# QUANTIFICATION OF COHESIVE HEALING OF ASPHALT BINDER BASED ON

# DISSIPATED ENERGY ANALYSIS

By

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A thesis submitted in partial fulfillment of the requirements for the degree of

# MASTER OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY Department of Civil and Environmental Engineering

MAY 2010

To the Faculty of Washington State University:

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#### ACKNOWLEDGEMENT

I am grateful for the opportunity of pursuing my master degree at the Washington State University. I would like to express my appreciation to Dr. Shihui Shen for her unlimited advice and generosity. This research project would not have been possible without her efforts. I would like to acknowledge my committee members Dr. Balasingam Muhunthan and Dr. Wen. I also would like to thank many current and former graduate students. I wish to appreciate my family; they have been always supportive. Finally, thanks to the Washington State University Foundation and the Washington State University Office of Research for their financial support of my research project.

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#### Abstract

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The effect of healing on asphalt material fatigue performance has been considered as an important property which is, at least partially, responsible for the significant difference between the laboratory and the field fatigue behavior. Although many studies have been conducted to characterize the asphalt healing and its mechanisms, very few researchers have clearly identified how different loading conditions can influence the effect of healing in a quantitative way. In addition, few suggestions have been provided on how to integrate the effect of healing to pavement design. This study develops fundamental dissipated energy analysis to quantify cohesive healing in asphalt binder. The key impact factors on healing are evaluated in to a systematic way under different loading and temperature conditions. Healing rate prediction model, modified fatigue life prediction model taking into account the effect of healing, and plateau value prediction model based on relative simple binder dynamic shear rheometer testing are developed, which can be used for a more accurate prediction of asphalt binder fatigue life. The methodology used in this study may also be applied to investigate and quantify adhesive healing at the aggregate-asphalt interface when aggregates are introduced into experimental testing.

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This thesis is dedicated to my Parents

# CHAPTER ONE

## **INTRODCTION**

#### **1.1 Introduction**

Healing, assessed physically for a natural body, is the process by which the cells in the body regenerate and repair to reduce the size of a damaged or necrotic area (wikipedia.org). Pavement researchers have started to notice the effect of healing in asphalt materials because of the significant difference between laboratory fatigue life (continuous loading) and field fatigue life (with rest periods). Without considering the effect of healing, the prediction of pavement life can be significantly shortened and a shift factor is needed to correct results. Recently, many researchers (Raithby et al. 1970, Bonnaure et al. 1980, 1982, Pronk et al. 1991, Daniel et al. 1996, Lytton et al. 1997 and 2001, Zhang et al. 2001, Little et al. 2001, Kim et al. 2002, 2003, Maillard et al. 2004, Carpenter et al. 2006 and Shen 2006) have demonstrated phenomenologically that asphalt material has the capability to heal cracks. It was observed that when given a certain amount of rest time among continuous loading sequence in a fatigue test, the modulus of hot mix asphalt (HMA) mixtures recovered and fatigue life increased. These studies have led to a new way of describing the performance of healable asphalt paving materials. A thorough understanding of asphalt material healing mechanisms and an integration of healing effect into pavement design procedures will help to select and design high healing potential materials, increase the material's resistance to damage and service life, reduce maintenance needs, and ultimately result in a more sustainable pavement system.

In an asphalt material system, two types of healing exist: a) adhesive healing at the asphalt – aggregate interface due to the rebonding of the asphalt to the aggregate; and b) cohesive

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healing within the asphalt binder due to the cross-linking of asphalt materials at the microcrack surface. The study conducted here aims to investigate the cohesive healing characteristics of asphalt binders. It quantifies the effect of healing at different loading and environmental conditions, and develops simple predictive models to characterize asphalt healing. The methodology used is based on fundamental dissipated energy concept, which can also be used to investigate and quantify the adhesive healing when aggregates are introduced into the experimental testing.

#### **1.2 Problem Statement**

The appearance and accumulation of healing in asphalt binder is an important research topic in the pavement area. Previous studies on binder healing have provided some guidance necessary to understand healing performance in asphalt binders. However, they are lacking in presenting a clear picture of the asphalt binder healing.

In the previous binder healing studies, researchers have mainly focused on applying long periods of rest (1 hour, 2 hours, and 12 hours) after continuous fatigue loading (Bahia et al,1999). However, under a real field conditions, the rest periods could be much shorter (in seconds), especially when a high traffic flow highway is to be considered. To evaluate the healing characteristics under such short rest periods, Shen, et al. (2006, 2009) introduced the concept of intermittent loading sequence into the fatigue test of asphalt mixtures and binders. Such loading sequence applies 0-10 second rest periods between continuous loading, and evaluates the total fatigue life extension due to the effect of short rest periods after every one or ten cycles.

In order to integrate asphalt healing into pavement design, it is necessary to develop prediction models, either phenomenological or fundamental, to effectively correlate asphalt binder healing to material properties and loading conditions.

With these considerations, this thesis is initiated to propose and develop healing prediction models to evaluate asphalt binder healing behavior. This study fits in the overall goal of identifying mechanism of asphalt healing and developing algorithms to integrate healing into pavement design.

## **1.3Objectives**

The overall objective of this research is to study the healing and fatigue behavior of asphalt binder based on laboratory dynamic shear rheometer testing and dissipated energy analysis. The specific objectives of this study are as follows:

- 1- Validation of the effect of temperature, frequency, rest period, strain level, and aging on fatigue and healing of different binders based on dissipated energy concept
- 2- Development of a healing prediction model that correlates asphalt healing to binder properties and loading conditions
- 3- Development of a healing rate incorporated fatigue prediction model and plateau value prediction model based on dissipated energy concept to evaluate fatigue life and plateau value of asphalt binder.

## **1.4Organization of Thesis**

This thesis consists of seven chapters. Chapter One is the introductory chapter, which summarizes the concerns that initiated this research and the main research objectives. Chapter Two presents a background of the study which includes fatigue, healing and dissipated energy of the asphalt binder. The research approach is given in Chapter Three in which the ratio of dissipated energy change approach, quantification of healing based on dissipated energy analysis and fundamental theoretical derivation are presented. The experimental method is given in Chapter Four. This chapter presents the materials and testing program. In Chapter Five, traditional fatigue life analysis and healing effect are discussed. Prediction models are developed based on experimental data which include healing rate prediction model, fatigue prediction model and plateau value prediction model. These are presented in the Chapter Six. In Chapter Seven, the conclusions developed from this research and some recommendations for future research in this area are presented.

#### **1.5 Glossary of Terms**

AE-Acoustic Emission DCSE-Dissipated Creep Strain Energy DE-Dissipated Energy DEM-Discrete Element Method DER-Dissipated Energy Ratio DSR- Dynamic Shear Rhenometer EI- Fatigue Life Extension Index HI-Healing Index HMA-Hot Mix Asphalt HR- Healing Rate IDE-Initial Dissipated Energy, kPa LC- Loading Cycles MEPDG-Mechanical Empirical Pavement Design Guide NDE- Non-Destructive Evaluation Nf- Number of Loading Cycle to Fatigue Failure Nf<sub>50</sub> – Defined Fatigue Failure at 50% Initial Stiffness Reduction Point PV- Plateau Value RDEC-Ratio of Dissipated Energy Change RP-Rest Period, in Seconds

#### **CHAPTER TWO**

## BACKGROUND

The background presents a historical literature review on fatigue and healing studies. It focuses on three topics: fatigue, healing, and dissipated energy. The findings provide validity and show the need for further study of healing phenomenon in asphalt binders.

#### 2.1 Fatigue

#### 2.1.1 Mode of Loading in Fatigue Behavior

Fatigue loading can be done in two different ways: stress controlled mode of loading and strain controlled mode of loading. Experimental results showed that if the controlled stress and controlled strain loading start with the same stress level, control-strain tests require more loading cycles than control-stress tests to cause the same level of damage (Masad, et al. 2008). Furthermore, it shows that complete failure of the specimen is more likely to occur in control stress loading than in control strain loading.

Monismith and Deacon (1969) used a mode factor based on percentage change in stress and strain due to reduction in mixture stiffness to take into account the loading mode effect. The mode factor is defined as:

$$MF = \frac{/A/-/B/}{/A/+/B/}$$
(2.1)

where, MF = Mode Factor;

A = The percentage change in stress due to a stiffness decrement of C percentage;

B = The percentage change in strain due to a stiffness decrement of C percentage; and

C = An arbitrary but fixed reduction in stiffness resulting from the accumulation of fatigue damage under the repetitive loading.

Tayebali, et al. (1994) analyzed the effect of mode-of-loading of HMA mixture by using the least squares calibrations of models of the following type:

$$N_{f} = a \exp^{b MF} \exp^{c V_{0}} (\varepsilon_{0} or \sigma_{0})^{d} (S_{0})^{e}$$
(2.2)

Where,

 $N_f$  = cycles to failure;

MF = mode factor assuming values of 1 and -1 for controlled-strain and controlled-stress loading, respectively:

 $V_0$  = Initial air-void content in percentage;

 $\varepsilon_0$  = Initial flexural strain in in/in;

 $\sigma_0$  = Initial flexural stress in psi;

 $S_0 =$  Initial mix stiffness in psi; and

a, b, c, d, e = regression constants.

Regression analysis revealed that at a given stress level in controlled-stress testing, stiffer mixes have greater fatigue resistance and at a given strain level in controlled-strain testing, stiffer mixes have less fatigue resistance.

The difference between controlled stress loading and controlled strain loading was explained by Masad et al. (2008) with the help of Paris Law. The increase in crack length leads to a rapid increase in the stress intensity factor until it reaches the fracture toughness of the material and unstable crack propagation growth takes place. The reduction in stress results in the

crack propagation under strain controlled loading being less rapid than in the stress controlled mode when both tests are started at the same stress.

## 2. 1. 2 Research Approaches to Evaluate Fatigue

There are different approaches used to characterize fatigue, as listed below.

- 1. Phenomenological Approach
- 2. Fracture Mechanics Approach
- 3. Dissipated Energy Approach (Discussed in the section 2.4)

#### 2.1 Phenomenological Approach

The phenomenological approach can be used to model fatigue in the asphalt concrete mixture. A fatigue failure criterion (eq 2.2) was developed by Monismith, et al. (1995) using phenomenological approach.

$$N_f = K \left(\frac{1}{\varepsilon_t}\right)^a \left(\frac{1}{S_{\min}}\right)^b$$
(2.3)
Where:

Where;

$$Nf$$
 = number of repetitions to failure;

 $\epsilon_t$  = magnitude of tensile strain repeatedly applied;

*S*mix = initial mixture stiffness; and

K, a, and b = experimentally determined coefficients.

A study by Si, et al. (2002) using phenomenological approach indicated that fatigue life is affected by the following factors: mode of loading, asphalt and aggregate type, among others.

#### 2. 2 Fracture Mechanics Approach

Crack of the asphalt mixture can be evaluated by a mechanical approach. Damage increases from initial stage to critical stage, following the crack propagation law. Initiation, propagation and failure are three different stages in fatigue process based on fracture mechanics. Crack growth rate (eq 2.4) was defined by Paris and Erdogan (1963) based on experimental results.

$$\frac{dc}{dN} = AK^n \tag{2.4}$$

Where

*c*=crack length;

*N*=number of loading repetitions;

A and *n*=parameters dependent on the material and on the experimental conditions;

K = stress intensity factor.

