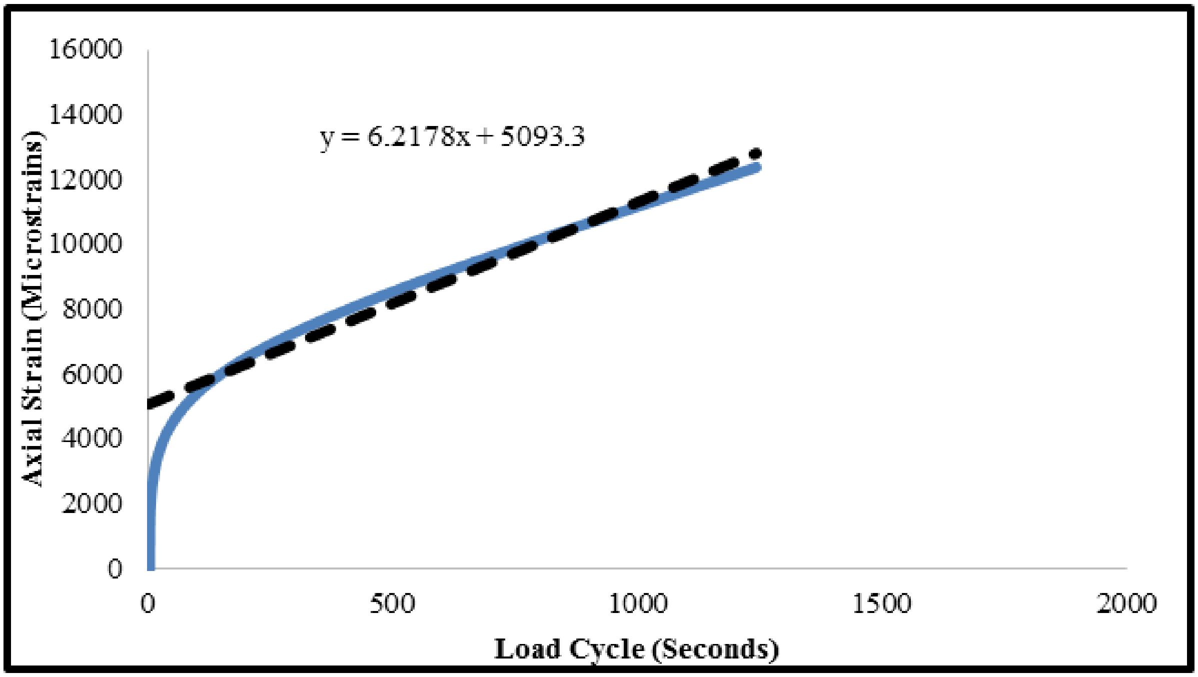

Figure 1 NHA-A Mixture

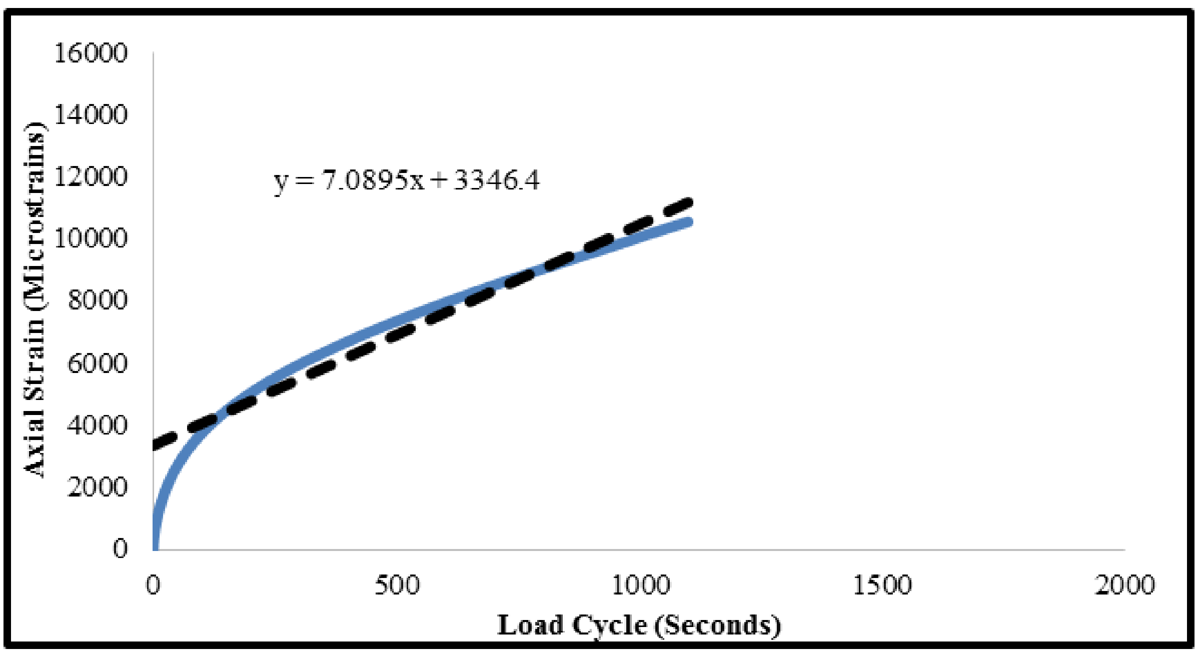

Figure 2 NHA-B Mixture

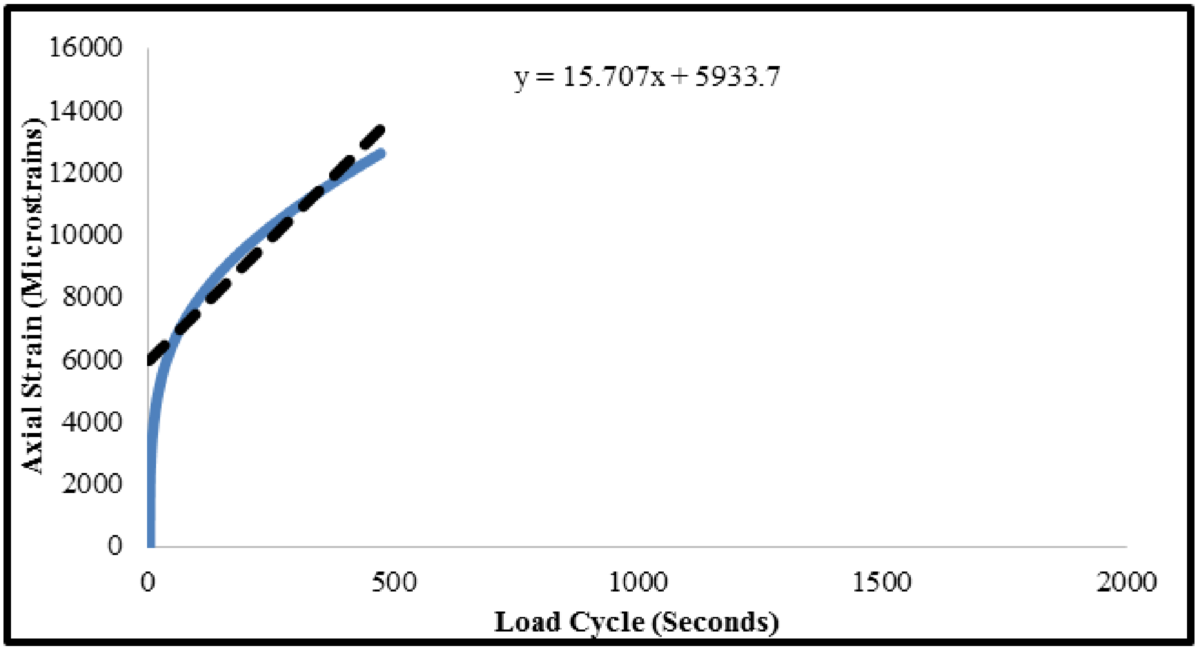

Figure 3 SP-B Mixture

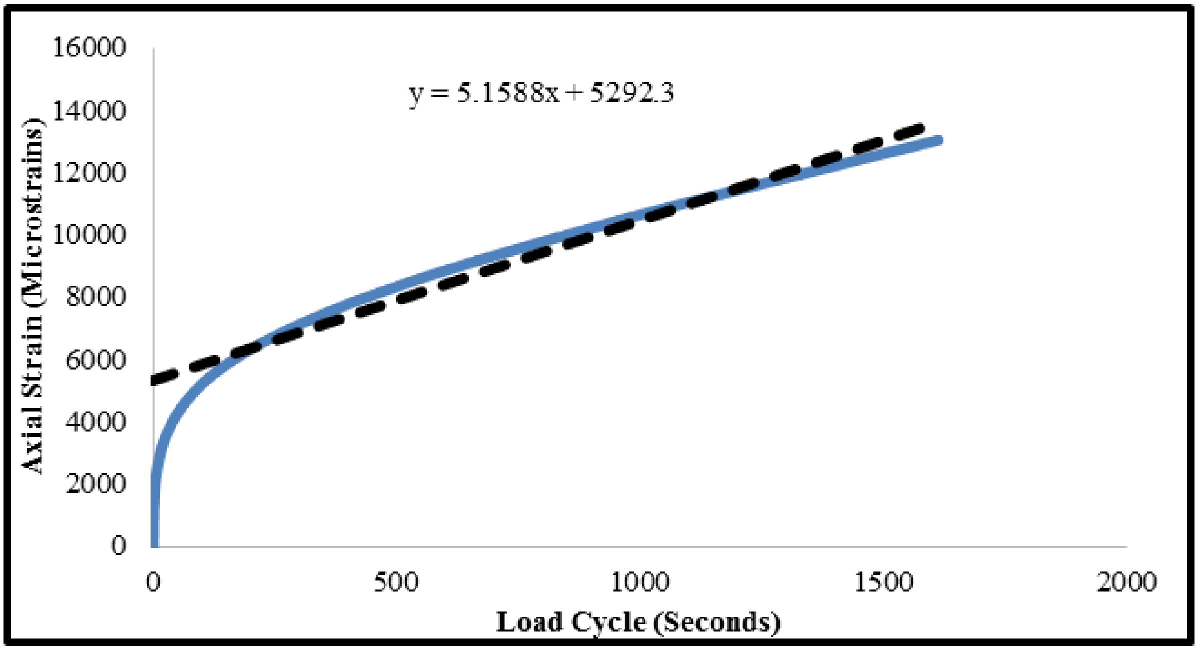

Figure 4 DBM Mixture

Where,

Generic Form of equation generated for plotted linear line is: $y = a + bx$

APPENDIX-V: FLOW NUMBER VALUES – WEARING COURSE MIX

Sample		**FN Value**	**Mean**	**S.D**	**COV %**
NHA-A	W-1	1241	1322	73	5.49
	W-2	1308			
	W-3	1417			
NHA-B	W-1	1032	1122	73	6.48
	W-2	1124			
	W-3	1210			
SP-A	W-1	496	474	20	4.18
	W-2	478			
	W-3	448			
MS-2	W-1	908	970	45	4.61
	W-2	990			
	W-3	1012			

APPENDIX-VI: FLOW NUMBER VALUES – BASE COURSE MIX

Sample		FN Value	Mean	S.D	COV %
NHA-A	W-1	1318	1242	56	4.52
	W-2	1224			
	W-3	1184			
NHA-B	W-1	1188	1101	65	5.90
	W-2	1083			
	W-3	1032			
SP-B	W-1	608	678	50	7.42
	W-2	702			
	W-3	724			
DBM	W-1	1491	1613	112	6.96
	W-2	1762			
	W-3	1586			

