EVALUATION OF CORRELATION BETWEEN PHENOMENOLOGICAL APPROACH AND FRACTURE MECHANICS APPROACH FOR ASPHALT CONCRETE FATIGUE PERFORMANCE

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ABSTRACT

Phenomenological approach and fracture mechanics approach are generally used to estimate the fatigue performance of asphalt concrete. The objective of this paper is to evaluate the relationship between these approaches and to characterize the fatigue behavior using fracture parameters. A series of Indirect Tensile Tests (IDT) and Disk-shaped Compact Tension Tests (DCT) were conducted to obtain the Dissipated Creep Strain Energy (DCSE) and Fracture Energy (FE) of HMA materials. The fatigue life (Nf) and Plateau Value (PV) of asphalt mixture was also estimated using four point bending beam fatigue tests which is a widely used phenomenological approach. Four different asphalt mixtures were investigated. Test results indicate there is a correlation between fracture parameters and beam fatigue results.

INTRODUCTION

Fatigue cracking caused by repeated load is considered to be one of the major distresses and has significant effect on the service life of the flexible pavement. In FAARFEILD, Cumulative damage factor (CDF) is used to evaluate the fatigue life of asphalt pavement. It is the ratio of applied number of load repetitions to the allowable number of load repetitions to failure. The fatigue model developed by Heukelom and Klomp [1] is used in FAARFIELD to determine the number of the coverage failure for the given horizontal strain and modulus of asphalt concrete modulus (Equation 1).

$$log_{10}(C) = 2.68 - 5 \times log_{10}(\varepsilon_h) - 2.665 \times log_{10}(E_A) \quad (1)$$

where:
C = Number of Coverages to Failure
E_A = Asphalt Concrete Modulus, psi
ε_h = Horizontal strain at the bottom of the surface asphalt layer

Laboratory testing is also used to evaluate the fatigue performance of the asphalt concrete. There are two main categories of approaches: phenomenological approach and fracture mechanics approach. Phenomenological approach uses repeated strain or stress to simulate the repeated traffic load. The number of cycles to failure or dissipated energy change between cycles is determined to estimate the fatigue cracking resistance. Fracture mechanic approach focuses on the cracking initiation and propagation. This method relates fatigue performance to the various materials fracture parameters such as fracture energy and energy release rate. The phenomenological approach is commonly used to determine parameters in fatigue models. However, the phenomenological approach is time-consuming and has high variation. The objective of this paper is to evaluate the relationship between phenomenological approach and fracture mechanics approach and to characterize the fatigue behavior using fracture parameters.

Flexural Beam Fatigue test is generally used in phenomenological approach. It applies a repeated flexural bending to an asphalt concrete beam. Failure criterion (Nf) is defined at the number of the cycles when the stiffness reduces to 50% of the initial stiffness [2]. Many studies [3, 4, 5] have shown that ratio of dissipated energy change (RDEC) provides a better indication of damage induced by the repeated load. RDEC is defined as the change of the dissipated energy between two cycles divided by the dissipated energy of previous cycle. There are three stages in a typical curve of RDEC versus the number of load cycles (Figure 1). A plateau is established at stage II after the initial period (stage I). The fatigue failure happens at the stage III where RDEC dramatically increases. The Plateau Value (PV) is the RDEC values where the stiffness reduces to 50% and has a unique relation with fatigue performance of asphalt concrete. The procedure developed by Carpenter and Shen [6] was used to calculate the PV in this study.

Two types of fracture mechanics approaches were investigated in this study: Indirect Tensile Test (IDT) and Disk-Shaped Compact Tension (DCT).

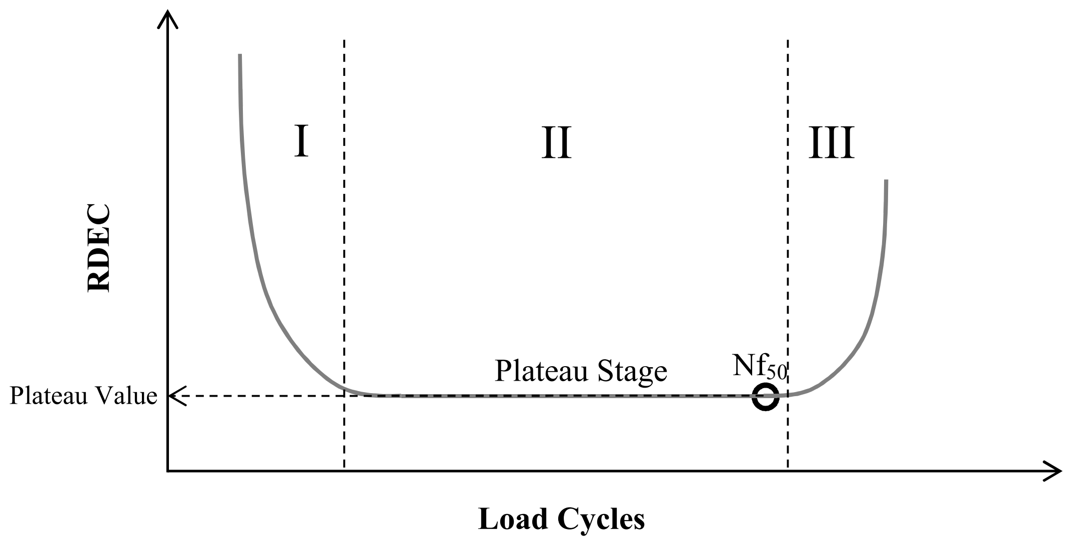

Figure 1. Typical RDEC versus Load Cycles.