Roque, et al. (2002) developed a viscoelastic fracture mechanics model for HMA based crack growth. This model was developed based on fracture mechanic theory along with threshold concept and limits. These experimental results indicated that the initial crack length for typical dense graded asphalt mixtures is about 10 mm. Therefore, in order to predict crack initiation, the average stress determined over the most critical 10-mm zone in the mixture is used to calculate the dissipated creep strain energy (DCSE) induced by loading. Thus, a 10 mm crack would be initiated when the induced DCSE in this zone exceeds the DCSE limit of the mixture. The authors identified three key parameters that govern the cracking performance of asphalt mixtures based on the HMA fracture model which are dissipated creep strain energy to failure, parameter covering the creep stain energy and healing rate parameter.

Roque, et al. (2004) evaluated mixture crack performance by using indirect tensile asphalt mixture properties (resilient modulus, creep compliance power law parameters, indirect tensile strength and dissipated creep strain energy to failure) and the HMA fracture mechanics model.

Carmona, et al. (2007) studied the fatigue fracture of disordered materials by means of computer simulation of the discrete element model (DEM). Cohesion between the elements is introduced in the model by beams between neighboring polymers. A two dimensional DEM was extended to capture microscopic failure mechanisms relevant for the process of fatigue. Results showed that damage recovery in the form of healing is known to play a crucial role for the long term performance of asphalt material.

Kim, et al. (2009) studied bulk material viscosity in conjunction with fracture (heterogeneous fracture model). A cohesive zone fracture contact was inserted along with a predefined path due to model and material symmetry. 1 mm/ in was the loading rate used in the simulation and experiment was carried out at  $-10^{\circ}$ C. Furthermore, the heterogeneous fracture simulations of asphalt concrete were used to study the complex fracture mechanisms in asphalt concrete that have been observed in the laboratory and in the field. Finally, a DEM fracture model was developed with bilinear cohesive zone models and viscoelastic bulk material models were used to simulate crack propagation in asphalt concrete laboratory compact tension specimens.

#### 2.1.3 Other Studies Related to HMA and Binder Fatigue

Soenen, et al. (1999) compared binder fatigue test results and laboratory fatigue properties of the corresponding mixtures at similar fatigue test conditions. This study revealed that binder fatigue tests are very well related to laboratory mix fatigue behavior with limited test data.

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Bahia, et al. (2001) found that G\* and sin (phase angle) do not capture the important factors in the fatigue life calculation of binders because damage cannot be calculated effectively by using these two parameters. Furthermore, Bahia, et al. (2001) have mentioned that when using fatigue data, many factors should be considered, including better definition of failure, identification of important factors, defining a specific protocol and selection of a criterion. Fatigue is affected by energy input, temperature, traffic speed and pavement structure. Selected energy level and defined failure point are important to define fatigue.

Bonnetti, et al. (2002) used the Np20 as the fatigue failure criteria in their study of binder fatigue. Np20 is defined as the number of cycles at which the dissipated energy ratio shows 20% deviation from the no damage ratio. This study revealed that the fatigue life of asphalt binder highly depends on binder type and testing conditions (temperature, frequency, initial dissipated energy).

Parls, et al. (2003) performed a binder fatigue performance test and evaluated bituminous material. This study revealed that the fatigue test is very sensitive to the loading condition. Furthermore, they found that a complex modulus obtained at the beginning of the testing is independent of the type of test.

Planchi, et al. (2003) mentioned that the temperature at which fatigue failure occurs after the largest no loading cycle is assumed to be the transition point where internal micro-damage and instability flow dominate the fatigue. If the rest period is introduced close to or after the fatigue point, it recovers a significant amount of stiffness but that will not last long after starting the loading cycle again.

Castro, et al. (2001) carried out a fatigue test for asphalt mixtures with rest periods. In this test, test specimens underwent cyclic loading for 0.1 sec and a rest period of an additional

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second. Furthermore, tests were performed at 20 °C with controlled displacement. The influence of rest period on fatigue life was evaluated by comparing with rest period and without rest period. These test results revealed that there is a significant increment in fatigue life in the fatigue test with rest period compared to the fatigue test without rest period.

Fatigue tests were conducted using the parallel plate DSR to evaluate the effects of fillers on the resistance to binder fatigue (Faheem, et al. 2008). Fatigue life was calculated as the number of loading cycles to reach a 50% drop in the G\*. The results of the G\* as a function of cycles clearly indicate significant improvement in the fatigue performance of asphalt binder after adding the fillers. The dropping rate of G\* for asphalt binder without filler was much faster than those of binder with 50% granite and limestone fillers. Compared to the performance of granite and limestone mastic, the G\* for 50% granite mastic dropped faster than that of 50% limestone mastic.

Fatigue studies related to binder healing, HMA healing, and dissipated energy are summarized in sections 2.2.1, 2.2.2 and 2.3 of this thesis, respectively.

#### 2.2 Healing

Healing occurs in materials and biological systems. Curing of a wound is a typical example to illustrate healing in the biological system. But it is a great challenge for researchers to identify healing in non-biological materials. Many studies have been conducted to evaluate and identify the healing potential in different materials. They are mainly focused on the self-healing capacity of polymer materials. Only a few studies have been done on the asphalt binders and HMA healing.

#### 2.2.1 Healing Mechanism

Healing mechanism based on crack closure was discovered by Elber (1970, 1971). Crack growth is influenced by several factors. They include the condition ahead of the crack tip, nature of the crack face contact behind the crack tip, history of loading, length of the crack and the stress state. Ritchie, et al. (1980), Suresh, et al. (1981) and Suresh (1984) have studied healing mechanisms based on the crack closure and categorized the various forms of fatigue crack closure which are induced by a variety of mechanical, micro-structural and environmental factors. Suresh (1991) categorized the healing mechanisms which promote retardation of fatigue crack growth. Those are plasticity induced crack closure, oxide-induced crack closure, roughness-induced crack closure, fluid induced crack closure and transformation-induced crack closure.

a) Plasticity induced crack closure: An automatic sharp notch or a saw-cut closes only at zero or compressive loads. However, the propagation of a fatigue crack gives rise to a wake of material that has been previously deformed plastically. During one cycle of crack growth, residual tensile strains are left in the material behind the advancing crack front, as only elastic recovery occur after the creation of the fracture surfaces. With an increase in the stress intensity factor and the size of the plastic zone due to crack advance, the material that was previously been deformed permanently within the plastic zone now forms an envelope of plastic zone in the wake of the crackfront.

b) Oxide-induced crack closure: It evolved as a consequence of attempts to rationalize apparent anomalies in the effect of environment on near-threshold fatigue crack growth. During the propagation of fatigue crack, the presence of moisture in the atmosphere leads to oxidation of the freshly formed fracture surfaces. Oxide-induced crack closure is promoted by moisture

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containing environments, elevated temperatures, high cyclic frequency, and lower strength, among other causes.

c) Roughness-induced crack closure: It has been recognized as one of the mechanisms by which certain micro-structural effect on fatigue crack growth can be rationalized. This phenomenon provides an explanation for many apparently anomalous effects of microstructure on fatigue crack growth. Experimental observations in a wide range of materials reveal that crack propagation in the near threshold fatigue region occurs by means of the single slip mechanism.

d) Viscous fluid-induced crack closure: The mechanisms by which viscous fluid penetrating within a growing fatigue crack influence crack propagation rates have also been the subject of widely differing interpretations. The effect of oil environment on influencing crack closure depends on several factors such as suppression of environmental embrittlement, minimization of oxide-induced crack closure, penetration of fluid within cracks and hydrodynamic wedging action.

e) Transformation-induced crack closure: It has been recognized that phase transformations at the tip of the fatigue crack can lead to retardation in crack growth rates.

Healing mechanisms related to HMA, binder and polymers are explained in sections 2.2.2, 2.2.3 and 2.2.4, respectively.

#### **2.2.2 HMA Healing**

Bonnaure et al. (1982) used intermittent loading to study the effect of rest period on fatigue life. Intermittent loading refers to the application of a certain number of loading cycles continuously, followed by a full stop of the loading for a certain period of time and then applying a certain number of loading cycles continuously followed by rest period; the process is then

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repeated. Rectangular beams with dimensions of 230mm x 30mm x 20mm were tested in the three point bending apparatus. The testing condition included two loading modes (control stress and control strain), three temperatures (5°C, 20°C, and 25°C), one loading frequency (40 Hz) and various rest periods (0, 3, 5, 10 and 25 times the length of the loading cycle). The authors found that rest periods have a significant beneficial effect on healing. The benefit seems to reach a maximum around a rest period equal to 25 times the loading cycle. The influence of the stress and strain levels on the increase in fatigue life due to rest periods seems to be negligible. Kim, et al. (1989) have mentioned that there are two different mechanisms occurring in a partially cracked asphalt concrete pavement during the rest period. One is relaxation of stresses in the system due to the visco-elastic nature of asphalt concrete and the chemical healing across micro crack and micro crack facing. Both of these mechanisms enhance the fatigue life of the asphalt pavement. When damage is large, the stress will decrease in the displacement control test, as the number of cycles increases. The difference in the stress at the same pseudo strain level is due to damage growth in the sample. Kim, et al. (1989) stated that if rest periods are introduced into the loading history and relaxation is the only phenomenon occurring during the rest period, the stress before the rest period should be equal to or less than the stress before the rest period for the same pseudo strain, based on corresponding principal theory. If the stress after the rest period is larger than the stress before the rest period at the same pseudo strain level, the increase in stress must logically be attributed to some chemical healing mechanism.

Kiggundu and Roberts (1988) defined the damage in HMA as "the progressive functional deterioration of a pavement mixture by loss of adhesive bond between asphalt binder and the aggregate surface and/or loss of cohesive resistance within the asphalt binder."

Kim, et al. (1990) evaluated the healing mechanism by conducting uniaxial tests, a relaxation test and a constant-strain-rate simple loading test with rest periods. The cyclic uniaxial test results showed the fracture healing of asphalt concrete. The nonlinear viscoelastic correspondence principle employing the concept of pseudo strain has been successfully used to account for the time-dependent effect of relaxation and to quantify the chemical healing which occurs during the rest period.

Elphingstone, et al. (1997) measured the surface energy of binders by using the Wihelmy plate apparatus. Nonpolar short range Lifshitz-van der Waals forces and long range polar acidbase forces contribute to total surface energy. Lytton, et al. (1998) found that when the shortterm healing rate increases, the non-polar surface energy reduces, and when the long-term healing rate increases, the polar acid-base surface energy reduces.

