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Research Article

Ratio of Dissipated Energy Change-based Failure Criteria of Asphalt Mixtures

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Abstract: A four-point bending fatigue test system researched by Cooper was used to evaluate the fatigue performance for different particle size and different asphalt content of asphalt mixtures. Based on the four -point bending fatigue test and dissipated energy method, the Ratio of Dissipated Energy Change (RDEC) was calculated that is indicative of the damage evolution in asphalt mixtures. And then based on the correlation of Ratio of Dissipated Energy Change (RDEC) and load cycles, a new fatigue failure criteria was presented that is materials failure happen when RDEC increase sharply. Under these failure criteria, fatigue life prediction model on RDEC is accepted and this model is independent on constant strain and constant stress modes.

Keywords: Asphalt mixtures, fatigue failure criteria, four-point bending fatigue test, ratio of dissipated energy change

INTRODUCTION

Fatigue damage is the mainly form for the damage of asphalt concrete pavement and the mechanism investigation about fatigue damage of asphalt concrete pavement have attracted extensively attentions recently years. However, the fatigue damage mechanism of asphalt mixtures is very complicated and shows closely dependence on many factors, in which the interaction between these factors exists. Therefore, it is urgent to develop a model, which not only can give an accurate prediction of the fatigue life but also to avoid the limitation of load patterns (such as stress control and strain control), to express accurately the fatigue damage behavior of asphalt mixtures.

The prediction of the fatigue life of the asphalt mixture mainly demonstrated indoor fatigue test through the researching a lot of literatures at home and abroad. Many asphalt mixture fatigue life prediction models, including phenomenological method, mechanical approximation method and dissipated energy method were reported. Phenomenological method uses fatigue curves to characterize the fatigue properties of the material. It holds that the fatigue of asphalt mixtures is the damage phenomena induced by the intensity attenuation accumulation under the repetition load (Moghadas *et al*., 2010; Park *et al*., 2009; Kim *et al*., 1997). However, this method cannot reflect the fatigue damage accumulation process and lack of an accurate definition on the fatigue failure criterion. In addition, difference test results would be gained for different test methods. Thus, the fatigue model obtained from phenomenological method is difficult to express the actual fatigue properties for asphalt mixtures. Mechanical approximation method is a strategy that used the fracture mechanics to explain the fatigue crack propagation law to determine the material fatigue life. This method considers material exist cracks initially without considering the stage of the formation of cracks. Its research focus is the investigations of fracture mechanism and the crack propagation law for materials (Kuai *et al*., 2009). Additionally, asphalt mixture is a viscoelastic material, the stress intensity factor K is not a constant at high temperature. Therefore, the application scope for mechanical approximation method was limited to some extent.

Early in 1972, Van Dijk proposed dissipated energy method would be an efficient method to study the fatigue issue of asphalt mixture (Van *et al*., 1972). Latter, Van Dijk and Visser used strain and stress control mode to test the fatigue of asphalt mixtures at different loading frequency and different temperatures (Van and Visser, 1977). The relationship between cumulative dissipated energy and fatigue life was given as following:

$$W_{\mathrm{fat}} = AN_{\mathrm{f}}^{Z} \tag{1}$$

in which,

W_{fat} = The cumulative dissipated energy when fatigue failure
N_f = The load cycle index when fatigue failure

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A, Z = The obtained test model parameters

Van Dijk intended to verify cumulative dissipated energy is the only independent factor to predict the fatigue life through the fatigue test. That to say W_{fat} is independent on the load mode, material style and other factors. However, the United States Strategic Highway Research Program Report SHRP A404 pointed out that this fatigue life prediction model depends on the load control mode (SHRP, 1994).

