

Analysis of fatigue on surface course using dissipated energy approach

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Abstract. As an important transportation infrastructure, pavement is subjected to repeated vehicle loads that may cause fatigue, which often leads to cracking. The point when this cracking initiates can be determined from the energy dissipated during the loading. This research investigates fatigue in Adi Soemarmo Airport mix-design using bitumen Pen 60/70 + EVA (Ethyl Vinyl Acetate) polymer. An Indirect Tensile Fatigue Test (ITFT) was conducted using stress-controlled loading mode to determine its fatigue life. The stress levels were 500, 600, and 700 kPa, while the loading frequency and the temperature were 10 Hz and 20 °C, respectively. The test exhibits strain levels for each loading cycle, which were used to determine the dissipated energy (DE). The result indicates that the DE increases when the number of loading cycles increases, due to progress of the strain levels. The values of DE are 7122.8, 8614.3, and 2654.9 J/m³ for loading levels of 500, 600, and 700 kPa, respectively, whereas the failure points for stress levels of 500, 600, and 700 kPa are 8171, 5161, and 841 cycles, respectively. Thus, the longer the time until the pavement failure point is reached (fatigue life), the greater the amount of energy that is dissipated.

1. Introduction

A pavement is an extremely important infrastructure for a transportation system, because it is a facility for vehicles to move from one place to another. When vehicles run along the pavement, which forces the pavement vertically and dynamically, each course of the pavement deforms. As it is viscoelastic, it returns to the former condition. After this has happened repeatedly, there is indirect stress-strain in the longitudinal direction at the bottom of the surface course [1]. If it happens continuously, with insufficient repetitive vertical and force rest time, the surface course will become fatigue cracked. Fatigue cracking is connected to the stiffness and strength of the pavement. So, the decrease of the stiffness leads to weakening of the pavement, which can finally crack [2].

By identifying the stress-strain of the pavement, a fatigue analysis can be done by developing S-N (stress amplitude–life) curves, called classical fatigue analysis [3]. In this method, a decrease of the stiffness modulus is observed until the specimen totally collapses with a transversal crack in the middle of the specimen. However, the classical method analyses the life of the specimen using the lowered values of the stiffness modulus before its collapse. In this way, it is not possible to observe when the crack is initiated. So, a more specific analysis by observing the dissipated energy is required. Under repeated loading, the pavement dissipates the energy as a response to the force. Then, when the dissipated energy reaches its peak, the pavement has initially lost its stability, which means that micro-cracking is happening. Therefore, the latter method is able to identify the fatigue life earlier than the former method by observing the pavement's dissipated energy.



2. Experimental

2.1. Indirect Tensile Fatigue Test (ITFT)

According to the configuration, the fatigue test consists of a simple flexure test, a direct axial loading test, and a diameter loading test [4]. These can be executed using two modes of loading: the strain-controlled and stress-controlled modes. This research used the diameter loading test (Indirect Tensile Fatigue Test, ITFT) with the stress-controlled mode.

In the ITFT, a compressive force is applied to a cylindrical specimen. The force is then distributed in the vertical and horizontal directions of the specimen [5]. When the vertical stress compresses the specimen, horizontal stress (called indirect tensile stress) occurs in the middle of the specimen. Because of the tensile stress, the specimen is displaced and becomes bigger when the force keeps compressing it until it collapses. Illustrations of the ITFT are shown in Figures 1.

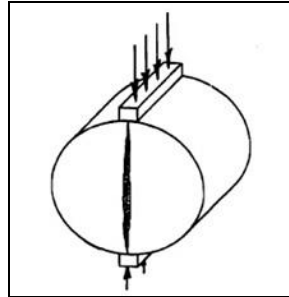


Figure 1. Illustration of ITFT when the specimen collapses.

2.2. Dissipated Energy Approach

During the performance of the test with repeated loading and relaxation, the energy of the specimen is dissipated, as it is viscoelastic at ambient temperatures. The viscoelastic materials make a different path on the time–load graph under loading and relaxation, forming an area. This phenomenon is called hysteresis. So, the dissipated energy is equal to the area of the graph [3].

The different path formed by loading and relaxation is caused by tensile stress-strain and phase-lag in each cycle. In stress-controlled mode, the stress is constant. However, the strain and phase lag get bigger during loading. This causes the dissipated energy to increase in line with the increase in the number of loading cycles. It was also reported by Francken and Clauwaert [6] that the dissipated energy rises in the stress-controlled mode but drops in the strain-controlled mode. So, the dissipated energy can be determined by Equation 1. After the energy dissipated in each cycle has been measured, the cumulative dissipated energy can be determined (2).

$$w_i = \pi \sigma_i \varepsilon_i \sin \phi_i \quad (1)$$

$$W = \pi \sum_{i=0}^{i=N} \sigma_i \varepsilon_i \sin \phi_i \quad (2)$$

where w_i is the energy dissipated in cycle i ; σ_i is the stress in cycle i ; ε_i is the strain in cycle i ; ϕ_i is the phase lag in cycle i ; and W is the cumulative dissipated energy.