Crack growth speed is the difference between fracture speed and healing speed. Schapery proposed the equation for fracture speed and healing speed in 1984 and 1988, respectively. Little et al. (1997) proposed another healing speed relationship (eq 2.6) by analogy with rate process theory and consistent with the form of of Schapery's fracture theory.

$$\dot{C}_{h} = \left(\frac{k_{h}E_{R}D_{1c}J_{R}}{2\tau_{h}}\right)^{1/m_{c}}\beta$$
(2.6)

 $C_h$  =healing speed;

- $k_h$ =function of m<sub>c</sub> equal to 1/3;
- $E_R$  =pseudostrain reference modulus;
- $D_{1c}$  =compressive creep compliance coefficient
- $J_R$  = rate of change of dissipated pseudostrain energy per unit of newly formed crack area;

 $\tau_h$  =healing surface energy;

 $m_e$  =slope of compressive curve of log compliance versus log time; and

 $\beta$  =length of the bonding zone.

Lytton, et al. (2001) analyzed the asphalt pavement healing test data by using the hyperbolic form of the equation (eq 2.7)

$$\dot{h} = \dot{h}_2 + \frac{\dot{h}_1 - \dot{h}_2}{1 + \left(\frac{\dot{h}_1 - \dot{h}_2}{h_\beta}\right)t_r}$$

$$\dot{h}_1 = \text{initial healing rate}$$

$$\dot{h}_2 = \text{final healing Rate}$$

$$h_\beta = \text{maximum healing index increase}$$

$$t_r = \text{rest period between loadings application}$$
(2.7)

Daniel, et al. (2001) studied changes in the stiffness of two asphalt concrete mixtures (AAM and AAD) due to temperature, fatigue damage growth, and healing during the rest period. The impact resonance method was used in this study as a means of determining the dynamic modulus of elasticity of a specimen nondestructively. Healing performance of the HMA mixtures were compared by using four different methods.

(a) Percentage Increase: The percent increase in number of cycles to failure is calculated based on the differences between control test (without rest period) and healing test (with rest period) (eq 2.8)

Percentage Increase = 
$$\frac{N_{f,healing} - N_{f,control}}{N_{f,healing}}$$
(2.8)

(b) Damage Indicator: It was developed to eliminate the effects of the different number of cycles to failure for the control test. It is defined as the ratio of cycles a specimen has endured at a particular rest period and the number of cycles to failure for a particular specimen (eq 2.9).

Damage Indicator = 
$$\frac{N_{at}}{N_{f,healing}}$$
 (2.9)

(c) Horizontal Increase: It is the ratio between the total number of cycles gained from rest periods and the number of cycles to failure. (eq 2.10).

Horizontal Increase = 
$$=\frac{\sum_{1}^{n} N_{f,i\,th\,RP}}{N_{f,healing}}$$
(2.10)

(d) Drop: It is comparing the drop in modulus and flexible stiffness before rest period to the corresponding increase after the rest period.

Si, et al. (2002) conducted research based on the pseudo-strain concept to demonstrate the healing in asphalt concrete pavement. Two asphalt binders were evaluated in this study, AAD-1 and AAM-1. Cylindrical specimens of 100 mm (4 in.) in diameter and 150 mm (6in.) in height were used. The specimens were fabricated using the Superpave servopac gyratory compactor with a ram pressure of 690kPa (100 psi), gyratory speed of 30 rpm, and gyratory angle of 2.5°. The mixing temperature was 149°C (300°F), the compaction temperature was 135°C (275°F) and the testing temperature was 25°C (77°F). Change in pseudo stiffness was used to quantify microdamage and healing during the fatigue test. Pseudo stiffness is the chord slope of the stress-pseudo strain hysteresis loop. Pseudo stiffness decreases consistently with increasing number of loading cycles, indicating that microdamage occurs during the fatigue test. The significant

recovery of pseudo stiffness after rest periods demonstrates a healing effect due to rest periods. The percentage of pseudo stiffness increase is defined as the HI, as given in eq (2.11).

$$HI = \frac{\phi_{after} - \phi_{before}}{\phi_{before}}$$
(2.11)

Where;

HI = healing index; $\phi_{after} = \text{pseudo stiffness after rest period; and}$  $\phi_{before} = \text{pseudo stiffness before rest period}$ 

Dissipated pseudo-strain energy is a strong and consistent quantifier of damage and healing. High levels of cumulative dissipated pseudo-strain energy are consistent with high levels of fatigue damage, whereas low levels of cumulative pseudo-strain energy are associated with fatigue damage resistance. Pseudo stiffness and/or pseudo-strain energy are better indicators of damage than either stiffness or total dissipated strain energy. The effects of rest periods on fatigue life extension due to healing of microcracks are significant. It has been demonstrated that longer rest periods result in more healing, and in turn in greater fatigue life.

Si, et al. (2002) defined a microdamage fatigue life extended index (EI) for asphalt concrete pavement. It is defined as the percent of increase of fatigue due to the healing effect as given in eq (2.12).

$$EI = \frac{N_C - N_B}{N_B} = \frac{\Delta N_f}{N_B}$$
(2.12)

Where;

EI = fatigue life extended index;

Nc = number of cycles; before introducing rest period;

 $N_B$  = number of cycles after introducing rest period due to pseudo stiffness increase;

Nf = extended fatigue life due to healing effect of rest period.

Si, et al. (2002) conducted a study to evaluate the effect of limestone and hydrated lime on micro damage and healing of asphalt concrete based on pseudo stiffness recovery. Limestone increases the stiffness of the mix (hydrated lime increases the stiffness of the mix significantly) and micro damage also increases. Thus, fatigue life of the mixture without limestone has longer fatigue life than with it in the continuous fatigue test. Different rest periods (2, 5,10,15,40 min etc) were introduced at different cycle (300, 10000) intervals to evaluate the healing effect. From their experimental results Si, et al. (2002) revealed that all the limestone mixtures produce a better healing than mixtures using other aggregates. In addition, mixtures with hydrated lime lead to better healing than those without hydrated lime. Furthermore, hydrated limes enhanced the healing more for stiffer material than for tender materials, and the effects on healing and micro damage are highly dependent on mixture type and binder.

Carpenter, et al. (2003) suggested from their study that there is a fatigue endurance limit below which asphalt mixtures tend to have an extraordinarily long fatigue life. Carpenter and Shen (2006) conducted intermittent loading tests to observe healing by using IPC four point bending beam fatigue equipment. Such intermittent pulse sequence of a fatigue – healing test is shown in figure 2.2. These results help to explain the differences in fatigue behavior at normal and low strain levels. The results show that healing does exist and that this healing effect on fatigue life can be indicated by an energy recovery per second of rest period; the effect of healing is more prominent at low strain levels or very long rest periods. At low strain conditions, the dominance of healing compared to the very low external load damage, considering energy equilibrium, can result in full damage recovery. This full recovery of energy explains the existence of a fatigue endurance limit (FEL). Below the FEL, HMA materials tend to have extraordinary long fatigue lives, which can be related to healing.



Loading time, second

# Figure 2.1 Harversine Load Pulse Sequence of Fatigue-Healing Test (Carpenter and Shen 2006)

Acoustic Emission (AE) has been widely used for the condition assessment and damage detection of many materials. It is a fast maturing non- destructive evaluation (NDE) tool. Detection of the sound caused by micro damage and plastic deformation in materials was used to design the AE technology. Seo, et al. (2008) studied the fatigue damage and healing behavior in asphalt concrete based on acoustic emission (AE). Tests were carried out for PG64-22 binder, 1 Hz frequency, temperature 20 °C and different rest periods (10, 20, 40, 80, 160, 320, 640 sec etc). Results showed that fatigue life becomes longer and AE energy accumulation becomes slower as the rest period between loading cycles increases. Furthermore, it was demonstrated that accumulative AE energy can be used as a parameter (AE) to identify the fatigue damage and healing in asphalt concrete.

#### **2.2.3 Binder Healing**

Pioneering work by Wool and O'Connor (1978 and 1981) on polymer healing has provided important knowledge about asphalt healing.

Different methods have been developed to quantify asphalt healing. Pseudo strain energy approach was used by Kim, et al. (1990) and Little et al. (2001) to describe healing with either intrinsic healing function that considers molecular structure, or wetting function that takes into account the cumulative effect of intrinsic healing and wetting.

Bahia et al. (1999) used an interrupted loading sequence to show the effect of healing. Asphalt binder was loaded in a Dynamic Shear Rheometer (DSR), and stopped after each 5000 loading cycles with resting times of 1 hour, 2 hours, and 12 hours. Tests were carried out with binder type PG64-22 and PG76-22 at temperatures ranging from 20 °C – 40 °C. However, such loading with long rest periods is not typical in the real field, especially for busy highways. Carpenter and Shen (2006 and 2009) therefore introduced an intermittent loading sequence by apply short rest periods (2-9 seconds) after every loading cycle in a flexural bending beam test to study the healing of HMA mixtures. Shen et al. (2009) later applied this loading sequence to the asphalt binder by using the DSR test.

Lytton, et al. (2001) developed a micromechanics fracture and healing model for asphalt based on an investigation of the rate of change in dissipated pseudo strain energy and the cohesive surface energy. Using X-ray CT and Dynamic Mechanical Analyzer (DMA), damage and healing was monitored and described in the continuum and micromechanics damage models (Song, 2005).

Kim, et al. (2002 and 2003) applied torsional loading (apparatus shown in figure 2.1) to quantify healing as the increase in fatigue life due to the application of rest periods during the

test. Their work also showed that the healing effect is most prominent when rest periods are applied before significant damage occurs.



Figure 2.2 Cylindrical Sample with Holders in DMA. (Kim, et al. 2003)

Kim, et al. (2003) investigated the effect of the processes on fatigue fracture and fracture healing during controlled-strain, dynamic mechanical analysis (DMA) testing. Sand asphalt samples were fabricated with two SHRP-classified binders: AAD-1 and AAM-1. DMA testing was performed at 25°C and at 10 Hz. The mechanical response during DMA testing was monitored using three different damage indicators:

- 1 Change in dynamic modulus
- 2 Change in pseudo stiffness
- 3 Change in dissipated strain energy

When either of these parameters is plotted versus the number of load cycles, two inflection points are apparent that define a significant change in sample behavior due to damage. The second inflection point is a reasonable definition of failure, and is strongly correlated with the peak of the plot of phase angle versus load repetitions. Furthermore, the phase angle drops precipitously at the second inflection point. By performing controlled-strain torsional fatigue tests at three different strain levels, each great enough to induce damage, a reproducible fatigue relationship (number of load cycles as a function of stress level) is developed. The introduction of several rest periods during testing lengthened fatigue life. Successful development of this testing method is suggested as a potential specification-type test method because of its efficiency, reproducibility, and reliability.

Kim, et al. (2006) studied healing characteristics of asphalt binders in different asphalt mixtures and quantified healing in terms of the recovered dissipated creep strain energy per unit of time. This study revealed that dissipated energy measurement obtained from the area of the hysteresis loop during the cyclic loading test should not be used to calculate fatigue damage because this hysteresis loop includes the irreversible (viscous) dissipated energy and reversible (elastic) dissipated energy; however, only the irreversible dissipated energy contributes to the damage. Kim, et al. (2006) found irreversible dissipated energy by using the rheological parameters obtained from static creep test data.