Zhang et. al [7, 8] introduced the dissipated creep strain energy (DCSE) and Fracture Energy (FE) which are two thresholds related to cracking initiation as shown in Figure 2 . The FE is defined as the area under the stress-strain curve. Elastic Energy (EE) is determined by the resilient modulus (M_R) and tensile strength. DCSE is the difference between FE and EE. DCSE is the threshold for repeated load situations with stress considerably lower than the tensile strength. The macro-cracking will initiate when dissipated energy approaches the DCSE. FE is the limit for a single large load. Roque and Buttlar [9] developed the procedures to calculate DCSE and FE based on IDT tensile strength test and resilient modulus test.

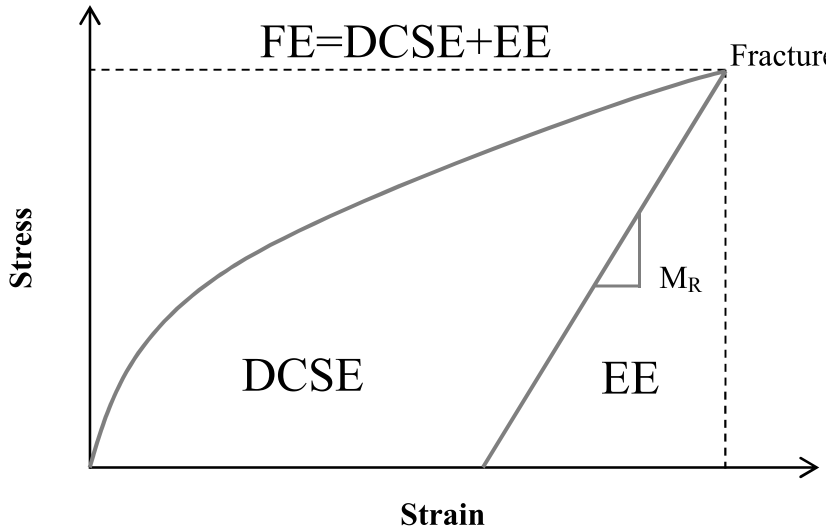

Figure 2. DCSE and EE from IDT Strength Test

Wagoner and Buttlar [10] developed the Disc-shaped Compact Tension Test (DCT) to determine the fracture energy for asphalt concrete based on ASTM E399 Standard Test Method [11]. Figure 3 shows the typical load versus Crack Mouth Opening Displacement (CMOD) curve. The fracture energy can be calculated using Equation 2.

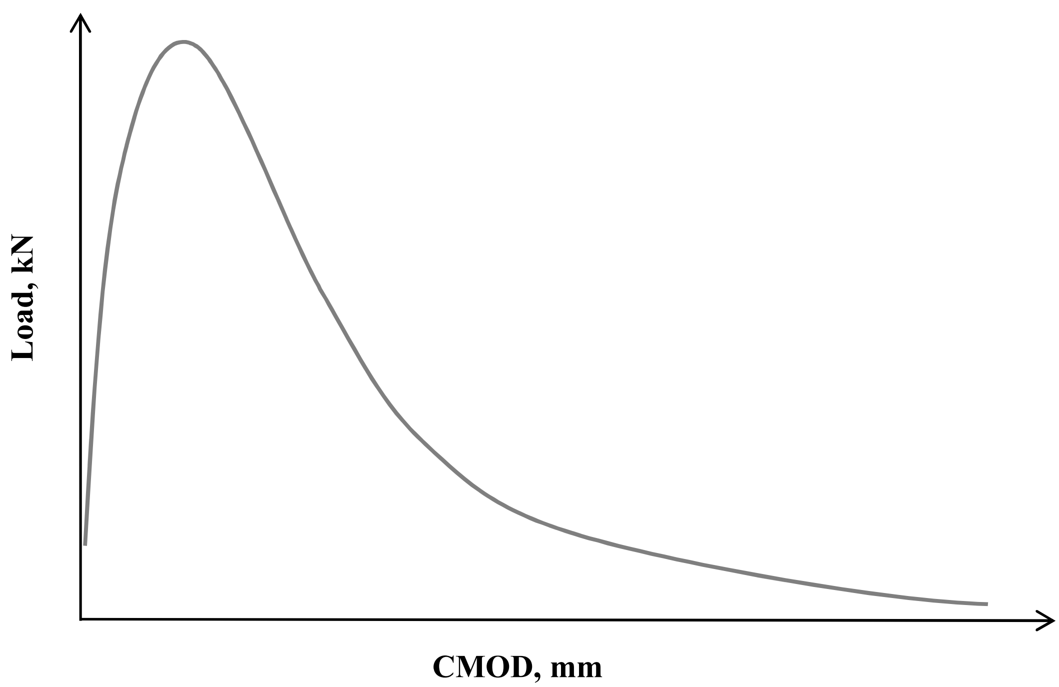

Figure 3. Load versus CMOD curve for DCT test

$$G_f = \frac{AREA}{B \times L} \quad (2)$$

where:
G_f = fracture energy, J/m^2
$AREA$ = area under load-CMOD curve, mm-kN
B = specimen thickness, m
L = initial ligament length, m

MATERIAL PROPERTIES AND SPECIMEN PREPARATION

Two binders (PG70-22 and PG76-22) included in this study were provided by NuStar Asphalt Refining, LLC. Table 1 indicates the properties of binders. Dynamic shear rheometer (DSR) tests were conducted on these binders. The results are represented in table 2.

Table 1. Asphalt binder properties.

Temperature	Property	Binder Grade		Test Method
		PG 70-22	PG76-22	
135ºC	Viscosity, cP	2787	1150	AASHTO T 316
N/A	Flash Point, ºC	296	282	AASHTO T 48
25ºC	Penetration, 0.1 mm	4.3	4.1	AASHTO T 49
N/A	Softening Point, ºC	51	57	AASHTO T 53

Table 2. DSR results of the asphalt binders.