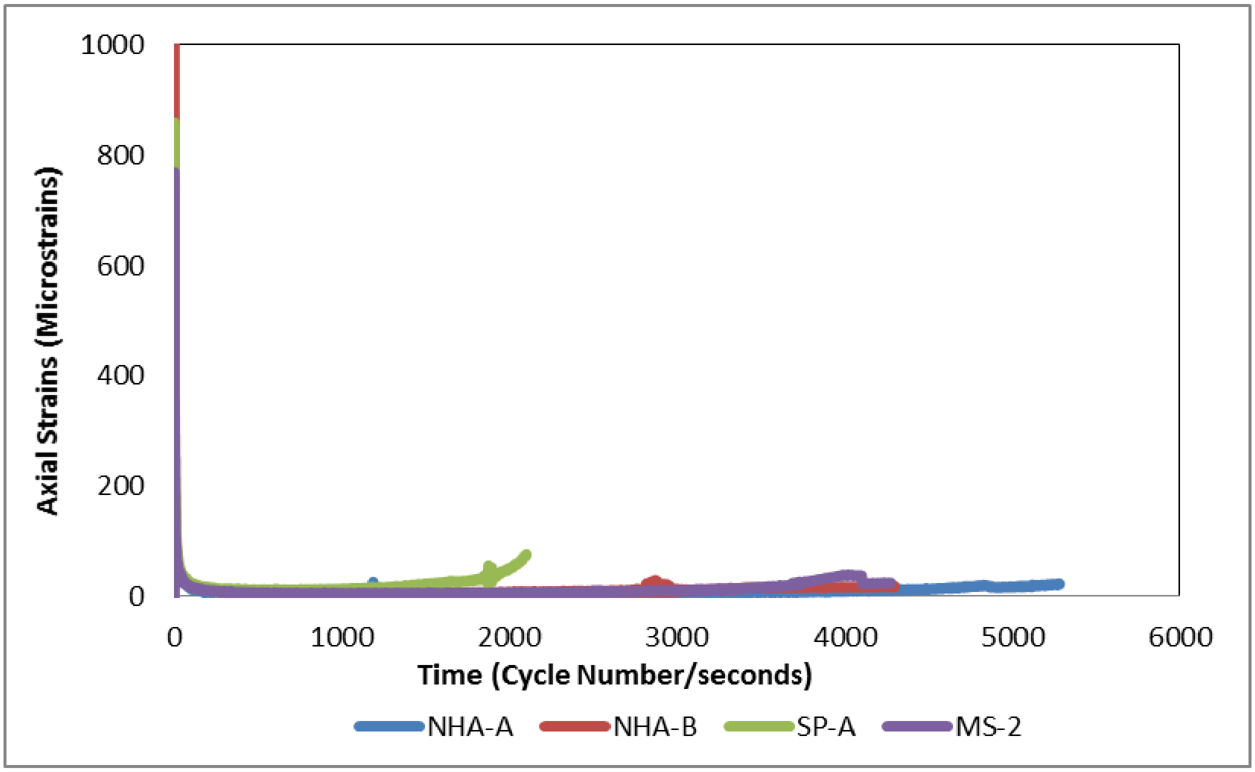

Figure 1Axial Strain Rate Vs Load Cycle Plot-Wearing Course Mixtures

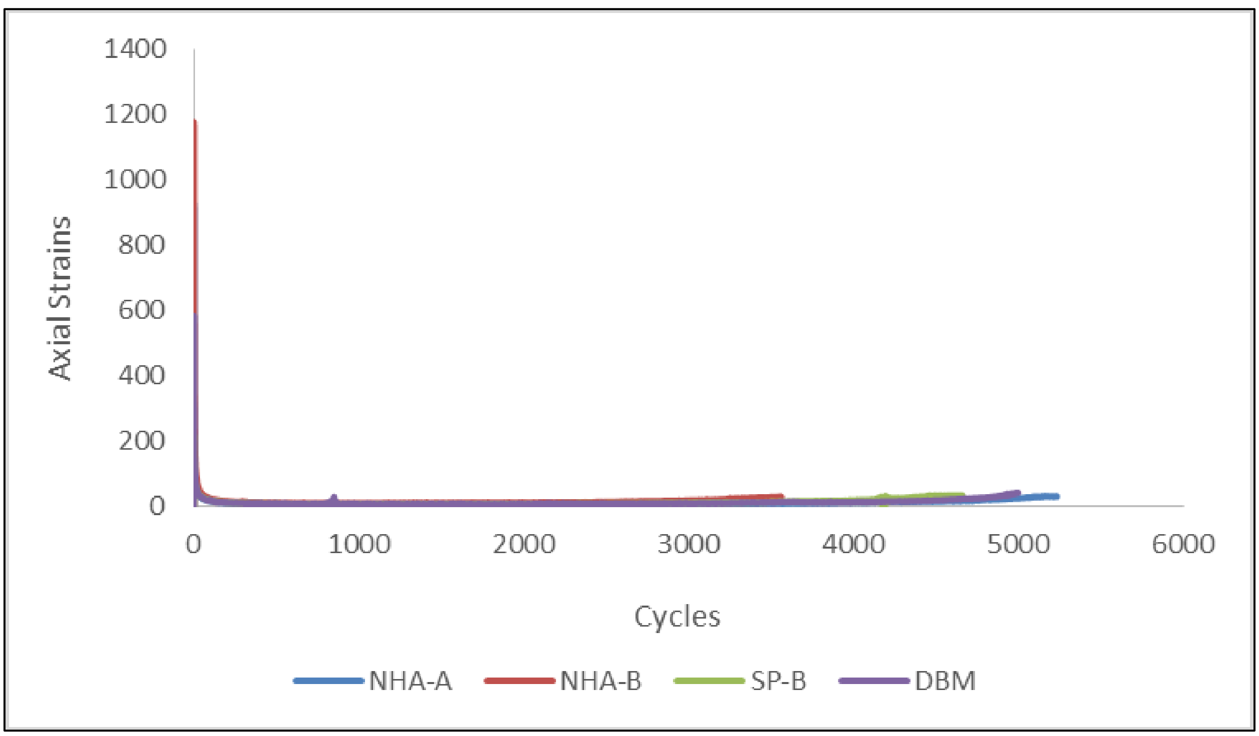

Figure 2Axial Strain Rate Vs Load Cycle Plot-Base Course Mixtures

APPENDIX-VII: MODEL STATISTICS – WEARING COURSE MIX (Individual)

Mixture	Parameter	Estimate	Std. Error	t-stat	N	R^2	95% Confidence Interval	
							Lower Bound	Upper Bound
NHA-A	α	90.821	2.918	31.12	5282	0.934	85.101	96.541
	β	0.741	0.004	185.25			0.733	0.748
NHA-B	α	17.386	0.649	26.79	4301	0.932	16.114	18.657
	β	0.909	0.005	181.80			0.900	0.918
SP-A	α	55.002	2.741	20.07	2102	0.932	49.627	60.377
	β	0.865	0.007	123.57			0.851	0.878
MS-2	α	20.944	0.998	20.99	4102	0.909	18.989	22.9
	β	0.905	0.006	150.83			0.893	0.917

NHA-A (wearing)

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	90.821	2.918	85.101	96.541
	b	.741	.004	.733	.748

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2.922E12	2	1.461E12
Residual	3.152E10	4024	7833428.077
Uncorrected Total	2.953E12	4026	
Corrected Total	4.802E11	4025	

Dependent variable: Strain

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .934.

NHA-B

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension 0	a	17.386	.649	16.114	18.657
	b	.909	.005	.900	.918

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3.318E12	2	1.659E12
Residual	4.542E10	5280	8602922.843
Uncorrected Total	3.363E12	5282	
Corrected Total	6.729E11	5281	

Dependent variable: S

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .932.