Shen, et al. (2009) conducted an analysis of binder fatigue and healing using laboratory Dynamic Shear Rheometer (DSR) testing. Tests were performed in controlled stress loading mode (60 kPa, 70 kPa, 180 kPa and 230 kPa), one frequency (10 Hz) and three different rest periods ( 2 sec, 4 sec and 6 sec). The ratio of dissipated energy change (RDEC) approach, which is based on fundamental dissipated energy concepts, was used in this study. This study revealed that asphalt binder healing affects the fatigue performance in both qualitative and quantitative ways. Furthermore, temperature effect, stress level effect and binder type effect on binder healing were evaluated in this study. This evaluation revealed healing potential increase with temperature increment and stress reduction. Furthermore, modified binder (PG70-28) has more healing potential than PG64-28 binder.

Little, et al. (2007 and 2009) pointed out the three primary healing processes for asphalt: (1) wetting of the two faces of a nanocrack; (2) diffusion of molecules from one face to the other; (3) randomization of the diffused molecules to attempt to reach the level of strength of the original material. Their effort skillfully related the intrinsic healing of asphalt to surface energy and molecular structure based on dissipated pseudo-strain energy.

Shan, et al. (2010) used the thixotropy concept to analyze fatigue and healing mechanisms in asphalt binder by using the model developed by Cheng and Evans (1965).

$$\frac{d\lambda}{dt} = a(1-\lambda)^c - b\lambda\gamma^d$$
(2.13)

Where,

 $\lambda$  = state variable;

a,c = coefficient related to microstructural build-up;

b,d = coefficient related to microstructural break-down; and

 $\gamma^{\cdot}$  = shear rate.

This concept can be used to explain the material behavior and efficient evaluation technique. The break-down and build –up of the microstructure during the fatigue and healing test can be related (equation 2.5) to properties observed by using this concept. Viscosity is the main parameter used to reflect micro structure changes for thixotropy. Shan, et al. (2010) used dynamic viscosity to characterize fatigue. Three terminal dynamic viscosity values (20%, 40%)

and 60% of the initial value), PG70-28 binder, five rest periods (1 hour, 6 hours, 12 hours, 24 hours and 48 hours), 4E05Pa stress level and 25 °C temperature were used to evaluate the efficiency of healing at different micro structure configurations. Results showed that binder performance improves after a rest period. Longer rest periods always yield more improvement, although specific effect depends on materials and the micro structure configuration immediately after the rest period began.

Given all the excellent work on asphalt healing and its fundamentals, the key factors that can impact asphalt healing, the quantitative contribution of asphalt adhesive healing to material performance, and the way to link healing to material and pavement design have not been fully identified.

#### **2.2.4 Polymer Healing**

Prager and Tirrell (1981) described the healing mechanism in polymers as follows:

"When two pieces of the same amorphous polymeric material are brought into contact at a temperature above the glass transition, the junction surface gradually develops increasing mechanical strength until, at long enough contact times, the full fracture strength of the virgin material is reached. At this point the junction surface has in all respects become indistinguishable from any other surface that might be located within the bulk materials: we say the junction has healed."

Five different stages of polymer healing were identified by Wool and O'Connor (1981). Those are surface rearrangement, surface approach, wetting, diffusion and randomization. In addition, the concept of minor chain was explained by Kim and Wool (1983) as follows:

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"By the end of the wetting stage, potential borders associated with the inhomogeneities at the interface disappear, and the stages of diffusion and randomization are the most important ones because chains are free to move across the interface and the characteristic strength of a polymer material appears in these stages."

Research has been done by different researchers in polymer healing. Dong, et al. (2008) reviewed the recent development of self healing polymer materials such as thermoplastic material and thermoset material. Self healing in thermoplastic material can be achieved from molecular interdiffusion, photoinduction, recombination of chain ends, reversible bond formation, living polymer approach, and nanoparticles (figure 2.3), among others. Self healing in the thermoset material can be explained by using different approaches such as hollow fiber approach (Zako, et al., 1999) and microencapsulation approach (Dry, 1992). Healing in thermoset materials can be achieved by using thermoplastic additives as healing agents and rearranging the polymer chain. Zako, et al. (1999) conducted a study to evaluate the performance of thermoplastic additives as a self-healing agent to thermoset materials which can increase healing capacity without altering the polymer matrix while also providing a solidifying crack filler capacity of rebounding fracture surface.



Figure 2.3 Schematic Diagram of Nanoparticle Movement during Crack Growth in the Thermoplastics (Dong, Et Al., 2008)



Figure 2.4 Concept of Healing Mechanism in Hollow Fibre-Based Self-Healing Composites (Dry, 1992)



Figure 2.5 Concept of Healing Mechanisms in Thermoplastic Bead-Based Self-Healing Composites (Zako, et al. 1999)

By analyzing the Kessler (2002) studies, Kessler et al (2003) revealed that healing efficiency in the polymer is significantly affected by temperature. Healing at an elevated temperature increases both the rate of polymerization and the ultimate degree of cure for the healing agent. Furthermore, Kessler (2002) justified that by increasing polymerization there is less chance for the healing agent to evaporate or diffuse away from the crack plane. Additionally, a higher degree of cure can result in a polymerized healing agent with superior mechanical and adhesive properties.

The self healing efficiency of polymer materials was evaluated by fatigue test. In this test the researchers considered successful healing as the recovery of stiffness lost due to damage induced by cyclic loading rather than changes in crack growth rate or absolute fatigue life change (Dong ,et al. 2008).

Xiao, et al. (2009) conducted experimental studies to evaluate healing agent (expoxyloaded capsules) effects on polymer healing. Results revealed that a significant amount of selfhealing efficiency (80%) can be achieved by adding a small amount (5% by weight) of the healing agent (expoxy-loaded capsules) with 30µm size for some polymer composites. Furthermore, self-healing efficiency depends on time. It increases with time and reaches a constant value after a certain period; this time varies for different polymer composites and depends on several other factors (temperature, etc.).

Microcapsules containing a solvent and reactive epoxy resin are a critical component for the development of cost-effective, low toxicity, and low flammability self-healing materials. Blaiszik, et al. (2009) found that microcapsules are satisfying the requirements for use in selfhealing materials including processing survivability, and thermal stability, and they are efficient in *in situ* rupture for delivery of the healing agent.

## **2.3 Dissipated Energy**

The use of energy in measurement provides two important advantages: 1) energy is scalar measure independent of direction of applied stresses and strain; and 2) energy encompasses stress, strain and material property in a single measure (Running, 1996). Dissipated energy has been used by many researchers (Rowe, 1993; Zhang, et al. 2001; Ghuxlan, 2001; Birgisson, et al. 2002; Roque, et al. 2002, 2004; Kim et al 2003; Shen, et al. 2005, 2006, 2007, 2009; Carpenter,

et al. 2006; Kim, et al. 2006; Bhasin, et al. 2009 and others) to evaluate the fatigue and healing behavior of asphalt mixture and binder.

# 2.3.1 Dissipated Energy in Cyclic Loading

The dissipated energy from cyclic loading can be determined by calculating the energy losses associated with the phase angle (figure 2.6). This energy loss can be found experimentally by calculating area of the hysteresis loop (figure 2.7).



Figure 2.6 Oscillating Stress, Strain and Phase Lag (Kim, et al. 2006)



Figure 2.7 Typical hysteresis Loop for Undamaged Nonlinear Viscoelastic Asphalt Concrete (Si, et al., 2002)

The amount of energy loss during one complete cycle can be calculated by integrating the increment of work done  $\sigma d\varepsilon$  over a complete cycle of time T, as follows:

$$\Delta DE = \int_0^T \sigma \frac{d\varepsilon}{dt} dt$$
 (2.13)

But  $\sigma = \sigma_0 \sin wt$  and  $\frac{d\varepsilon}{dt} = w\varepsilon_0 \cos(wt - \delta)dt$ 

So 
$$\Delta DE = \int_0^T w \sigma_0 \varepsilon_0 \sin wt \cos(wt - \delta) dt$$
 (2.14)

By integrating eq (2.14), we can get following expression for energy loss per loading cycle

$$DE_{i} = \pi \sigma_{i} \varepsilon_{i} Sin \delta_{i}$$
(2.15)

## **Control stress**

Substitute  $\sigma = G^* \varepsilon$ in eq (2.15)

$$\varepsilon_{i} = \frac{\sigma_{i}}{G_{i}}$$
Control strain
$$\sum_{b \in \pi^{i}(Sin\delta)} \text{ in eq. (2.15)}$$

(2.17)

Substitute

in eq (2.15)

$$DE_i = \frac{\pi \sigma_i^2 Sin \delta}{G_i^*}$$

Where.

DEi = the dissipated energy at cycle i;

 $\sigma, \varepsilon$  = the controlled stress or strain i;

= the phase angle at cycle i;  $\delta$ 

- $G_i^*$  = the complex modulus at cycle i.
- = Angular frequency. W

Micro crack damage occurring in asphalt binder was demonstrated by Kim, et al. (2003) by using cyclic loading test results. The changes in area and slope of the hysteresis loop during continuous cyclic loading reflect that micro damage has occurred. Furthermore, Kim, et al. (2003) revealed that stress-strain loops shifted downward with the reduction of dissipated energy, which is determined from the area inside the stress-strain curve (figure 2.8). The stresspseudo strain relationship within the frame work of continuous damage mechanism has been used for the characterization of damage. The underlying concept in this approach is based on separating the energy that is dissipated due to the damage from the viscoelastic energy. Thus, the area inside the hysteresis loop of the stress-pseudo strain curve is the actual damage energy (figure 2.9).

In addition, Kim et al. (2003) revealed that the propensity for micro damage occurrence in different mixtures can be determined by measuring the difference in secant slopes (pseudo stiffness) of the stress–pseudo strain plots during fatigue testing (figure 2.9).



Figure 2.8 Stress –Strain Loop (Kim, et al. 2003)



Figure 2.9 Stress-Pseudo Strain Loop (Kim, et al. 2003)

Kim, et al. (2006) proved from their test results that the loop area does not represent irrecoverable dissipated creep strain energy alone. It appears that the loop area contains not only irreversible energy, but also reversible energy.

# 2.3.2 Research Approaches Using Dissipated Energy

Different approaches have been developed based on the concept of dissipated energy for studying HMA and asphalt binder, which mainly falls into four groups.

- 1. Initial dissipated energy approach
- 2. Cumulative dissipated energy approach
- 3. Work ratio approach
- 4. Ratio of dissipated energy change (Discussed in section 3.1)

## **2.3.2.1 Initial Dissipated Energy Approach**

Initial dissipated energy is the dissipated energy measured at initial loading cycles. Rowe (1993) and Ghuxlan (2001) found that initial dissipated energy is a significant factor that affects HMA fatigue behavior. SHRP-A-404 (1994) developed a fatigue life prediction model (eq 2.17) based on initial dissipated energy and percentage of voids filled with bitumen.

$$N_f = 6.72e^{0.049VFB} (w_0)^{-2.047}$$
(2.18)

Where,

N<sub>f</sub> =fatigue life

 $W_{o =}$  Initial dissipated energy

VFB=percentage of voids filled with bitumens

Carpenter and Shen (2006) found that initial dissipated energy is not applicable for low strain level fatigue tests and it does not consider the healing effect.