In view of the limitation of the above mentioned methods, a four-point bending fatigue test system researched by Cooper was used to evaluate the fatigue performance for different particle size and different asphalt content of asphalt mixtures in this study. Based on the four-point bending fatigue test and dissipated energy method, the Ratio of Dissipated Energy Change (RDEC) was calculated that is indicative of the damage evolution in asphalt mixtures. And then based on the correlation of Ratio of Dissipated Energy Change (RDEC) and load cycles, a new fatigue failure criteria was presented that is materials failure happen when RDEC increase sharply. Under this failure criterion, fatigue life prediction model on RDEC is accepted and this model is independent on constant strain and constant stress modes.

THE FUNDAMENTAL OF DISSIPATED ENERGY

Hysteresis loop equation: Assuming a sinusoidal strain or stress α sin ωt is applied to the asphalt mixture specimen, the specimen will generate a stress or strain response b sin (ωt + φ) at the same frequency, in which φ is the lag phase angle. Suppose:

$$x = a \sin \omega t \tag{2}$$

$$y = b \sin(\omega t + \varphi) \tag{3}$$

Substituting Eq. (2) into (3) to get the Eq. (4), as expressed as following:

$$\cos \omega t = \frac{y}{b \sin \varphi} - \frac{x \cos \varphi}{a \sin \varphi} \tag{4}$$

Combining Eq. (2) and (4), we can get the hysteresis loop equation, the stress-strain response equation of asphalt mixture sample for each load cycle, as expressed in following equation:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{2xy \cos\varphi \sin\varphi^2}{ab} = \sin\varphi^2 \tag{5}$$

The schematic diagram of hysteresis loop equation was shown in Fig. 1.

The calculation of dissipated energy: Asphalt mixture is a viscoelastic material and the destruction of viscoelastic material is an energy dissipation process, which is a process of damage evolution. The energy dissipated by each one strain cycle W_i can be determined by the area of stress-strain curve hysteresis loop, as shown in Fig. 1. W_i can be calculated by the following formula according to others research results (Zhang *et al*., 1998):

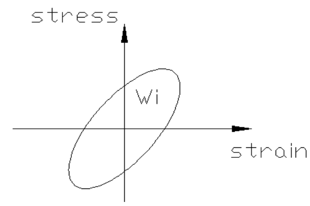


Fig. 1: Schematic diagram of stress-strain hysteresis loop

Table 1: Proportion of mineral aggregate

Sieve/mm	Mass percentage/% AC10	AC20
26.500	100	100
19	100	95
16	100	85
13.200	100	71
9.500	95	61
4.750	60	41
2.360	44	30
1.180	32	22.5
0.600	22.5	16
0.300	16	11
0.150	11	8.5
0.075	6	5

$$W_i = \int y dx = \pi \sigma_i \varepsilon_i \sin \varphi_i \tag{6}$$

W_i, σ_i, ε_i, φ_i is the dissipated energy, stress amplitude, strain amplitude and phase angle for the i-th load cycle. In the whole process of fatigue life, cumulative dissipated energy W_{fat} is the sum of all the loop area, the calculation formula is expressed as following:

$$W_{fat} = \sum_{i=1}^{n} W_i \tag{7}$$

FOUR-POINT BENDING FATIGUE TEST

Trabecular specimen preparation: The dominating steps to prepare rectangular beam four-point bending fatigue specimen includes mixture mixing, rolling and cutting. In this study, the content of AC-10, AC-20 asphalt is selected about 4 and 6% for the asphalt mixture, respectively. The porosity is designed about 2%. Diabase produced from Heyuan Yu Feng quarry is used as aggregate. Limestone slag produced form Guandong Yunfu is selected as slag. Asphalt is Tipco 70 # asphalt, the proportion of mineral aggregate is shown in Table 1.