Temperature	Property	Binder Grade		Binder
		PG 70-22	PG76-22	
70^{o}C		1.590		
76^{o}C	G*/sinδ, kPa	0.785	1.933	Unaged Binder
82^{o}C			1.015	
64^{o}C		3.345		
70^{o}C	G*/sinδ, kPa	1.659	3.625	Rolling Thin Film Oven Residue
76^{o}C			1.931	
25^{o}C		3660		
28^{o}C	G*/sinδ, kPa	2398	2214	Pressure Aging Vessel Residue
31^{o}C			1737	

Two aggregates elected in this study were Dolomite (NAPTF mix) and Gneiss (JFK mix). NAPTF mix is used for research conducted at the Federal Aviation Administration (FAA) National Airport Pavement Test Facility (NAPTF), Atlantic City, NJ, and is well documented. JFK mix was used at runway at John F. Kennedy (JFK) airport in New York. Aggregate gradations and mix design properties are summarized in Table 3 and Figure 4.

Table 3. Mix design properties

	Aggregate	
Property	NAPTF	JFK
Aggregate Type	Dolomite	Gneiss
Aggregate Bulk Specific Gravity	2.853	2.658
Asphalt Binder Content, % by Wt.	4.8	5.6
Superpave NMAS, mm	12.5	19
Air Void Content, Vol. %	3.4	3.9

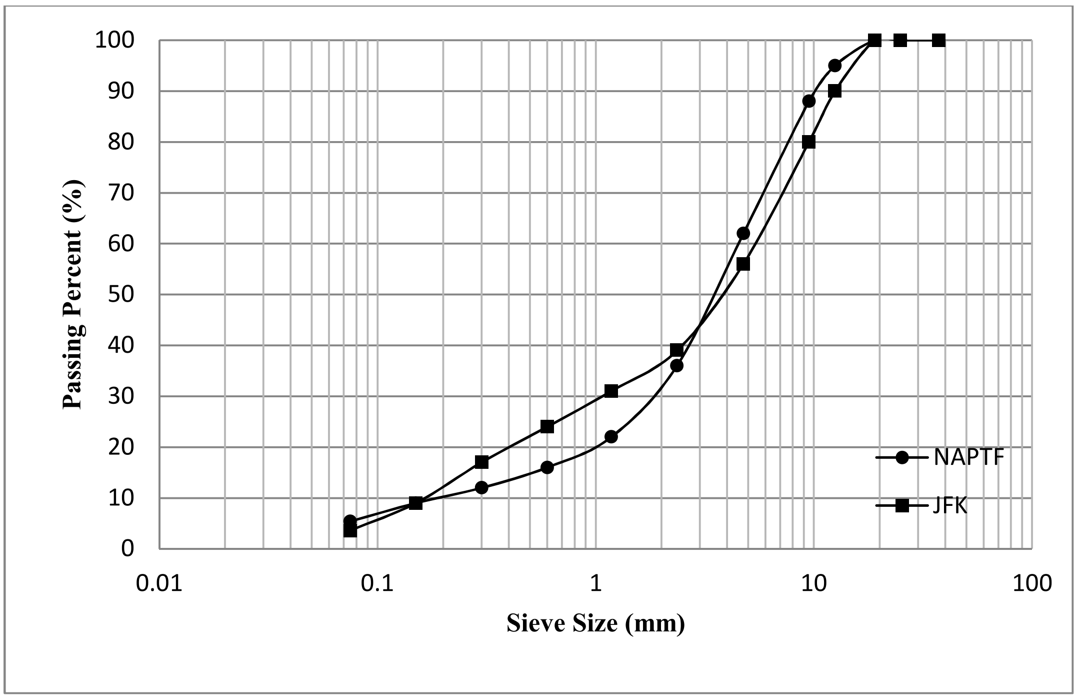

Figure 4. Aggregate Gradation

TEST PROGRAM

A full factorial experiment design consisting of two factors (asphalt binder and aggregate) was used. There were two types of asphalt binders and two types of aggregates. Therefore, four different mixes were prepared for testing: NAPTF72-22, NAPTF76-22, JFK72-22 and JFK76-22.

To produce the beam fatigue test specimens, the asphalt mixtures were prepared and compacted using the rolling wheel compactor in accordance with AASHTO PP3 [12]. After compaction asphalt concrete slabs were cut into dimensions of 380mm × 63mm × 50mm. The flexural beam fatigue test according to ASTM D7460 [13] was used to determine the fatigue resistance of asphalt concrete. The test was conducted under three strain levels (300με, 600με and 900με) at temperature of 15ºC. Three replicates were fabricated for each strain level. A repeated sinusoidal load at frequency of 10 Hz without rest periods was applied to the specimens. A test system consisting of a load frame, an environmental chamber, a closed loop control and data acquisition system made by Industrial Process Controls, Ltd. (IPC) was used. Figure 5 represents the beam fatigue test set up.

Samples for IDT test were compacted using gyratory compactor. The resilient modulus test and strength test were performed on a 150mm diameter by 38 mm thick specimens. There were three replicates fabricated for each mix. The resilient modulus test were conducted at four temperature (-10ºC, 0 ºC, 15 ºC and 25ºC) and six frequency (25Hz, 10Hz, 5 Hz, 1Hz, 0.5Hz and 0.1 Hz). The strength test were conducted in accordance with AASHTO T322 [14] at 15ºC as shown in Figure 6.

DCT specimens were compacted using gyratory compactor and fabricated according to ASTM 7313 [15]. The tests were performed at 10ºC as in represented in Figure 7.