## 2.3.2.2 Cumulative Dissipated Energy Approach

The summation of dissipated energy released from the material during the fatigue test is called cumulative dissipated energy. Cumulative dissipated energy and the number of loading cycles to failure is related as:

$$W_N = A(N_f)^z$$
 (2.19)

 $W_N$  = Cumulative dissipated energy to failure

 $N_f =$  Number of loading cycle to failure

A,z = experimentally derived mix coefficient

Van Dijk (1975, 1977) studied dissipated energy to evaluate fatigue in HMA materials. He found a strong relationship between cumulative dissipated energy and the number of loading cycles to failure.

Stiffness ratio and dissipated energy ratio were introduced by Tayebali et al (1992). Stiffness ratio is the ratio of stiffness at loading cycle to initial loading. Dissipated energy ratio is the ratio of cumulative dissipated energy up to loading cycle to cumulative dissipated energy until fatigue life.

## 2.3.2.3 Work Ratio Approach

Work ratio is defined as the ratio between the products of the initial dissipated energy in cycle 1 and N1 divided by the cumulative dissipated energy, as shown in equation 2.19. This idea was introduced by Van Dijk and Visser (1977).

$$\psi_{N1} = \frac{w_0 N_1}{W_{N1}} \tag{2.20}$$

Where,

 $w_0 =$  Initial dissipated energy

 $N_1$  = Number of load cycles to crack initiation

 $W_{N1}$  = Cumulative dissipated energy at cycle  $N_1$ 

Rowe (1993) calculated the work ratio in terms of the initial rheology property of the mixtures and mode of loading factor.

## 2.3.3 Fracture related to dissipated energy

The relationship between dissipated energy and fracture is illustrated by HMA fracture mechanical model (Zhang et al.,2001; Roque et al.,2002; Birgisson et al., 2002; Roque et al., 2004). This model was developed based on the principle that both crack initiation and crack growth are controlled by the tolerance of a mixture to creep strain energy induced by applied loads. A crack will initiate and/or grow when the energy dissipated by the asphalt mixture exceeds the dissipated creep strain energy threshold can be determined to be a fundamental mixture property that is independent of loading, including rate of loading. Fracture related to dissipated energy is discussed further in section 2.2.2.3.

#### 2.4 Summary

Based on the literature review above, fatigue and healing tests were carried out to evaluate asphalt binder fatigue and healing behavior by using dynamic shear rhenometer (DSR). Many studies have been done to evaluate and identify the healing potential in different materials. A significant number of studies have been aimed at polymer healing by many researchers, but those studies are mainly focused on the self healing capacity of polymer materials. Only a few studies have been done on the asphalt binder healing.

Existing binder healing studies are lacking in providing a clear physical picture of asphalt binder healing mechanisms. It is necessary to develop a healing prediction model based on fundamental material properties, applied load, and loading speed.

After a broad literature review and research investigation, it is felt that dissipated energy based on fundamental energy concept has the capacity to effectively evaluate and understand the healing phenomenon of asphalt binders. Healing study by using dissipated energy fits the overall goal of identifying the mechanism of asphalt healing and developing algorithms in pavement design. Therefore, in the later chapters this approach is introduced and discussed, and applied to the healing study of asphalt binders.

## **CHAPTER THREE**

# RATIO OF DISSIPATED ENERGY CHANGE APPROACH FOR BINDER FATIGUE AND HEALING ANALYSIS

## **3.1 Introduction**

The ratio of dissipated energy change (RDEC) approach has been proved to be a good approach for the characterization of asphalt materials fatigue and healing properties (Carpenter et al. 2006, Shen et al. 2005, 2006, 2007, 2009, Bhasin et al. 2009). It will be applied in this thesis for the study of adhesive asphalt healing. This approach is based on the theory of viscoelasticity and considers that not all dissipated energy is responsible for damage propagation. Only the relative amount of energy dissipation coming from each additional load cycle, while excluding the energy dissipated through viscoelastic behaviors such as viscous damping, will produce further damage (Shen et al. 2005). This approach has resulted in development of an energy parameter, plateau value (PV), which is an indication of the ratio of dissipated energy change (RDEC) during a fatigue test. Plateau value (PV) has been demonstrated (Carpenter et al. 2006, She et al. 2006, 2005, 2009) as a unique parameter which links individual components of material properties and loading conditions to fatigue life, fatigue endurance limit, and healing, thus to be easily integrated into the pavement design algorithm. A low plateau value (PV) can be found either in high fatigue resistant materials, low external loading amplitude, or both. Readers are referred to other sources (Carpenter et al. 2006, Shen et al 2005, 2006, 2007) for details of the RDEC approach and its application in asphalt binders and mixtures.

$$RDECm = \frac{\left|DE_{m} - DE_{n}\right|}{DE_{m} \times (m-n)}$$
(3.1)

Where:

RDECm = Ratio of Dissipated Energy Change value at cycle m,

DEm, DEn = Dissipated Energy at Cycle m and n,

m,n=loading cycle,m>n.

### **3.2 Dissipated Energy Variation with Loading Cycle**

Under the controlled strain loading mode, the development of dissipated energy in the binder fatigue-healing test showed three distinctive stages (Figure 3.1(a)): (I) dissipated energy reduces with increasing dissipated energy reduction rate, (II) dissipated energy reduces gradually with an almost constant slope (constant energy change rate), and (III) dissipated energy reduces with a reducing dissipated energy reduction rate. This corresponds to the three stages of the ratio of dissipated energy change (RDEC), as shown in figure 3.1(b). Although slightly different from the RDEC plot for HMA mixtures (Carpenter et al. 2006, Shen et al. 2005, 2007), it is typical that the second stage is a plateau stage, and the RDEC value at the second stage is almost constant, which is considered as the plateau value (PV). The analysis of the testing data indicates that such plateau stage starts from approximately the 15% initial shear modulus reduction until the 50% initial shear modulus reduction.



Figure 3.1 Dissipated Energy Changes in a Binder's Constant Strain Fatigue Test (a) Dissipated Energy Vs. Loading Cycles, (B) Schematic Plot of the Corresponding Ratio of Dissipated Energy Change Plot with Three Distinctive Stages

## 3.3 PV- Nf Relationship

Experimental results showed a unique PV- Nf relationship for controlled stress loading mode and controlled strain loading mode of HMA mixtures (Shen, et al. 2006). Under the controlled strain loading mode, the dissipated energy analysis further verified that the PV –Nf relationship still holds for the binder fatigue-healing tests. For all of our tests with different binder types, aging properties, and tested at different temperatures, frequencies, and strain levels, the PV was found to uniquely relate to the fatigue life of initial 50% modulus reduction with a power law relationship, as shown in Figure 3.2.



Figure 3.2 PV-Nf Plots for all Testing Data

Unlike asphalt mixtures, it was found for asphalt binders that there was no unique relationship between PV and Nf under stress controlled and strain controlled loading modes (figure 3.2). PV value calculated from the experimental data and theoretical derivation has almost the same value as shown in the figure 3.2 for strain controlled mode of loading. This finding is supported by limited experimental data, and was theoretically derived using fundamental visco-elastic characteristics. A presentation of the derivation process is provided below.

## (a) Strain Controlled Mode of Loading

Dissipated Energy at  $m^{th}$  loading cycle (DE<sub>m</sub>) is found by substitute i = m in the eq(2.17)

$$DE_m = \pi G_m^* \varepsilon_m^2 \sin \delta_m \tag{3.2}$$

Dissipated Energy at  $n^{th}$  loading cycle (DE<sub>n</sub>) is found by substitute i = n in the eq(2.17)

$$DE_n = \pi G_n^* \varepsilon_n^2 \sin \delta_n \tag{3.3}$$

By substitute eq (3.2) and eq (3.3) into eq(3.1)

$$PV = \frac{\left|\pi G_m^* \varepsilon_m^2 \sin \delta_m - \pi G_n^* \varepsilon_n^2 \sin \delta_n\right|}{\pi G_m^* \varepsilon_m^2 \sin \delta_m (m-n)}$$
(3.4)

Experimental results showed that the approximate dissipated energy changing rate is constant between 15% initial G\* reduction and 50% initial G\* reduction.

$$\mathbf{m} = N_{f50} \tag{3.5}$$

$$\mathbf{n} = N_{f15} \tag{3.6}$$

Where,

- $N_{f50}$  = No of loading cycle to get 50 % initial G\* reduction
- $N_{f15}$  = No of loading cycle to get 15 % initial G\* reduction

Substitute eq(3.5) and eq(3.6) into eq(3.4)

$$PV = \frac{\left|\pi G_{N_{f50}}^{*} \varepsilon_{N_{f50}}^{2} \sin \delta_{N_{f50}} - \pi G_{N_{f15}}^{*} \varepsilon_{N_{f15}}^{2} \sin \delta_{N_{f15}}\right|}{\pi G_{N_{f50}}^{*} \varepsilon_{N_{f50}}^{2} \sin \delta_{N_{f50}} (N_{f50} - N_{f15})}$$
(3.7)

It is strain controlled mode of loading. So, Strain is constant

$$\mathcal{E}_{N_{f50}} = \mathcal{E}_{N_{f15}} \tag{3.8}$$

Furthermore, experimental results showed that there will not be much variation in the phase angle throughout the test.

$$\delta_{N_{f^{50}}} = \delta_{N_{f^{15}}}$$

(3.9)

Then, substitute eq(3.8) and eq(3.9) into the eq(3.7)

$$PV = \frac{\left|G_{N_{f50}}^{*} - G_{N_{f15}}^{*}\right|}{G_{N_{f50}}^{*}(N_{f50} - N_{f15})}$$
(3.10)

$$PV = \frac{\left|\pi G_{N_{f50}}^* \varepsilon_{N_{f50}}^2 \sin \delta_{N_{f50}} - \pi G_{N_{f15}}^* \varepsilon_{N_{f50}}^2 \sin \delta_{N_{f50}}\right|}{\pi G_{N_{f50}}^* \varepsilon_{N_{f50}}^2 \sin \delta_{N_{f50}} - N_{f15}}$$
(3.11)

After 50% of initial G\* reduction, G\* is equal to 50% of the initial G\*

After 15% of initial G\* reduction, G\* is equal to 85% of the initial G\*.

So,

$$G_{N_{f50}}^{*} = 0.5 G_{initial}^{*}$$
(3.12)  
$$G_{N_{f10}}^{*} = 0.85 G_{initial}^{*}$$
(3.13)

Substitute eq(3.12) and eq(3.13) into eq(3.11)

$$PV = \frac{\left|0.5G^{*}_{initial} - 0.85G^{*}_{initial}\right|}{0.5G^{*}_{initial}(N_{f50} - N_{f15})}$$
(3.14)

$$PV = 0.7(N_{f^{50}} - N_{f^{15}})^{-1}$$
(3.15)

Experimental results showed that  $N_{f15\%}$  is between 0.4 to 0.6 times of  $N_{f50\%}$ 

So, approximately  $N_{f15} = 0.5N_{f50}$  (3.16)

Then substitute eq(3.16) into eq(3.15)

,

$$PV = 1.4 (N_{f^{50}})^{-1}$$
(3.17)

So,

# (b)Stress Controlled Mode of Loading

Following a similar procedure, PV- Nf relationship was derived from the fundamental theoretical equation and asphalt binder material behavior in a stress controlled mode of loading.