Fig. 2: Four-points bending fatigue test setup

Test process and parameters: The four-point bending fatigue test was demonstrated on pneumatic servo test system developed by British Cooper equipped with asphalt mixture quartile point bending fatigue test fixture launched by U.S. highway development strategy research program, the test apparatus is shown in Fig. 2. The data control and acquisition system is the CRT-SA4PT-BB test software developed by Cooper. The dates of σ_i, ε_i, φ_i are achieved synchronously on this test software. According to the number of repeated load, sampling frequency is set as 1 (the number of repeated load <500), 100 (500<the number of repeated load<1000) and 500 (the number of repeated load>10000)), respectively.

The prepared specimen is conserved on an environmental chamber for four hours to get the test temperature of 20°C for the specimen, before the fatigue test is demonstrated. Both the stress control (750, 1000 and 1500 Kpa, respectively) and strain control (200, 400 and 600 με, respectively) load modes are applied on the specimen. The load is applied in the form of sine wave with a frequency in 10 Hz. Finally, the dissipated energy of asphalt mixtures trabecular specimenis calculated by Eq. (6) and (7) for the different test conditions.

EXPERIMENTAL RESULTS AND DISCUSSION

The dependence curve of dissipated energy and the number of load cycles is exhibited in Fig. 3.

In this study, the Rate of Dissipated Energy Change (RDEC) is employed to describe the fatigue behavior of asphalt mixtures. The application of the rate of dissipated energy change in quantifying the fatigue of materials was firstly proposed by Carpenter and Jansen (1997). In his research, he found a close relation between Rate of Dissipated Energy Change (RDEC) (the ratio of the absolute difference of dissipated energy between the i-th and the i+1-th load and the dissipated energy of the i-th load, during the repeated loading) and material fatigue life. The Dissipated Energy Change Rate (RDEC) can be calculated as following:

$$RDEC = \frac{\left|DE_{i+1} - \mathrm{DE_i}\right|}{\mathrm{DE_i}} \tag{8}$$

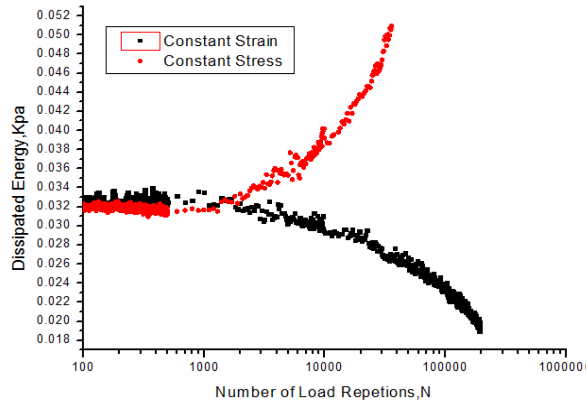


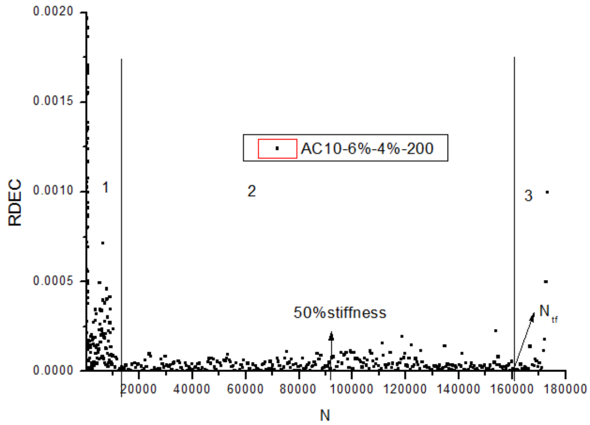
Fig. 3: Dissipated energy vs number of load cycles to failure using two modes of loading, constant stress and constant strain

where, DE_i and DE_{i+1} is the dissipated energy of i-th and i+1-th repeated load, respectively. However, the number of load cycles for some materials may larger than 20 million, owing to the variation of fatigue life of materials. Thus, it is hard to achieve fatigue test data gradually. In view of this, the above formula about the calculation of Rate of Dissipated Energy Change (RDEC) can be corrected, as expressed in Eq. (9):