Using the dissipated energy, the fatigue life is defined as the point at which the graph of the dissipated energy ratio (DER) versus the load cycle number deviates from a straight line [7]. So, DER and fatigue life can be determined by Equations 3 and 4, respectively.

$$R_\sigma = n E_i^* \quad (3)$$

where R_σ is the DER in the stress-controlled fatigue test and E_i^* is the stiffness modulus.

Knowing the cumulative dissipated energy and DER, the relationship between them can be identified (4).

$$W = AN^Z \quad (4)$$

where A and Z are experimental coefficients [8].

2.3. Materials

The aggregate is taken from Kulonprogo quarry, Yogyakarta, and the gradation of the aggregate for the asphalt mixture using Adi Soemarmo runway's, which is shown in Table 1.

Table 1. Existing pavement gradation of Adi Soemarmo Airport

Sieve Opening Size		% Passing
Inch	mm	
1	25.4	100
3/4	19	100
1/2	12.7	84.54
3/8	9.5	79.13
No.4	4.76	76.57
10	2	65.30
40	0.42	26.47
80	0.177	11.97
200	0.074	5.41

(Source: *Final Report of Inspection of the Quality and Quantity of Extension Construction of R/W, T/A, and Paved Shoulder Stage II*)

However, the bitumen (Pen 60/70) of the mixture is modified using EVA (ethylene vinyl acetate) polymer. EVA is a polymer that can make the bitumen more plastic, so the strength improves. This polymer will improve the performance of the mixture, as confirmed by Indirect Tensile Strength (ITS) Test and Unconfined Compression Strength (UCS) Test. The use of 4% EVA can optimize the mixture strength as well as the temperature resistant [9].

3. Results and Discussion

From the Marshall test, the optimum bitumen content is determined, as shown in Table 2.

Table 2. Marshall test result using Bitumen Pen 60/70 and EVA 4%

Test Results	4.5%	5.0%	5.5%	6.0%	6.5%	7.0%	Specification
Stability (kg)	986.33	1017.81	1370.66	1375.52	1285.77	1156.13	975.51
Flow (mm)	3.17	3.20	4.55	4.00	3.47	2.90	2.5–4
Porosity (%)	10.137	8.909	6.636	8.116	4.389	2.409	2–5
Density (gr/cc)	2.211	2.225	2.264	2.213	2.286	2.317	
MQ (kg/mm)	316.337	323.669	287.254	345.114	373.070	404.818	

According to all of the properties of the Marshall test, the optimum bitumen content is 6.5%. So, it is used for the specimen's formula. Three specimens were used for the ITFT in Udayana University, Denpasar, and the results are listed in Table 3. The data in Table 3 were used for developing a model of fatigue and initial stiffness, which was done by Nugroho [10].

Table 3. ITFT result

No.	σ (kPa)	N_f (cycles)
1	500	10401
2	600	6600
3	700	1250

With the data, the cumulative dissipated energy is calculated, as shown in Table 4. The DER is determined using the stiffness modulus and then graphs of DER versus the number of cycles are built, as shown in Figures 2, 3, and 4.

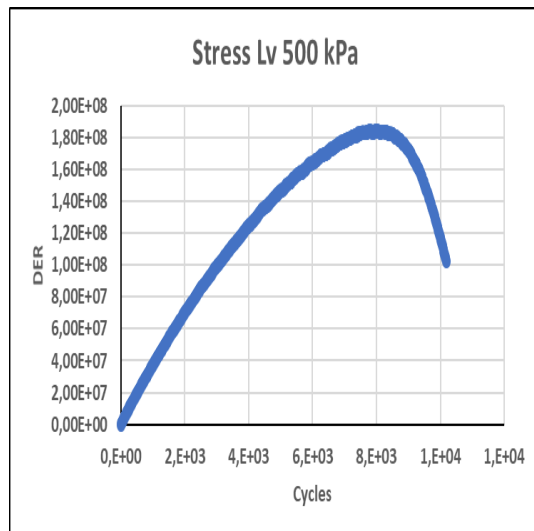


Figure 2. Relationship between DER and the number of load cycles under a stress level of 500 kPa