Dissipated Energy at  $m^{th}$  loading cycle (DE<sub>m</sub>) is found by substitute i = m in the eq(2.16)

$$DE_m = \frac{\pi \sigma_m^2 \sin \delta_m}{G_m^*}$$
(3.18)

Dissipated Energy at  $n^{th}$  loading cycle (DE<sub>n</sub>) is found by substitute i = n in the eq(2.16)

$$DE_{n} = \frac{\pi \sigma_{n}^{2} \sin \delta_{n}}{G_{n}^{*}}$$
(3.19)

By substitute eq (3.18) and eq (3.19) into eq(3.1)

$$PV = \frac{\left|\frac{\pi\sigma_m^2 \sin\delta_m}{G_m^*} - \frac{\pi\sigma_n^2 \sin\delta_n}{G_m^*}\right|}{\frac{\pi\sigma_m^2 \sin\delta_m}{G_m^*}(m-n)}$$
(3.20)

Experimental results showed that approximately dissipated energy changing rate is constant between 10% initial G\* reduction and 50% initial G\* reduction.

$$\mathbf{m} = N_{f50} \tag{3.21}$$

$$\mathbf{n} = N_{f10} \tag{3.22}$$

Where,

 $N_{f50}$  = No of loading cycle to get 50 % initial G\* reduction  $N_{f10}$  = No of loading cycle to get 10 % initial G\* reduction Substitute eq(3.21) and eq(3.22) into eq(3.20)

$$PV = \frac{\left|\frac{\pi\sigma_{N_{f50}}^{2}\sin\delta_{N_{f50}}}{G_{N_{f50}}^{*}} - \frac{\pi\sigma_{N_{f10}}^{2}\sin\delta_{N_{f10}}}{G_{N_{f10}}^{*}}\right|}{\frac{\pi\sigma_{N_{f50}}^{2}\sin\delta_{N_{f50}}}{G_{N_{f50}}^{*}}(N_{f50} - N_{f10})}$$
(3.23)

It is stress controlled mode of loading. So, Stress is constant

$$\sigma_{N_{f50}} = \sigma_{N_{f10}}$$
 (3.24)

Furthermore experimental results showed that there will not be much variation in the phase angle throughout the test.

So, 
$$\delta_{N_{f50}} = \delta_{N_{f10}}$$
(3.25)

Substitute eq(3.25) and eq(3.26) into eq(3.27)

$$PV = \frac{\left|\frac{\pi \sigma_{N_{f50}}^{2} \sin \delta_{N_{f50}}}{G_{N_{f50}}^{*}} - \frac{\pi \sigma_{N_{f50}}^{2} \sin \delta_{N_{f50}}}{G_{N_{f50}}^{*}}\right|}{\frac{\pi \sigma_{N_{f50}}^{2} \sin \delta_{N_{f50}}}{G_{N_{f50}}^{*}} (N_{f50} - N_{f10})}$$

$$PV = \frac{\left|\frac{1}{G_{N_{f50}}^{*}} - \frac{1}{G_{N_{f50}}^{*}}\right|}{\frac{1}{G_{N_{f50}}^{*}} (N_{f50} - N_{f10})}$$
(3.26)
$$(3.27)$$

In addition, 50% of initial G\* reduction is equal to 50% of the initial G\* and 10% of initial G\* reduction is equal to 90% of the initial G\*.

So,

$$G_{N_{r_{50}}}^* = 0.5 G_{initial}^*$$
(3.28)

$$G_{N_{f10}}^* = 0.9 \ G_{initial}^*$$
 (3.29)

Substitute eq(3.28) and eq(3.29) into eq(3.27)

$$PV = \frac{\left|\frac{1}{0.9G^{*}_{initial}} - \frac{1}{0.5G^{*}_{initial}}\right|}{\frac{1}{0.5G^{*}_{initial}}(N_{f50\%} - N_{f10\%})}$$
(3.30)

$$PV = 0.44(N_{N_{f50}} - N_{N_{f50}})^{-1}$$
(3.31)

Experimental results showed that  $N_{f10}$  is between 0.4 to 0.6 times of  $N_{f50}$ 

So, approximately,

$$N_{f10} = 0.5 N_{f50} \tag{3.32}$$

Substitute eq (3.38) into eq (3.37)

$$PV = 0.88 (N_{f^{50}})^{-1}$$
(3.33)

Derived equations for strain controlled loading mode (eq 3.17) and stress controlled loading mode (eq 3.33) showed that each type of loading mode has separate unique PV-Nf relationships. This is further confirmed in Figure 3.2 where the PV-Nf relationship from stress controlled and strain controlled loading modes are clearly different from each other. However, the PV-Nf relationship obtained from the derivation equations (eq 3.18) consistently matches the experimental testing results.

# **3. 4 Definition of the Healing Rate**

A healing rate defined as the slope of the ln (PV)-RP curve is used to quantify the effect of healing (Figure 3.3). It represents the rate of energy recovery per unit of rest time, and is not affected by the length of rest time used in the healing test. In other words, although extending the rest time can increase the total effect of healing, it is not an effective method a materials engineer should purely rely on. Instead, modifying the material physical and chemical property should be considered for maximizing healing effect and improving the service of the material life.



Figure 3.3 Schematic of ln(PV) - RP Variation

#### **CHAPTER FOUR**

## MATERIAL AND TESTING PROGRAM

## 4.1 Materials

Two types of binders that are typically used in the Eastern region of Washington State were used in this study, PG64-28 and PG70-28. To evaluate the effect of aging on healing, these binders were also subjected to the Rolling Thin Film Oven (RTFO) test (AASHTO T 2140) and the Pressure Aging Vessel test (PAV) (AASHTO ASTM D 454) to produce laboratory results for short term and long term aged binder for fatigue and healing testing.

These binders were thoroughly tested for their fatigue and healing characteristics under various testing conditions. Although limited binder types were used, this study aimed to develop a general testing protocol and data analysis methodology for the evaluation of asphalt binder healing, which can be further validated and expanded for other binder sources.

#### 4.2 Fatigue and Healing Test

This test used the oscillatory Dynamic Shear Rheometer (DSR) test to characterize the fatigue and healing of asphalt binders. Although not a standard testing method, the DSR test is considered as a useful technique and has been extensively used in the investigation of asphalt binders because it allows the strain amplitude and the time scale (loading frequency) to be varied independently (Monismith, et al. 1985, Bahia, et al. 1999, Anderson, et al. 2001). By using a parallel plate set up in DSR, the nature of traffic loading in asphalt pavements can be simulated and the dissipated energy can be evaluated effectively (Bahia, et al. 1999). However, edge effect in the parallel plate set up can be a concern because it may cause heterogeneous flow (plastic flow), especially at high temperatures. Anderson, et al. (2001) suggested performing the binder

fatigue test at lower temperatures (higher initial complex modulus G\*) in DSR testing to ensure that the binder fails in the form of "fatigue" rather than "instability flow". Bahia, et al. (1999), Delgadillo, et al. (2005) and Martono, et al. (2007) compared the results from parallel plate and cone/plate (cylinders torsion testing) for a few asphalts and concluded that the results were very similar and differences were negligible. They suggested that the geometry of parallel plate could be used and the errors resulting from the heterogeneous flow field could be accepted as part of the experimental error.

To verify the actual failure modes of binders fatigue and healing tests conducted during this study, the surface of the DSR specimen was inspected carefully after complete failure (detachment of upper and lower specimen). Hairline cracks extending from the center of the specimen to the outer edge were noticed for specimens tested at temperatures of 20°C degrees or lower, while a combination of hairline cracks and ring flows were observed in specimens tested at 25°C or higher. These findings confirmed that the major failure mode is fatigue cracking, while some plastic flow can occur when tested at higher temperatures. Furthermore, it was noticed that the hairline crack surface vanished and gradually turned into a smoother surface after the specimen was kept at room temperature (about 25°C) for 2 hours. This could be explained as an asphalt wetting phenomenon, as indicated in the literature (Bhasin, et al. 2009).

A Gemini 150 Dynamic Shear Rheometer (DSR) from Malvern Inc. (figure 4.1) was used to conduct a binder fatigue and healing test. Compared with previous generation DSRs, the newer version of DSR can apply an extended torque range up to 150mNm without having compliance effects. A DSR testing Geometry Schematic is given in figure 4.2. Owing to the special design of the software and hardware, the Malvern Gemini 150 has the capability of using an intermittent loading sequence with short rest periods added after every certain number of cycles (ten cycles in this study). The low inertia (total system inertia with plates and motor) and the excellent bearing torque mapping technology offered by Malvern enables quick and accurate results that can be recorded after every rest period. Such intermittent loading sequences were adopted in this study to better simulate field loading conditions, particularly for busy highways with short rest periods (Carpenter et al. 2006, Shen et al. 2009). By using the intermittent loading sequence, the continuous loading nature was maintained so that the dissipated energy could still be calculated for each load cycle and the ratio of dissipated energy change (RDEC) approach could be used. Other setups in the DSR test include 8mm diameter spindle with 2mm gap, and constant strain loading modes with three repetition tests. An 8 mm diameter and 2mm thick sample was prepared in the silica mold. For the failure criteria, the traditional 50% stiffness reduction approach has been widely used by pavement researchers (Tsai et al. 2005, Johnson et al. 2007) and was adopted by this study. Different studies have demonstrated that this failure criteria is not simply an arbitrary definition. It can be reasonably related to the field performance (Tayebali et al. 1993) and the true failure based on a dissipated energy analysis (Ghuzlan et al. 2001). Except as specified, all tests were conducted at standard conditions of 25°C degree temperature, 10Hz frequency, and 3% controlled strain using original binder.



**Figure 4.1 Dynamic Shear Rheometer** 



Figure 4.2 DSR Testing Geometry Schematic (Shen, et al. 2006)

The healing behavior of different asphalt binders (PG64-28 and PG70-28) were evaluated in different testing conditions (temperature, frequency and strain level), rest period (0, 2, 4, 6 sec) and aging condition (short term aging and long term aging). Tests were carried out only by changing one testing condition from the standard testing condition. Standard testing conditions consisted of frequency 10Hz, temperature 25°C and strain level 3%.

#### **CHAPTER FIVE**

## **BINDER FATIGUE AND HEALING ANALYSIS**

## **5.1 Traditional Fatigue Life Analysis**

## **5.1.1 Effect of Rest Period**

Traditional fatigue analysis was conducted to evaluate the effect of healing due to rest periods on the fatigue performance of asphalt binder. The most direct impact of rest periods on fatigue performance of asphalt binder is the dynamic shear modulus (G\*) reduction rate. As shown in figure 5.1 for PG64-28 binder tested at 25°C temperature, 10Hz frequency, and 3% controlled strain level, more loading cycles are needed for the G\* to be reduced to 50% when 6 second rest periods are used because the number of cycles for 50% G\* reduction is typically used to define fatigue failure. Figure 5.1 indicates that rest periods can significantly extend the fatigue life for PG64-28 binder.