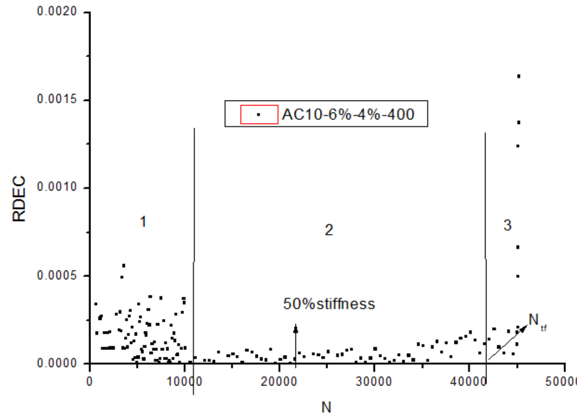
$$RDEC = \frac{\left|DE_j - \mathrm{DE_i}\right|}{\mathrm{DE_i}\left(j - i\right)} \tag{9}$$

In which, DE_i and DE_j is the dissipated energy of i-th and j-th repeated load (j>i), respectively. The number of intervals between i and j is determined by the sampling frequency. Basing this correction, not only the calculation efficiency can be improved, but also application in the longer life asphalt mixtures specimenis developed. According to Eq. (9), the dependence of dissipated energy ratio on the number of load cycles with the mode of strain control and that with the mode of stress control are shown in Fig. 4 and 5, respectively.

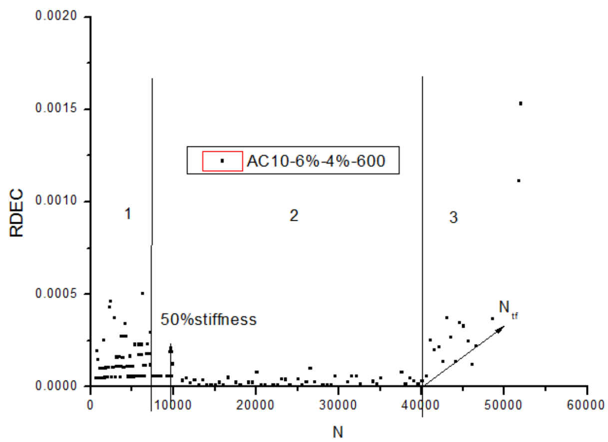
As shown in Fig. 4 and 5, the dependence curves for dissipated energy ratio on the number of load cycles can be divided into three stages no matter with the mode of strain control or the mode of stress control. Stage one ($REEC_1$): the rate of dissipated energy change in a chaotic state due to asphalt mixture specimen resist the deformation induced by the load, under the repeated loading. Nevertheless, a gradually decreasing trend can be observed. Stage 2 ($RDEC_2$): with the increase for the number of load cycles, RDEC maintain a low and stable Value (PV). At this time, the rate of dissipated energy change is a stable state, indicting specimen damage evolution occurs at a steady rate; Stage 3 ($RDEC_3$): with the further increase for the number of load cycles, RDEC increase dramatically,



(a) 200 με



(b) 400 με



(c) 600 με

Fig. 4: The dissipated energy ratio versus number of load cycles in different strain level

illustrating the damage is enhanced sharply and the resulting fatigue failure occurs for specimen.

Furthermore, there is no obvious increase for the Rate of Dissipated Energy Change (RDEC) for both the modes of strain control and stress control and the different control levels basing on the presented fatigue failure criteria, which was defined as the stiffness modulus decreased to 50% of the initial value under repeated loading. Therefore, damage evolution of material still in a stable state, there still exists some residual strength to resist the repeated loading.