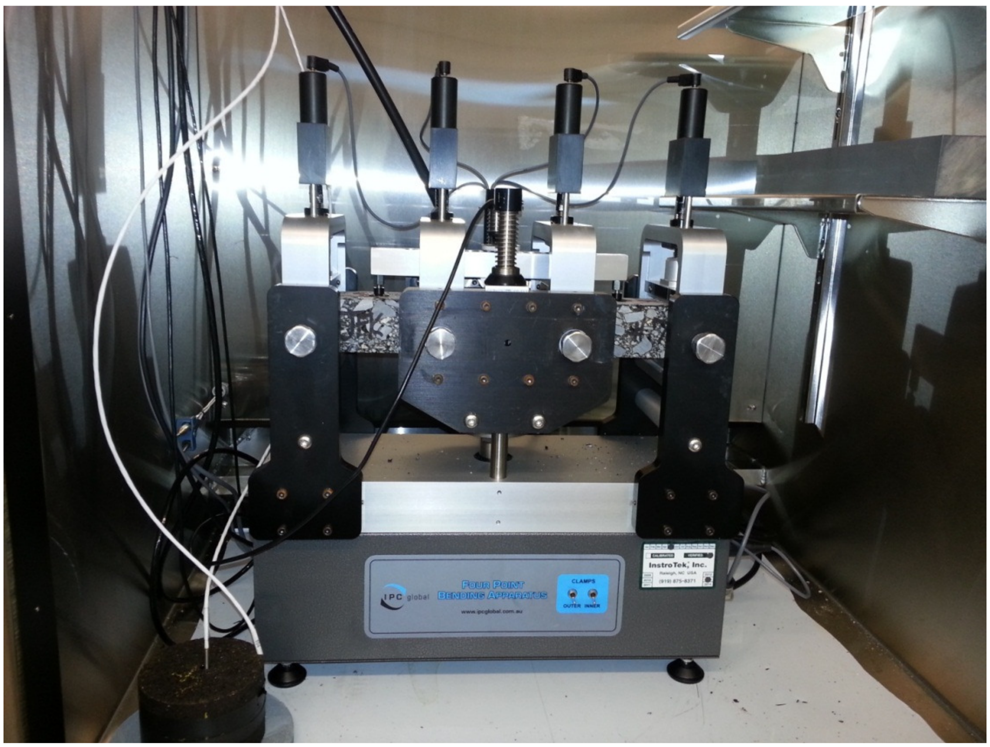

Figure 5. Flexural Beam Fatigue Test

Figure 6. IDT Test

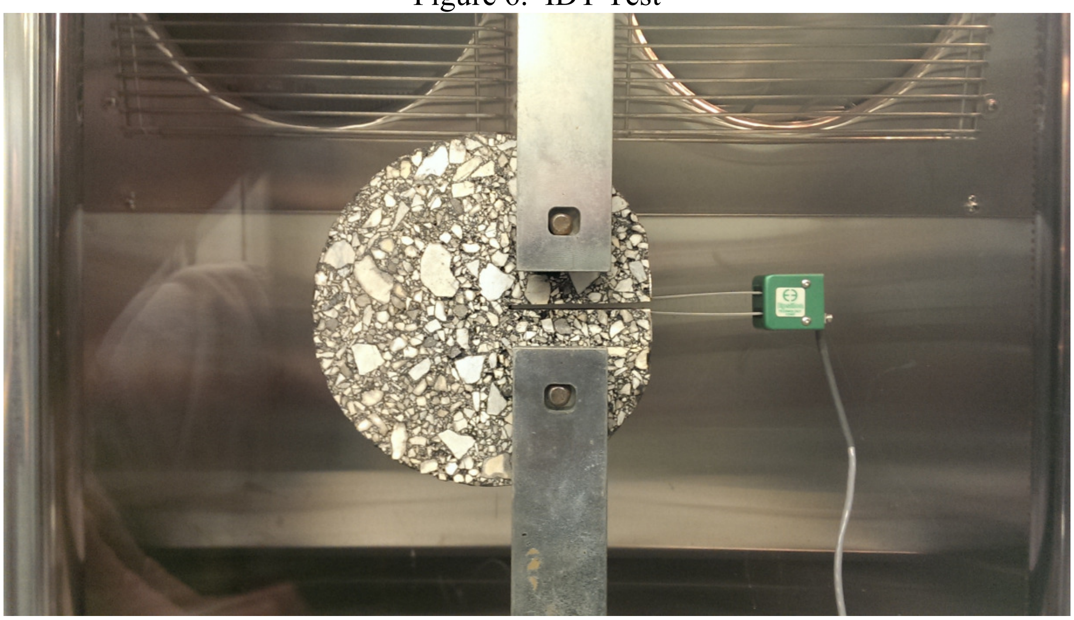

Figure 7. DCT Test

RESULT AND DISCUSSION

For flexural beam fatigue there were three replicates for each mixture at each strain level. The average fatigue life (Nf) versus applied tensile micro-strain are shown in Figure 8. JFK70-22 mix has the lowest fatigue life at all there strain levels. PV was calculated using Equation 3.

$$PV = \frac{1-(1+\frac{100}{Nf})^{f}}{100} \tag{3}$$

where:
PV = Plateau Value
Nf = Number of cycles at 50% stiffness reduction
f =Slope of the regressed dissipated energy-load cycle curve

DCSE was determined using the procedures developed by Roque and Buttlar [9] based on IDT tensile strength test and resilient modulus test. Figure 9 indicates the DCSE of each mix.

DCT test was used to measure the fracture energy (FE). The result is shown in Figure 10.