Superpave-A

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	55.002	2.741	49.627	60.377
	b	.865	.007	.851	.878

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	1.300E12	2	6.499E11
Residual	1.711E10	2100	8146689.524
Uncorrected Total	1.317E12	2102	
Corrected Total	2.527E11	2101	

Dependent variable: St

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .932.

MS-2

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	20.944	.998	18.989	22.900
	b	.905	.006	.893	.917

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2.224E12	2	1.112E12
Residual	4.124E10	4099	1.006E7
Uncorrected Total	2.266E12	4101	
Corrected Total	4.543E11	4100	

Dependent variable: STR

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .909.

APPENDIX-VIII: MODEL STATISTICS - BASE COURSE MIX

(Individual)

Mixture	Parameter	Estimate	Std. Error	t-stat	N	R^2	95% Confidence Interval	
							Lower Bound	Upper Bound
NHA-A	α	12.318	0.477	25.82	5235	0.935	11.382	13.253
	β	0.947	0.005	198.40			0.938	0.956
NHA-B	α	103.101	3.018	34.16	4662	0.950	97.184	109.018
	β	0.738	0.004	184.50			0.731	0.745
SP-B	α	2.845	0.137	20.76	3564	0.939	2.576	3.113
	β	1.133	0.006	188.80			1.121	1.144
DBM	α	6.348	0.269	23.60	5001	0.909	5.820	6.876
	β	1.030	0.005	206			1.019	1.040

<u>**NHA-A**</u>

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	12.318	.477	11.382	13.253
b	.947	.005	.938	.956

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	3.028E12	2	1.514E12
Residual	4.201E10	5234	8025795.868
Uncorrected Total	3.070E12	5236	
Corrected Total	6.418E11	5235	

Dependent variable: Strain

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .935.

NHA-B

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	103.101	3.018	97.184	109.018
	b	.738	.004	.731	.745

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2.681E12	2	1.340E12
Residual	2.202E10	3563	6180104.556
Uncorrected Total	2.703E12	3565	
Corrected Total	4.413E11	3564	

Dependent variable: S

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .950.

Superpave-B

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	2.845	.137	2.576	3.113
	b	1.133	.006	1.121	1.144

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2.363E12	2	1.181E12
Residual	3.611E10	4661	7746789.947
Uncorrected Total	2.399E12	4663	
Corrected Total	5.946E11	4662	

Dependent variable: St

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .939.

DBM

Parameter Estimates

Parameter		Estimate	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
dimension0	a	6.348	.269	5.820	6.876
	b	1.030	.005	1.019	1.040

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	2.731E12	2	1.365E12
Residual	3.909E10	5000	7817811.019
Uncorrected Total	2.770E12	5002	
Corrected Total	6.257E11	5001	

Dependent variable: Str

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .938.

APPENDIX-IX: MODEL STATISTICS – WEARING COURSE MIX (Combined)

Parameter	Estimate	Std. Error	t-Stat	R^2	95% Confidence Interval	
					Lower Bound	Upper Bound
α	225.617	6.323	35.68	0.75	213.224	238.011
β	0.609	0.004	152.25		0.602	0.616

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	9.378E12	2	4.689E12
Residual	4.563E11	15510	2.942E7
Uncorrected Total	9.834E12	15512	
Corrected Total	1.858E12	15511	

Dependent variable: Strains

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .754.

APPENDIX-X: MODEL STATISTICS – BASE COURSE MIX (Combined)

Parameter	Estimate	Std. Error	t-Stat	R^2	95% Confidence Interval	
					Lower Bound	Upper Bound
α	276.344	7.069	39.09	0.71	262.489	290.199
β	0.559	0.003	186.33		0.553	0.565

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	1.232E13	2	6.159E12
Residual	7.468E11	21204	3.522E7
Uncorrected Total	1.306E13	21206	
Corrected Total	2.575E12	21205	

Dependent variable: Strains

a. R^2= 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .710.