Determination of Failure Point of Asphalt-Mixture Fatigue-Test Results Using the Flow Number Method

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Abstract. The failure point of the results of fatigue tests of asphalt mixtures performed in controlled stress mode is difficult to determine. However, several methods from empirical studies are available to solve this problem. The objectives of this study are to determine the fatigue failure point of the results of indirect tensile fatigue tests using the Flow Number Method and to determine the best Flow Model for the asphalt mixtures tested. In order to achieve these goals, firstly the best asphalt mixture of three was selected based on their Marshall properties. Next, the Indirect Tensile Fatigue Test was performed on the chosen asphalt mixture. The stress-controlled fatigue tests were conducted at a temperature of 20°C and frequency of 10 Hz, with the application of three loads: 500, 600, and 700 kPa. The last step was the application of the Flow Number methods, namely the Three-Stages Model, FNest Model, Francken Model, and Stepwise Method, to the results of the fatigue tests to determine the failure point of the specimen. The chosen asphalt mixture is EVA (Ethyl Vinyl Acetate) polymer-modified asphalt mixture with 6.5% OBC (Optimum Bitumen Content). Furthermore, the result of this study shows that the failure points of the EVA-modified asphalt mixture under loads of 500, 600, and 700 kPa are 6621, 4841, and 611 for the Three-Stages Model; 4271, 3266, and 537 for the FNest Model; 3401, 2431, and 421 for the Francken Model, and 6901, 6841, and 1291 for the Stepwise Method, respectively. These different results show that the bigger the loading, the smaller the number of cycles to failure. However, the best FN results are shown by the Three-Stages Model and the Stepwise Method, which exhibit extreme increases after the constant development of accumulated strain.

1. INTRODUCTION

The fatigue test using the stress-controlled mode has a short failure period. This makes the failure point hard to determine. Several studies have been developed to define the failure point, one of which is called the Flow Number Method. The Flow Number Method is a part of the results of the NCHRP research project on asphalt performance. This research assumed that the Flow Number Method is better than other methods for determining the failure point. It was found that the Flow Number Method obtained a better correlation with the field performance [1], [2]. This study aims to determine the failure point of the results of fatigue tests on asphalt mixture using the Flow Number Method and to compare the most applicable theory of the Flow Number Method based on the graphical results of fatigue tests on asphalt mixtures for a particular asphalt mixture.
The failure point is determined just before the total collapse of the specimen. In stress-controlled mode, the flow number is defined as the cycle number at which the tertiary phase initiates. This study uses four Flow Number models, namely the Three-Stages Model, the FNest Model, the Francken Model, and the Stepwise Method. These models have the same correlation between the permanent strain ($\varepsilon_p$) and cycle number (N). The scientific approaches of the Flow Number models are explained below.

### 1.1 Three-Stages Model

The Three-Stages Model has three phases of failure, determined as the primary, secondary, and tertiary stages. Every phase has its own approach, shown in Eqs. 1–3 below [3].

#### Primary stage:

$$\varepsilon_p = aN^b; N < N_{PS}$$

#### Secondary stage:

$$\varepsilon_p = \varepsilon_{PS} + c(N - N_{PS}); N_{PS} \leq N < N_{ST}$$

#### Tertiary stage:

$$\varepsilon_p = \varepsilon_{ST} + d(\varepsilon_{ST}^{(N - N_{ST})} - 1); N \geq N_{ST}$$

$N_{PS}$ is the load repetition number at the initiation of the secondary stage, $N_{ST}$ is the load repetition at the initiation of the tertiary stage, $\varepsilon_{PS}$ is the permanent strain at the initiation of the secondary stage, and $\varepsilon_{ST}$ is the permanent strain at the initiation of the tertiary stage. $a$, $b$, $c$, $d$, and $f$ are materials constants. In this model, $N_{ST}$ is the flow number.

### 1.2 FNest Model

The FNest Model is shown in Eqs. 4 and 5 below [4].

$$\varepsilon_p = \frac{1}{\beta}\ln\left(1 - \frac{N}{N_{PS}}\right)^\alpha$$

$$F_N = \gamma\ln\left[1 - \exp\left(\frac{1}{\alpha} - 1\right)\right]$$

FNest Model was developed by Archilla and Diaz [5]. The $\alpha$, $\beta$, and $\gamma$ parameters are calculated to develope relation of permanent strain and number of cycles. Furthermore, these parameters are used to determine FN.