Figure 11 demonstrates the relation between DCSE and fatigue life (Nf) at three strain levels. It shows that higher DCSE correspond longer fatigue life (Nf). There is a stronger correlation at 300 micro strains than higher strain levels.

As mentioned earlier, PV can be used to evaluate the fatigue resistance of asphalt concrete. Lower PV means lower damage produced between load cycles. Figure 12 shows the PV-DCSE curve at different strain levels. The PV reduces with the increase of DCSE. Similar to Figure 11, higher correlation between PV and DCSE is observed at 300 micro strains.

Figure 13 and 14 represents Nf-FE and PV-FE relationship separately. The correlation at 600 and 900 micro strains are both insignificant for Nf-FE and PV-FE. At 300 micro-strains, the R squared value is high which means there are strong correlations. The relationship of Nf-FE and PV-FE follows the same trend as in Figure 11 and 12. At lower strain levels difference of Nf is more significant than at higher strain levels. This is shown in Figure 8. The high variation of beam figure test results would have less effect on the correlation at lower strain level. Therefore, stronger correlation is observed at 300 micro strains.

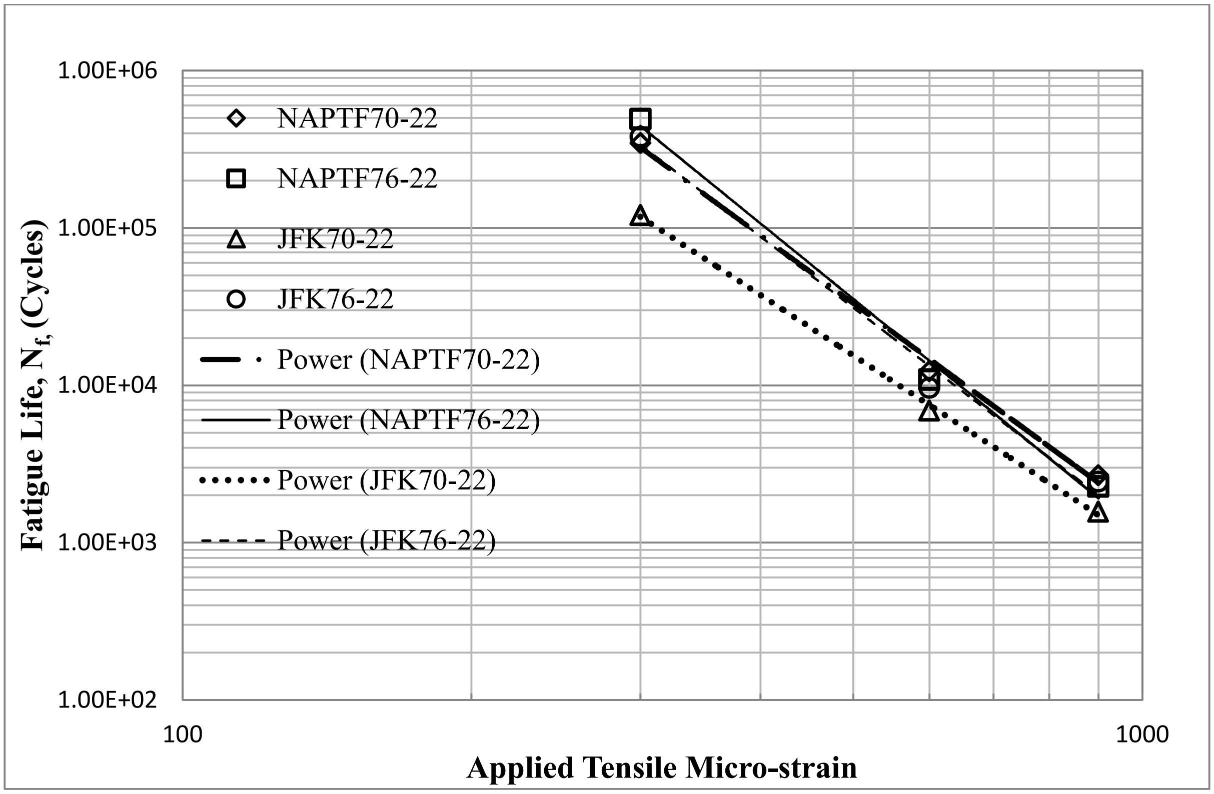

Figure 8. Fatigue Life (Nf) versus Applied Tensile Micro-strain

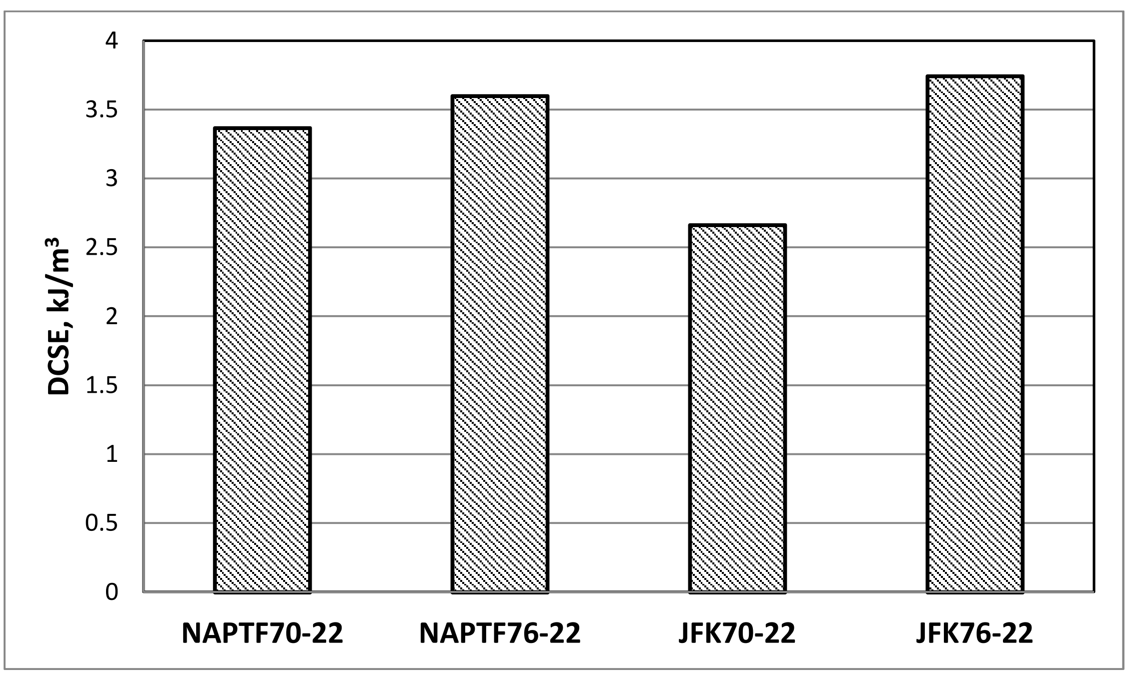

Figure 9. DCSE from IDT Test

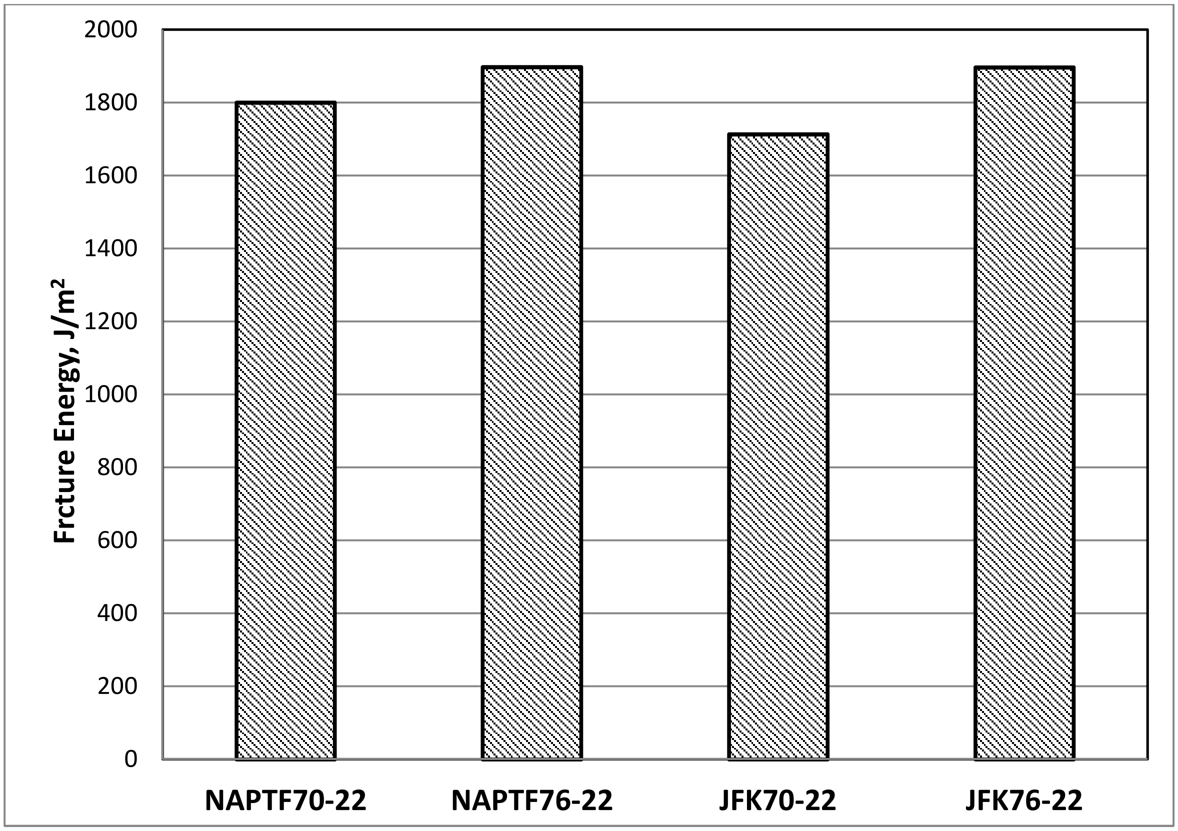

Figure 10. FE from DCT Test

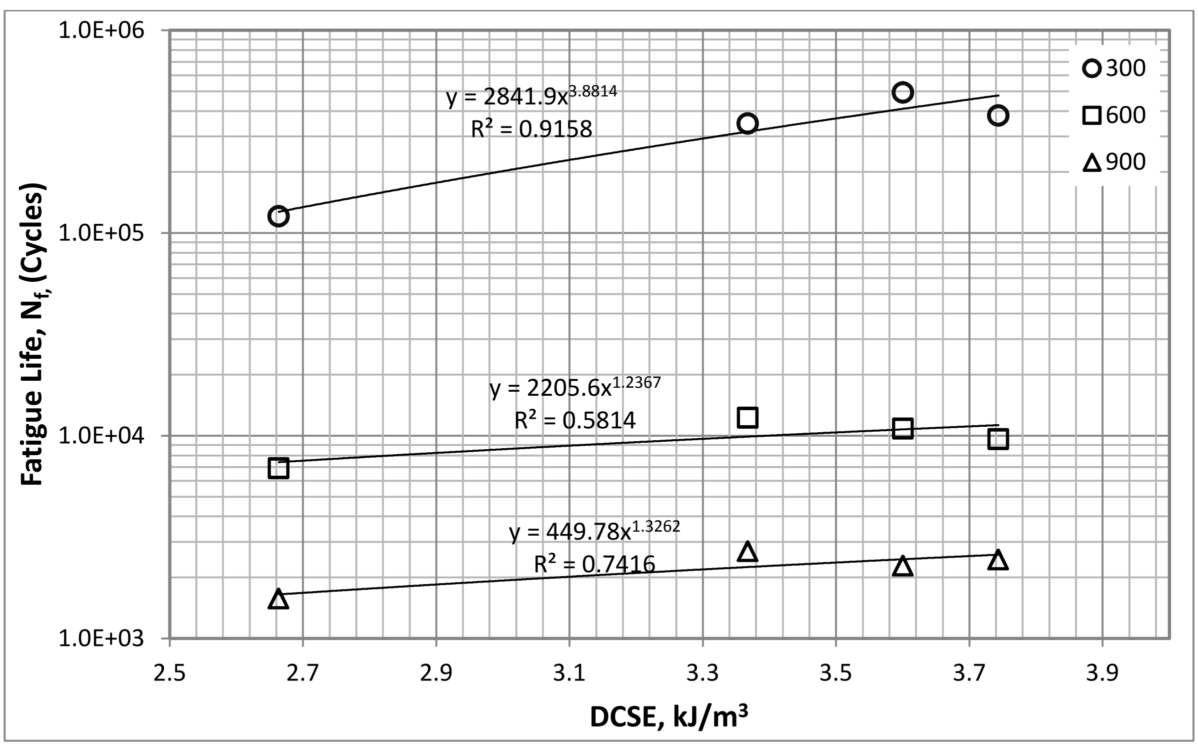

Figure 11. Relation between Fatigue Life (Nf) and DCSE

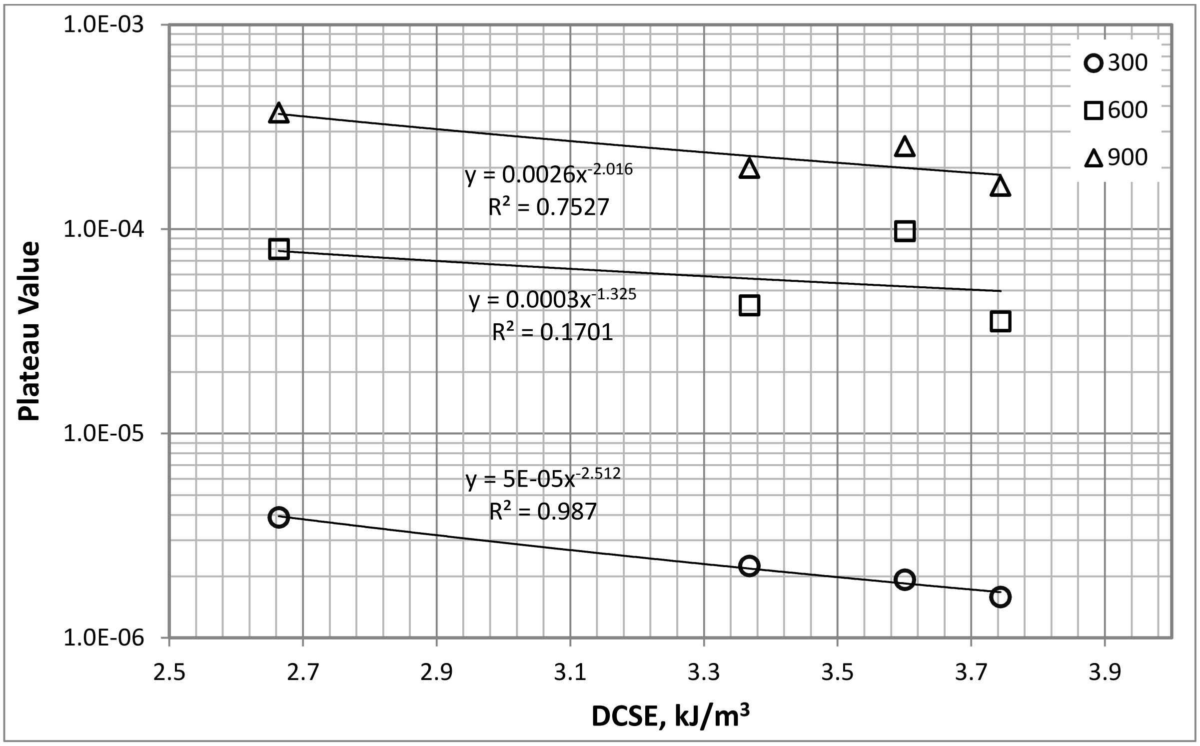

Figure 12. Relation between PV and DCSE

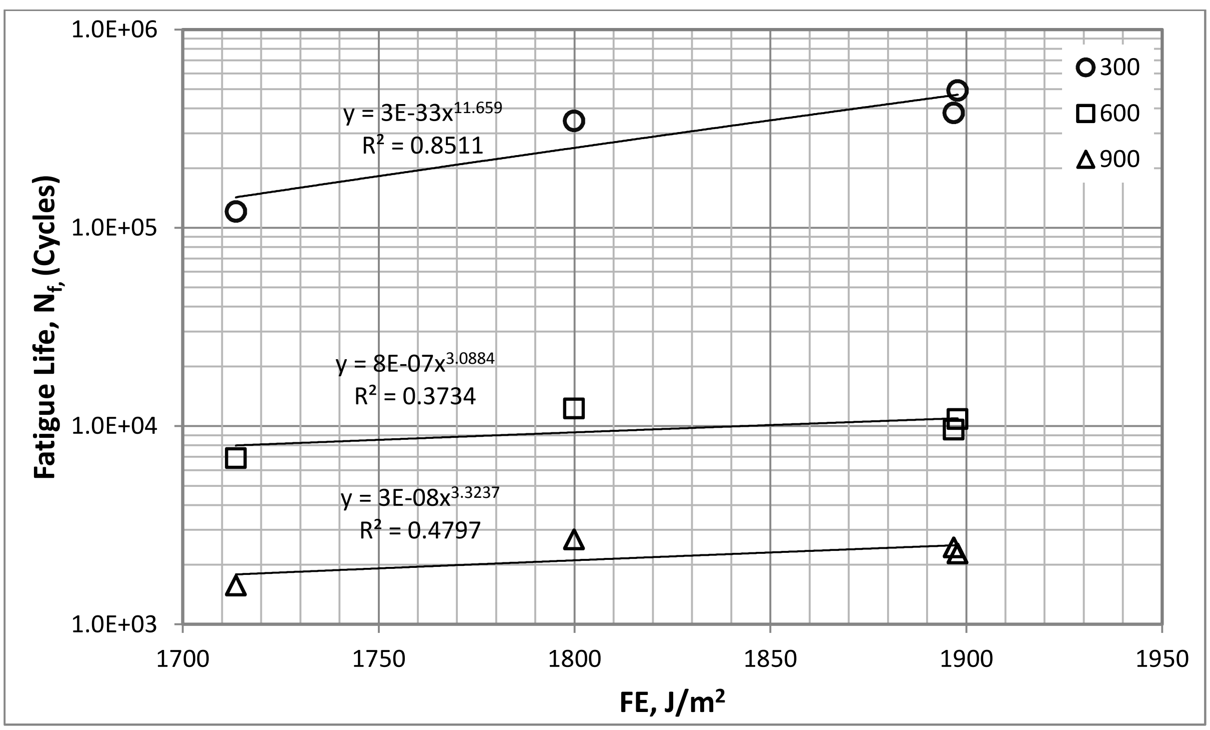

Figure 13. Relation between Fatigue Life (Nf) and FE