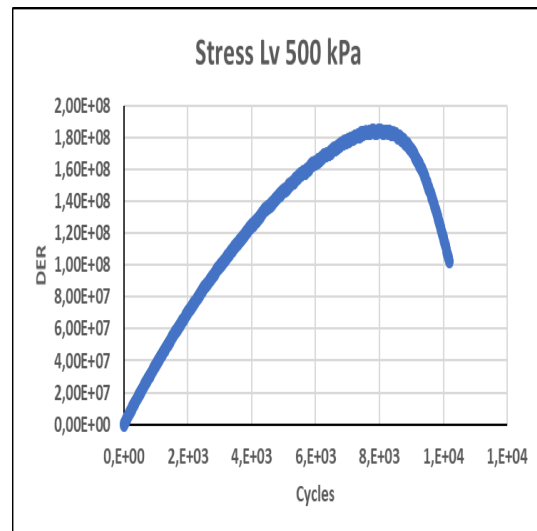


Figure 3. Relationship between DER and the number of load cycles under a stress level of 600 kPa

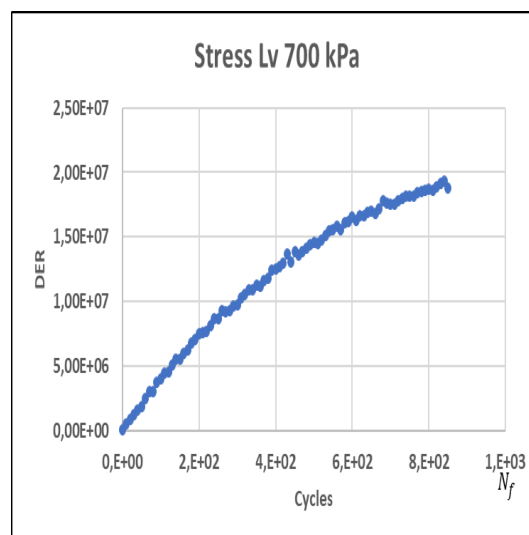


Figure 4. Relationship between DER and the number of load cycles under a stress level of 700 kPa

Table 4. Summary of N_R

No.	σ (kPa)	N_R (cycles)
1	500	8171
2	600	5161
3	700	841

If these results are compared with the results of the results of Nugroho's classical analysis [10], the fatigue life found by using the dissipated energy approach is lower than that found by the classical approach. The initiation of cracking of the specimen does not occur at the time of specimen collapse in the test. Cracking is initiated by micro-cracks, which are identified by observing the dissipated energy. Therefore, the dissipated energy analysis determines the fatigue life by using a more specific analysis that identifies the unseen cracks in the specimens.

Furthermore, the mathematic model of the relationship between N_R and W can be built as shown in Figure 8 using a graph of $\log N_R$ versus $\log W$. From the graph, the trend line can be determined and the coefficients A and Z are calculated, resulting in values of 99.312 and 0.495, respectively. Finally, the model equation is completed (5).

$$W = 99.312 N_R^{0.495} \quad (5)$$

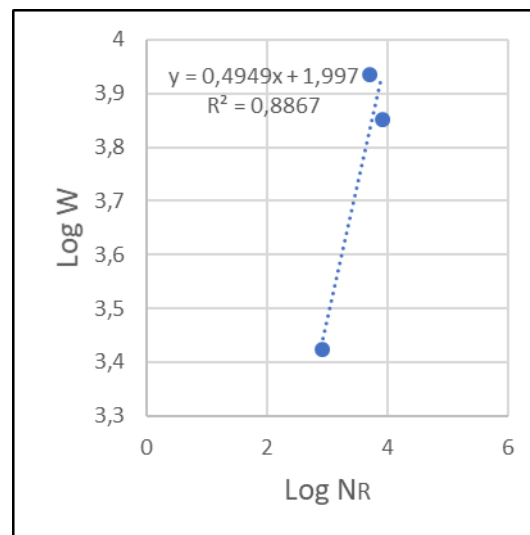


Figure 5. Relationship between $\log N_R$ and $\log W$

4. Conclusion

After the analysis and discussion, it can be concluded from the research that the greater the number of loading cycles, the higher the strain that takes place in the specimens. The increase in strain leads to more dissipation of the energy of the specimens. However, the relationship between cumulative dissipated energy and stress level is inversely proportional, with a decrease of cumulative dissipated energy followed by an increase of the stress level. Furthermore, the fatigue life determined by using the dissipated energy approach (N_R) is directly and inversely proportional to the cumulative dissipated energy and stress level, respectively.

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