Herein, the number of load cycles (N_{tf}) corresponding to the mutation of $RDEC_2$~$RDEC_3$ is selected to describe the fatigue life. Fatigue life prediction model proposed by Shen is used to fit the fatigue test date for the two control modes (strain control and stress control), Shen and Carpenter (2005) as expressed in following:

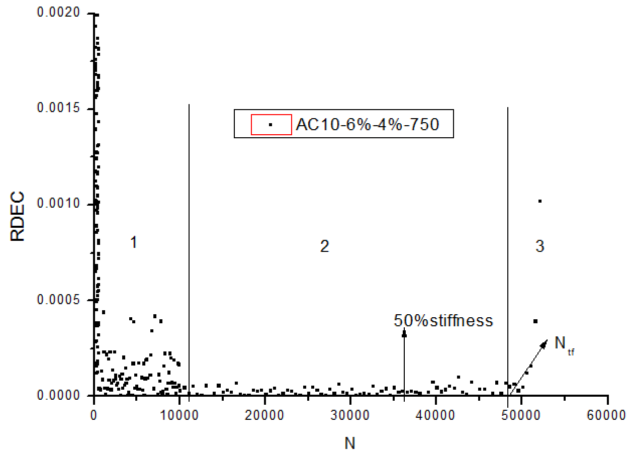
$$PV = cN_f^d \tag{10}$$

in which,

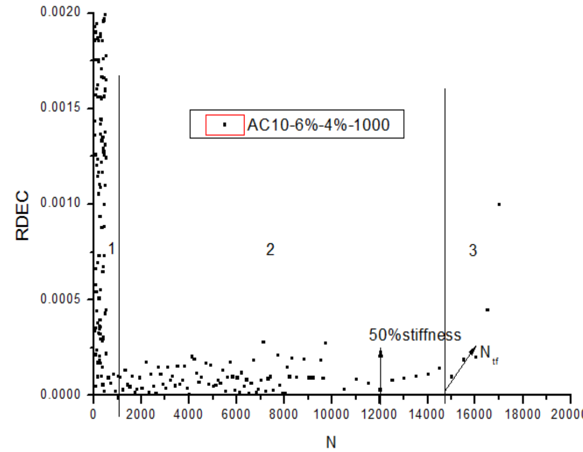
PV = The average value of $RDEC_2$
c and d = The fitting parameters
N_f = The number of load cycles for fatigue failure

In this study N_f is recognized as the number of load cycles for fatigue failure as shown in Fig. 4 and 5.

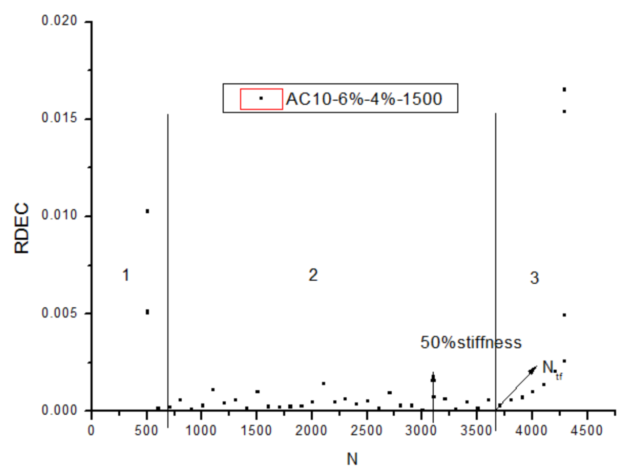
The fatigue life fitting curves for two different materials with varied load control mode and control levels are shown in Fig. 6, basing on the above mentioned fatigue life prediction model. From the diagram in a double logarithmic coordinates, we can see that there is a strong correlation (R^2 = 0.97 or 0.99) between PV and fatigue life for both of fine-grained (AC10) and medium-grained (AC20) asphalt mixture, no matter what kind of load patterns is demonstrated. In can also be seen than from the diagram, this fatigue life prediction model based on Rate of Dissipative Energy Change (RDEC) is independent of the load control