Figure 5.1 Binder G\* Deterioration Curve at Standard Condition for PG64-28 Binder

Figure 5.2 compares fatigue life when different rest periods are applied. For the PG64-28 binder, fatigue life was 2.4 times longer with a 6 second rest period at standard testing conditions. Similar observations were obtained for the PG70-28 binder. With a 6 second rest period and tested under the same condition, binder fatigue life was extended 3.1 times.



Figure 5.2 Fatigue Life Extensions at Standard Condition for PG64-28 and PG70-28

## 5.1.2 Effect of testing conditions and aging

Further evaluation of the fatigue data indicates that testing conditions and the degree of aging have significant impact on fatigue life extension due to healing. As shown in Figure 5.3, 5.4, 5.5 and 5.6 under controlled strain loading modes, frequency and strain inversely affect fatigue life, while temperature and the degree of aging (from short term rolling thin film oven (RTFO) aging to long term pressure aging vessel (PAV) aging) directly influence fatigue life. The effect of frequency, temperature, strain, and aging on fatigue behavior is significantly enhanced when rest periods are introduced, while the trend of impact remains the same. With six

second rest periods, the difference of fatigue life is greater than the no rest period case for the same 5 degree temperature difference or 5Hz frequency difference.

In addition, the testing indicated aging has a positive effect on fatigue life. The PAV aged binder produced much longer fatigue life compared with the original and RTFO aged binder. This finding supports many other researchers who suggest that aging is sensitive to the type of asphalt used and that stiffness increase associated with aging does not necessarily reduce asphalt fatigue life (Tayebali, et al. 1993, Ghuzlan, et al. 2001, Tasi, et al. 2005). Roque et al. (2002) explained why aged-hardened mixtures exhibit a slower rate of crack growth in the laboratory, but perform poorly in the field. The creep strain rate decreases significantly as the aged-hardening progresses; therefore, for the condition of controlled cracking, the rate of damage accumulation and crack growth decreases as age-hardening increases. However, for the random loading conditions occurring in the field, the higher stiffness age-hardened mixtures will attract more stress and are very likely to be subjected to individual loading cycles that will exceed the diminishing energy limits of the mixture.

Furthermore, fatigue life of the polymer modified binder (PG70-28) was higher than the PG64-28 in all of the testing conditions, as shown in figures 5.3, 5.4, 5.5 and 5.6.

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Figure 5.3 Effects of Strain on Fatigue Life Extension Due to Healing for Both PG64-28 and PG70-28



Figure 5.4 Effects of Temperature on Fatigue Life Extension Due to Healing for Both PG64-28 and PG70-28



Figure 5.5 Effects of Frequency on Fatigue Life Extension Due to Healing for Both PG64-28 and PG70-28



Figure 5.6 Effects of Aging on Fatigue Life Extension Due to Healing for Both PG64-28 and PG70-28

## 5.2 Factors affecting asphalt healing based on an analysis of dissipated energy

In this section, the effect of testing conditions, binder type and aging on binder healing will be discussed in a detail using the ratio of dissipated energy change approach.

## 5.2.1 Effect of Testing Condition on Healing

## 5.2.1.1 Effect of strain level on healing

A strain sweep test was first conducted to determine the linear strain ranges of the two binders. For the same frequency, the strain was increased and the dynamic shear modulus (G\*) was recorded. The linear visco-elastic strain ranges were considered as the strain within 5% dynamic shear modulus reduction (Johnson, et al. 2008), which for both PG64-28 (figure 5.7) and PG70-28 (figure 5.8) binders are within 4.25% at 25°C temperature and 10Hz frequency. The testing strain was then selected to include strains both within and out of the linear range, between 2.5% and 6%. These strain levels in the asphalt binder approximately correspond to the HMA mixture bulk strain between 400 to 1000 micro strains (Johnson, et al., 2008).



Figure 5.7 Strain Sweep Test Result for PG64-28 Binder in 10 Hz Frequency and 25°C Temperatures



Figure 5.8 Strain Sweep Test Result for PG70-28 Binder in 10 Hz Frequency and 25 °C Temperatures

The oscillatory fatigue-healing tests with rest periods from zero to 6 seconds were then performed for the original binder at 25°C, 10Hz frequency, and different constant strain levels. The energy based ratio of dissipated energy change approach, RDEC, was used for data analysis. As shown in figure 5.9, a binder ln(PV)–rest period (RP) relationship was developed for the PG64-28 and PG70-28 binders at each strain level. A healing rate (HR), defined as the slope of the ln (PV) - RP curve, was used to quantify the effect of healing to represent the rate of energy recovery per unit of rest time, and is not affected by the length of rest time used in the healing test. In other words, although extending the rest time can increase the total effect of healing, it is not an effective method for achieving extended fatigue life. Instead, modifying the material's physical and chemical property should be considered for maximizing healing effect and improving the service life of the material.

Following the same procedure, the healing rates for the PG64-28 and PG70-28 binders at different strain levels were determined, and the results are presented in Figure 5.9. As shown, for both binders with the increase of controlled strain level, the healing rate was reduced given all other testing conditions being the same. In particular, it appears that when the strain level reaches a threshold (around 6%), the effect of rest period becomes negligible. This finding confirmed the results suggested by Shen et al. (2009) in a controlled stress loading mode that strain level inversely affects healing effect. The effect of strain on healing appears to be non-linear, in that healing rate reduces at a lower rate when strain increases. This information suggests that healing is a function of micro damage accumulation rate. At higher strain levels, damage accumulates in a much faster way, and the capability of asphalt molecules to self-heal the damage within short rest period is consequently reduced.
Figure 5.10 also confirms the effect of binder type on healing, showing that PG70-28 consistently has higher healing rate when compared with the PG64-28 binder tested at the same conditions.



Figure 5.9 ln(PV) - RP for Different Binders in Various Strain Levels



Figure 5.10 Strain Effect on Healing Rate For PG64-28 And PG70-28

# **5.2.1.2 Effect of Temperature on Healing**

Temperature is usually considered as an important factor on healing, as it influences the thermal dynamics and the flowability of asphalt molecules. By conducting healing tests at various temperatures (15C, 20C, 25C, and 30C), the effect of temperature on healing was investigated. As shown in Figure 5.11, the PV–rest period (RP) relationship was developed for the PG64-28 and PG70-28 binder at different temperatures to find the HR. With the increase of temperatures (Figure 5.12), the healing rates for both binders are increased, showing increased healing capacity.



Figure 5.11 ln(PV)- RP for Different Binders in Various Temperatures



Figure 5.12 Temperature Effect on Healing Rate for PG64-28 and PG70-28

# 5.2.1.3 Effect of Frequency on Healing

The effect of loading frequency on healing was evaluated by comparing the healing rates for binders tested at different frequencies (10Hz, 15Hz, 20Hzand 25Hz). As shown in Figure 5.13, the PV–rest period (RP) relationship was developed for the PG64-28 and PG70-28 binders at different frequencies to find the HR. As shown in Figure 5.14, for both binders, with the increase of loading frequency, the healing rates were reduced at a lower rate. The relation of healing rate and frequency is not linear. One possible explanation for this is that high loading rates fasten the micro damage accumulation, which may have reduced the effect of healing.



Figure 5.13 ln(PV)- RP for Different Binders in Various Frequencies



Figure 5.14 Frequency Effect on Healing Rate for PG64-28 and PG70-28

# **5.2.2 Effect of Binder Type in Healing**

Healing, as a self-recovery capability of asphalt material, is fundamentally related to asphalt chemical property and molecular forces as Lifschitz-van der Waals. Binder type, related to the chemical properties and molecule composition of the asphalt, has been considered as the single most important factor that results in the different healing potentials of asphalt.

Two types of binder typically used in the state of Washington, PG64-28 and PG70-28 binder, were tested. Healing rate (HR) of PG64-28 and PG70-28 were compared at different strain levels (figure 5.15) with constant frequency and temperature. This test revealed that HR of PG 70-28 is was than PG64-28 in all the strain levels. Furthermore, HR of PG64-28 and PG70-28 were compared at different temperatures (figure 5.16) with constant strain level and frequency. This result proved that HR of PG70-28 is greater than the HR of PG64-28 in all strain levels. In addition, HR of PG64-28 and PG70-28 were compared at different frequencies (figure 5.17) with constant strain level and temperature. This result showed that HR of PG70-28 is greater than the HR of PG70-28 is greater than the HR of PG64-28 in all strain levels.

greater than the HR of PG64-28 in different strain levels. Ultimately, all of the results indicated that the PG70-28 binder has higher healing effect than the PG64-28 binder at all testing conditions.

Although it is possible that the higher degree of molecule cross-linking in the polymer modified binder PG70-28 may be responsible for its higher healing capacity, further study from the microscopic perspective is suggested to identify the healing mechanism.



Figure 5.15 HR–Strain for PG64-28 and PG70-28 Binder at Temperature 25°C and Frequncy 10Hz.



Figure 5.16 HR-Temperature for PG64-28 and PG70-28 Binder at Strain 3% and Temperature 25°C



Figure 5.17 HR –Frequency for PG64-28 and PG70-28 Binder at Strain 3% and Frequncy 10Hz.

## **5.2.3 Effect of Aging on Healing**

Although fatigue is a long term performance of asphalt material which is usually characterized for binders after long term aging (or pressure vessel aging), the property of healing is not necessary a long term behavior. Healing can happen at any stage of the material's service life, especially during the microcrack initiation and stable propagation stages. Therefore, in this study, the effect of both short term and long term aging on asphalt cohesive healing is evaluated.

As shown in Figure 5.14, ln(PV) – rest period (RP) relationship is developed for the original and RTFO aged (PG64-28 and PG70-28) binders to find the HR. Healing rate for original binder after RTFO aging and after PAV aging are compared, and the results can be seen in Figure 5.19. As shown, both short term and long term aging reduced the healing rate greatly. Particularly, the PV reduction due to rest periods is very minimal for PAV aged binder; thus, the

healing rate has to be estimated using the prediction equation developed in Equation 6.1 and 6.2. For both PG64-28 and PG70-28 binders, their healing effect after PAV aging is negligible.