### 1.3 Francken Model

The Francken Model is a composite model between the power part and the exponential component [6]. The Francken Model is defined in (1.6), where $A$, $B$, $C$, and $D$ are the regression constants and (1.7) shows the second derivation [7]:

$$\varepsilon_p(N) = AN^B + C(\varepsilon_{DN}^D - 1)$$

$$\frac{d^2\varepsilon_p}{dN^2} = (A \times B \times (B - 1) \times N^{(B-2)}) + (C \times D^2 \times \varepsilon_{DN})$$

### 1.4 Stepwise Method

The Stepwise Method is a traditional method to find the minimum point on a correlation curve between strain rate and cycles by smoothing the measured permanent deformation. There are three simple steps as follows: firstly, the measured permanent deformation is smoothed by reallocating the measured result under the assumption that the permanent strain will either remain the same or increase over the number of load cycles [5]. Second, the strain rate is calculated on the basis of the modified permanent deformation above mentioned. Equation (1.8) is used to calculate the strain rate [4]. Third, the flow number is defined
as the minimum strain rate value by combining the curve of the permanent strain versus cycles and the curve of strain rate versus cycles.

\[ \text{Strain Rate} = \frac{\Delta \varepsilon}{N} \]  

(1.8)

2. EXPERIMENTAL

This study used split aggregate with 19 mm (3/4 inch) as the maximum dimension and asphalt pen 60/70, EVA modified asphalt, and SBS (Styrene Butadiene Styrene) as the binder materials. A cylinder specimen with a thickness of \( \pm 63.5 \text{ mm} \) and diameter of \( \pm 100 \text{ mm} \) was used in this research.

These kinds of mixtures were tested by the Marshall test to find their Optimum Bitumen Contents (OBCs). Also the Marshall test was used to find the Marshall characteristic of the asphalt mixtures in order to choose the best one. The best asphalt mixture will be tested by the fatigue test method. This research uses the Indirect Tensile Fatigue Test (ITFT) in the stress-controlled mode at a temperature of \( 20^\circ \text{C} \) and frequency of 10 Hz. The ITFT method is based on BS EN-12697-24. The fatigue test used loads of 500, 600, and 700 kPa. The results of this test are resilient modulus, permanent strain, and deformation at related number of load repetitions (cycles). The next step is the determination of the failure point by the Flow Number method based on the fatigue test of the asphalt mixture.

3. RESULTS AND DISCUSSION

According to the results of Michael [8] and Nugroho [9], all of the asphalt mixtures showed OBCs as large as 6.5%. However, EVA-modified bitumen showed the best Marshall characteristic based on the stability, flow, porosity, density, and Marshall quotient. Therefore, the EVA-modified asphalt mixture was tested by the fatigue test. The results of the fatigue test were processed to determine the failure point using four Flow Number Method, namely the Three-stages Model, FNest Model, Francken Model, and Stepwise Method.

3.1 Three-Stages Model

![Diagram of Three-Stages Model P = 500 kPa](image)

**Table 1. Three-Stages Model Approach**

| P (kPa) | Primary Stage | Secondary Stage | Tertiary Stage |
|---------|---------------|-----------------|---------------|
| 500     | \( \varepsilon_p = 22.184N^{-0.764} \) | \( \varepsilon_p = \varepsilon_p + 4.29134E - 06(N - 761) \) | \( \varepsilon_p = \varepsilon_p + 156.7793(e^{-0.00212(N - 6421)} - 1) \) |
| 600     | \( \varepsilon_p = 61.064N^{-0.7541} \) | \( \varepsilon_p = \varepsilon_p + 7.75801E - 06(N - 341) \) | \( \varepsilon_p = \varepsilon_p + 152.1617(e^{-0.00328(N - 4541)} - 1) \) |
| 700     | \( \varepsilon_p = 145.43N^{-0.5415} \) | \( \varepsilon_p = \varepsilon_p + 4.06938E - 05(N - 611) \) | \( \varepsilon_p = \varepsilon_p + 166.8984(e^{-0.00204(N - 511)} - 1) \) |
This research used Solver tools in Microsoft Excel to obtain the material constants. The result of \( N_{ST} \) under loads of 500, 600, and 700 kPa are 6621, 4841, and 611 cycles respectively.