(a) 750 KPa

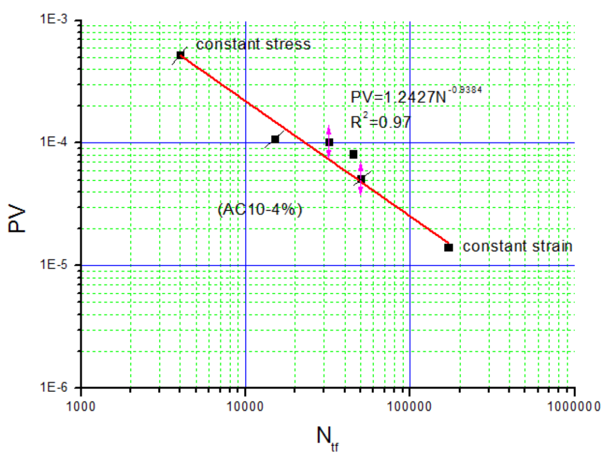


(b) 1000 KPa

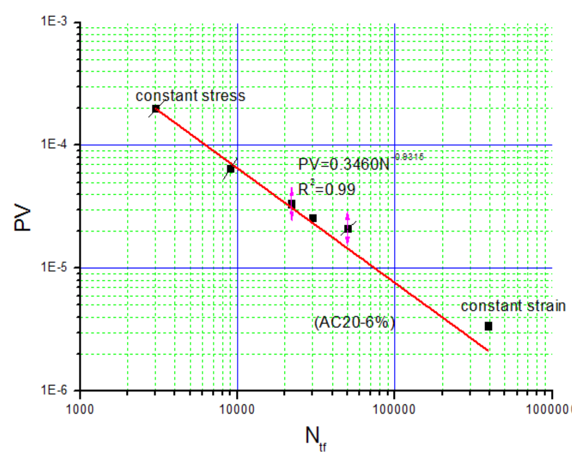


(c) 1500 KPa

Fig. 5: The dissipated energy ratio versus number of load cycles in different stress level



(a) AC10, content of asphalt is 4%



(b) AC20, content of asphalt is 6%

Fig. 6: Correlation between PV and number of cycles to fatigue failure in different load modes (N_{tf} as the failure criteria)

mode. In another words, one fitting curve would be obtained for both the modes of strain control and stress control.

In summary, it is irrational to demonstrate the indoor fatigue test of asphalt mixture using the traditional failure criteria, which was defined as the stiffness modulus decreased to 50% of the initial value. Application of Rate of Energy Dissipation Change (REDC) to describe fatigue failure criterion shows a clear physical meaning. In addition, the independence of fatigue life prediction based Rate of Dissipated Energy Change (REDC) model on load control modes is verified.

CONCLUSION

The relation between Rate of Dissipated Energy Change (REDC) and fatigue life was exploited through a four-point bending fatigue test with different asphalt mixture and varied load control modes and a new fatigue failure criteria was proposed. Under this failure criterion, the feasibility of the Rate of Dissipated Energy Change (REDC) to predict fatigue was confirmed and the independence of load control modes was demonstrated. The main conclusions of this study are as follows:

- It is irrational to demonstrate the indoor fatigue test of asphalt mixture using the traditional failure criteria, which was defined as the stiffness modulus decreased to 50% of the initial value. At this time, the Rate of Dissipated Energy Change (RDEC) keeps a lower stable level, indicating the damage evolution of material is stable. In other words, there still exists some residual strength to resist the repeated loading; a quite residual life should not be neglected.
- Fatigue evolution increases dramatically as the Rate of Dissipated Energy Change (RDEC) gets mutation, the asphalt mixture specimen fatigue failure occurs. Application of Rate of Energy Dissipation Change (REDC) to describe fatigue failure criterion shows a clear physical meaning.
- The feasibility of the Rate of Dissipated Energy Change (REDC) to predict fatigue was confirmed and the independence of load control modes was demonstrated through using the fatigue failure criteria proposed in this study.

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