Figure 5.18 ln(PV) - RP for Neat and RTFO Aged Binders



Figure 5.19 Effect of Aging on Healing Rate

#### **CHAPTER SIX**

# PREDICTION MODELS FOR ASPHALT BINDER FATIGUE AND HEALING

#### **6.1 Healing Rate Prediction Model**

A healing rate prediction model helps to estimate healing rates according to binder properties and loading conditions. This model could be further used to compare the healing characteristics of different asphalt binders, to correlate binder healing to HMA mixture healing, and eventually be integrated into the pavement design for a more reasonable evaluation of asphalt material fatigue and healing performance. By relating the healing rate with fundamental material properties and loading conditions such as strain, complex shear modulus, and loading frequency, this model takes into account the effect of loading level, temperature, aging, and loading rates. Equation 6.1 shows the HR prediction model for the PG64-28 binder with a prediction R-square of 0.97 and a standard error of estimate of 0.04. A similar equation for the PG70-28 binder is shown in Equation 6.2 with an R-square value of 0.93 and a standard error of estimate of 0.06. Figure 6.1 shows the comparison of the predicted and the calculated HR based on testing. While preliminary, this data indicates that it is very promising to extract asphalt healing from a relatively simple DSR test. Once correlated with HMA mixture healing rates, the results can possibly be integrated into mechanistic-empirical based pavement design procedures.

$$HR = 10^{4.632} \gamma^{-2.703} G^{*-1.375} (f)^{-0.756}$$
(6.1)

$$HR = 10^{4.808} \gamma^{-1.194} G^{*-1.027} (f)^{-0.753}$$
(6.2)

Where, HR = Healing Rate,

 $G^*$  = Initial complex shear modulus (Pa)

- $\gamma$  = Shear strain (%)
- f = Frequency (Hz)



# Figure 6.1 Comparison of Predicted and Calculated Healing Rates for PG64-28 and PG70-28 Binders Tested at Different Conditions Using the Material Prediction Model.

### **6.2 Super-position Relationship**

Further study indicates that the "linear superposition" theory applies to the healing rate when it is described as the damage recovery rate. By using energy parameter PV based on the Miner's Law that damage is accumulative (Miner, 1945), the change of healing rate can be simply considered as the sum of individual effect due to temperature, frequency, strain and other changes (Equation 6.3).

$$HR = HRo + \alpha \times \Delta T + \beta \times \Delta F + \delta \times \Delta \varepsilon$$
(6.3)

Where,

HR = the healing rate for any condition

HRo = the healing rate for a known reference condition

 $\Delta T$ ,  $\Delta F$ , and  $\Delta \varepsilon =$  the deviation of temperature, frequency, and strain from the known condition

 $\alpha$ ,  $\beta$ ,  $\delta$  = the rate of healing rate change given a unit temperature, frequency, and strain change, which are determined from laboratory healing test

Specifically, using a reference condition of 25C temperature, 10Hz frequency, and 3% strain level, the healing rate at any condition can be determined using Equation 6.4 for PG64-28 binder and Equation 6.5 for PG70-28 binder. Here,  $HR_0$  is 0.216 for PG64-28 and 0.290 for PG70-28.

$$HR = HR_o + 0.025\Delta T - 0.022\Delta F - 12.38\Delta\gamma$$
(6.4)

$$HR = HR_{o} + 0.1864\Delta T - 0.2264\Delta F - 10.94\Delta\gamma$$
(6.5)

As illustrated in figure 6.2, the predicted healing rates match with the healing rates from tests quite well. These results are important because it indicates that there is no interaction among different impact factors on healing potential. In addition, the  $\alpha$ ,  $\beta$ ,  $\delta$  parameters demonstrate how different factors can affect healing for different binder types. Because all three parameters are higher for the PG70-28 binder, it is clear that the temperature, frequency, and strain level have higher influence on healing for the PG70-28 binder when compared with the

PG64-28 binder. Such information is particularly useful for pavement design to estimate the healing rates based on a known reference condition.



Figure 6.2 Comparison of Predicted and Calculated Healing Rates for PG64-28 and PG70-28 Binders Tested at Different Conditions Based on the Linear SuperpositionTheory.

### **6.3 Fatigue Prediction Model**

The fatigue prediction model, which takes into account the effect of healing, was developed by correcting a base fatigue life from continuous loading with a healing function, as shown in Equation 6.6. Equation 6.7 gives the fatigue life prediction model for the PG64-28 binder with a prediction R-square of 0.94 and a standard error of estimate of 0.06. A similar equation for PG70-28 binder is shown in Equation 6.8, with an R-square value of 0.94 and a standard error of estimate of 0.05. As illustrated in Figure 6.3, the fatigue life matches with the fatigue life from tests quite well.

$$N_{f50} = k_1 (N_{f50(WOR)})^{k_2} (\exp(RP))^{k_3 * HR}$$
(6.6)  
N<sub>f50</sub> = Fatigue Life

 $N_{f50(WOR)}$  = Fatigue Life without rest period

 $K_1, k_2, k_3, = Constant values$ 

RP = Rest Period

Fatigue prediction models for PG64-28 and PG70-28 were given in equations 7 and 8, respectively.

$$N_{f^{50}} = 2.04 (N_{f^{50}(WOR)})^{0.924} (\exp(RP))^{0.628^{\mu}R}$$
(6.7)

$$N_{f50} = 0.937 (N_{f50(WOR)})^{1} (\exp(RP))^{0.752^{\circ}HR}$$
(6.8)



Figure 6.3 Comparison of Predicted and Calculated Fatigue Life for PG64-28 and PG70-28 Binders Tested at Different Conditions Based on the Fatigue Prediction Model.

#### 6.4 Plateau Value Prediction Model

When the RDEC value is almost constant, it is considered as the plateau value (PV). Analysis of the testing data indicated that such plateau stage starts from approximately the 15% initial shear modulus reduction until the 50% initial shear modulus reduction under the stain controlled loading mode in asphalt binder. PV value represents the fundamental asphalt binder material behavior during loading. Furthermore, PV has unique relationship with asphalt binder fatigue life. Thus, fatigue life of the asphalt binder can be obtained by predicting the PV value from this prediction model.

This prediction model was developed based on plateau value (PV) with continuous loading, rest period and healing rate, as shown in equation 6.9. Equation 6.10 shows the plateau value prediction model for the PG64-28 binder with a predicted R-square of 0.92 and a standard error of estimate of 0.08. A similar equation for the PG70-28 binder is shown in Equation 6.11, with an R-square value of 0.97 and a standard error of estimate of 0.05. As illustrated in Figure 6.4, the plateau value match with the plateau value from tests fits quite well.

$$PV = k_1 (PV_{(WOR)})^{k_2} (\exp(RP))^{k_3 * HR}$$
(6.9)

PV = Plateau Value

PV (WOR) = Plateau Value without Rest Period

HR = Healing Rate

RP = Rest Period

and  $k_1$ ,  $k_2$ ,  $k_3$  = Constant Value





Figure 6.4 Comparison of Predicted and Calculated Plateau Value for PG64-28 and PG70-28 Binders Tested at Different Conditions Based on the Plateau Value Prediction.

#### **CHAPTER SEVEN**

# CONCLUSIONS AND RECOMMENDATIONS

### 7.1 Conclusions

This study conducted an energy based ratio of dissipated energy change (RDEC) analysis to quantify the effect of cohesive healing within asphalt binders and identify its key impact factors. Based on the experimental investigation and data analysis, a number of conclusions can be drawn from this study. This study used the traditional failure definition as the complex modulus value reaches the 50% of the initial complex modulus for binder fatigue failure. Under controlled strain loading modes, frequency and strain inversely affect fatigue life, while temperature and the degree of aging (from short term rolling thin film oven (RTFO) aging to long term pressure aging vessel (PAV) aging) directly influence fatigue life. The binder after PAV aging was found to have negligible healing potential. The effect of frequency, temperature, strain, and aging on fatigue behavior is greatly enhanced when rest periods are introduced, while the trend of impact remains the same.

A healing rate, defined as the slope of the ln (PV) – RP curve, is successfully used to quantify the effect of asphalt healing at different conditions. Binder type is considered as the most important factor, as it is related to the chemical properties and molecule composition of the asphalt. For all testing conditions, the polymer modified asphalt binder PG70-28 has higher healing rates than the non-modified PG64-28 binder.

Temperature, loading rates (frequency), strain level, and the degree of aging are all identified to have important effects on healing. With the increase of temperatures, healing rates increase in an almost linear way, which is considered to relate to the thermal dynamics of asphalt material. At higher temperatures, the asphalt binder becomes more flowable, so that more "wetting" and "diffusion" activities will occur at the cracked surface. Frequency inversely affects the healing potential of asphalt binder; the higher the frequency, the lower the healing rates. However, the effect of frequency on healing rates reduces at high frequencies, which may due to the accelerated micro damage accumulation. Similarly, the healing rates were reduced at increased strain levels, which also follow a non-linear relation. The results suggested that healing rate is a function of micro damage accumulation rate. At higher strain levels and higher loading rates, the damage accumulates faster, resulting in reduced effect of damage recovery. The aging effect also reduces the healing potential of asphalt binder. With the increase of the degree of aging (from short term aging to long term aging), asphalt molecules become further oxidized and less able to actively heal the microcracks.

Under controlled strain loading modes and standard testing conditions (25°C temperature, 10Hz frequency, 3% strain, un-aged), the PG64-28 binder had 2.4 times fatigue life extension when 6 second rest periods were applied after every ten cycles of continuous oscillation, while the PG70-28 binder had 3.1 times fatigue life extension.

Several phenomenological material models were developed in this study that can help to estimate the healing rate, the characterization of asphalt binder fatigue and healing behavior, the correlation of binder healing to HMA mixture healing, and finally the integration of healing into pavement design.

A healing rate prediction model was developed based on an initial complex modulus, loading frequency and shear strain, which uniquely relates healing to the rate of dissipated energy recovery per unit of rest time. It is hypothesized that the method presented in this study can also be used to include the effect of adhesive healing at the aggregate-asphalt interface by testing asphalt mastics or sand asphalt mixtures using the DSR or the rotational solid bar test.

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A modified fatigue prediction model was developed by adjusting fatigue life from continuous loading with a healing function accounting for the effects of rest periods and healing rate. The ratio of dissipated energy change (RDEC) approach was confirmed to be applicable for asphalt binder healing analysis. A plateau value prediction model was successfully established based on plateau value with continuous loading, rest period and healing rates. This model provided another means of estimating the fatigue life of asphalt binders because plateau value has been found to be strongly related to fatigue life.

The research results suggest that the linear superposition theory applies to the cohesive healing of asphalt binders. The effect of temperature, strain, and loading rates can be linearly added to the healing rates without any interaction effect. Consequently, the healing rates at any testing condition can be estimated based on the healing rate of a known reference condition, which is particularly useful and important for the future integration of healing into pavement design.

#### 7.2 Recommendations

In this study, the testing was limited to two types of binders (PG64-28 and PG70-28). Further studies should be carried out for more binder types. These studies should serve as a validation of the findings of this study, including the major impact factors on healing and the effectiveness of the healing rate prediction model, as well as the linear superposition concept.

In addition, mineral fillers have been found in the literature (Si, et al. 2002; Kim, et al. 2003; Bianchetto et al. 2007) to have clear impact on fatigue and other performance factors of asphalt mastics. The effect of these fillers on binder healing can be evaluated quantitatively using the method developed in the research to provide healing investigations for both cohesive and

adhesive healing. Torsional solid bar test using the DSR setup could be used to investigate the healing behaviors of asphalt mastic with mineral fillers, or sand asphalt mixtures.

Further studies should be carried out to evaluate the fundamental healing mechanisms and to identify the triggers of healing. It is crucial for the purpose of material characterization and pavement design to clearly understand what material properties, conditions, or mechanisms will ultimately contribute to the healing of surfaces. The study conducted here serves as the first step of this long journey, and it should be continued with more fundamental studies.

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