### 3.2 FNest Model

![Figure 2. Diagram of FNest Model. P = 500 kPa](image)

**Table 2. Probability Distribution Parameters of FNest Model**

| No. | P (kPa) | A    | B     | \( \gamma \) | FN   | Model |
|-----|---------|------|-------|-------------|------|-------|
| 1   | 500     | 2.0387 | 0.00232 | 10700      | 4271 |        |
| 2   | 600     | 3.4373 | 0.00208 | 6432.181   | 3267 |        |
| 3   | 700     | 3.4257 | 0.00177 | 1058.899   | 537  |        |

Table 2 shows the probability distribution obtained by the FNest Model approach to determine FN. In this model, FN is determined by (1.5) with the help of Solver tools to find the probability distribution parameter. Figure 2 shows the results of the permanent strain model based on (1.4). The failure points for the load, namely 500, 600, and 700 kPa, are 4271, 3267, and 537 cycles.

### 3.3 Francken Model

In the Francken model, FN is derived by the Francken Model approach. Based on the permanent strain approach, regression constants which have the same structure as (1.6) is defined. The first derivative of the permanent strain results in the strain slope. The minimum strain slope is FN in the Francken Model. The strain slope is the transition phase from the negative axis to the positive one in the second derivative of the Francken Model. So the failure points under loads of 500, 600, and 700 kPa are 3401, 2431, and 421 cycles respectively.
Table 4. FN calculation for Stepwise Method

| P (kPa) | Min. Ø | FN  |
|---------|---------|-----|
| 500     | 0.6477  | 6901|
| 600     | 0.1136  | 6841|
| 700     | 0.68397 | 1291|

The fatigue failure phase in the Stepwise Method are the same as in the Francken Model. In the primary phase, the strain rate decreases extremely from the beginning until N cycles of the test. In the secondary phase, the strain rate curve is relatively flat. Until the strain rate starts to increase again, this is the ending of the secondary phase and the beginning of the tertiary one. The tertiary phase is the crack initiation. FN is allocated at the minimum point of the strain rate. So the failure points for the load repetitions of 500, 600, and 700 kPa are 6901, 6841, and 1291 cycles.

Based on the model results, the bigger the loading, the smaller the number of cycles to failure. The results of each method are summarized in Table 5 and Figure 5. Moreover, each method has a different FN value. A high variability factor leads to different FN values [3]. Each model has a different failure criteria based on its equation. Each equation consists of different independent and dependent variables. These differences result in different values of FN.

4. CONCLUSION

This paper presents a summary of the determination of FN for EVA-modified asphalt mixture. The failure point of results of the fatigue tests of the EVA-modified asphalt mixture was determined using the Flow Number Method with four model approaches, namely the Three-Stages Model, FNest Model, Francken Model, and Stepwise Method. The failure points of the Three-Stages Method with load repetitions of 500, 600, and 700 kPa are 6621, 4841, 611. The failure points of the FNest Model with the same load repetitions are 4271, 3266, and 537. With the same load repetition, the failure points of the Francken Model are found to be 3401, 2431, and 421. Lastly, the failure points of the Stepwise Method are 6901, 6841, and 1291 for the same load repetition.

Based on the FN calculation, the Stepwise Method has the highest FN value. Moreover, based on the curve result, the FN values obtained by the Stepwise Method and the Three-Stage Model are allocated to the tertiary phase, when the strain rate increases extremely. Therefore, based on the FN calculation and the curve result, the Stepwise Method and the Three-Stage Model are fitter models for determining the failure point using the Flow Number Method for EVA-modified asphalt mixture at a temperature of 20°C and frequency of 10 Hz. Both failure points are allocated in a critical area but are still in the right place.

REFERENCES

[1] Witczak M, Kaloush K, Pellinen T, El-Basyouny M and Von Quintus H 2002 NCHRP Rep. 465
[2] Zhou F and Scullion T 2003 J. Transp. Res. Board 1832(1) 209–216
[3] Ameri M, Sheikhmotevali A H and Fasihpour A 2014 Road Mater. Pavement Des. 15 182–206
[4] Goh S W and You Z 2009 Const. Build. Mater. 23 3398-3405
[5] Archilla A R and Diaz L G 2011 J. Transp. Res. Board 2210 1–8
[6] Biligiri K P, Kaloush K E, Mamlouk M S and Witczak M W 2007 J. Transp. Res. Board 2001(1) 63–72
[7] Pramesti F P 2015 Laboratory and Field Asphalt Fatigue Performance Matching Theory with Practice (Delft: Delft University of Technology)
[8] Michael 2016 Analisis Fatigue pada Surface Course dengan Pendekatan Dissipated Energy (Surakarta: Universitas Sebelas Maret)
[9] Nugroho A M 2016 *Analisis Fatigue pada Wearing Course dengan Metode Classical Fatigue* (Surakarta: Universitas Sebelas Maret)