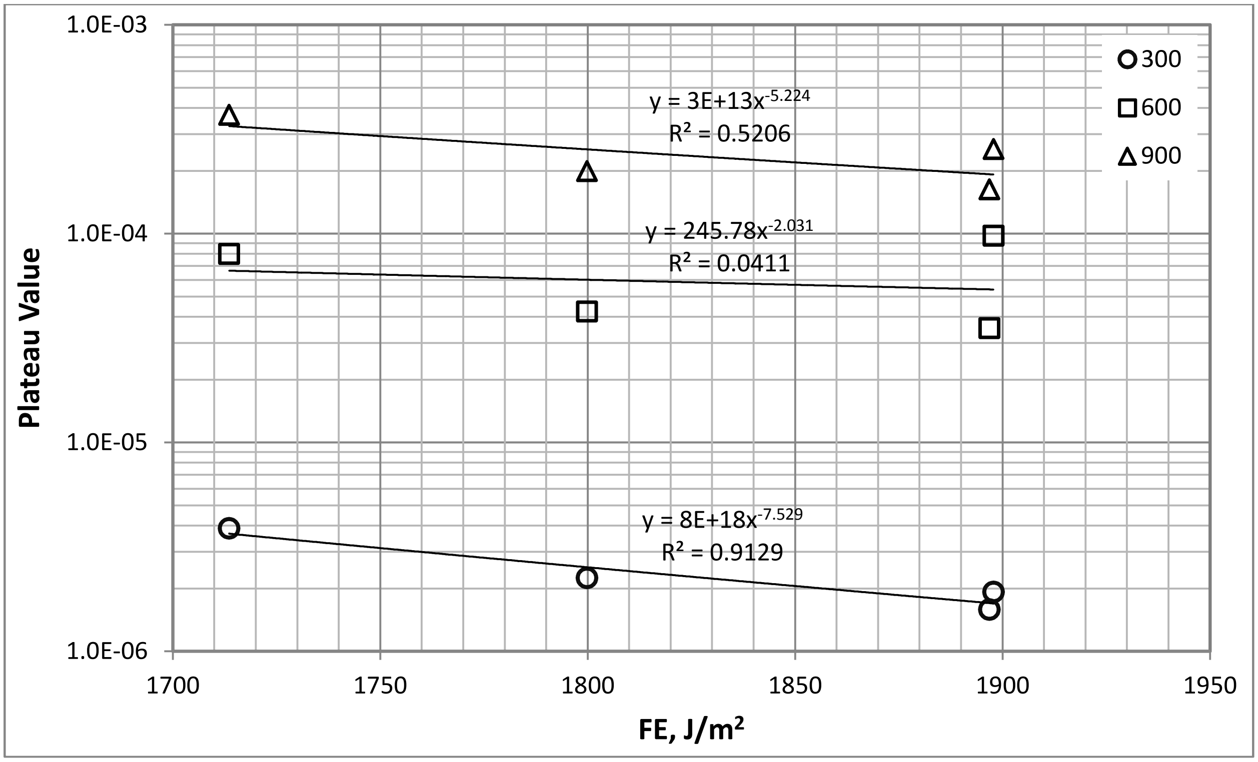

Figure 14. Relation between PV and FE

SUMMARY

- Nf and PV of asphalt concrete were determined using beam fatigue test. The DCSE and FE were obtained using IDT test and DCT test separately.
- A strong correlation is observed between DCSE and Nf and also between DCSE and PV. The correlation is more significant at low strain level.
- Mixes with high DCSE has high Nf and low PV.
- There is a high correlation at 300 micro strain between FE and Nf as well as between FE and PV.

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