

Study of the Effect of Temperature Changes on the Elastic Modulus of Flexible Pavement Layers

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Abstract: In general, the stiffness of flexible pavement is influenced by environmental changes, whereby temperature and rainfall affect the asphalt layer and non-asphalt layer, such as the subgrade, respectively. Normally, the effect of temperature on flexible pavement can be measured using two methods. The first is a destructive test whereby core samples are tested in a laboratory using a Universal Testing Machine (UTM). The second is a non-destructive in situ test using equipment such as a Falling Weight Deflectometer (FWD) and Spectral Analysis of Surface Waves (SASW). This study was conducted to investigate the effect of temperature at different tensile levels on the Soekarno-Hatta and Purwakarta Cikampek roads in Bandung, West Java, Indonesia. It is observed that different tensile levels and testing methods result in various elastic modulus values of flexible pavement. The higher the temperature applied to the flexible pavement layer, the more the elastic modulus values decrease. In contrast, the lower the temperature imposed on the flexible pavement layer, the more the elastic modulus values increase. Different testing methods (FWD, UTM and SASW) on the flexible pavement layer are also affected by temperature changes.

Keywords: Elastic modulus, flexible pavement, FWD, SASW, UTM

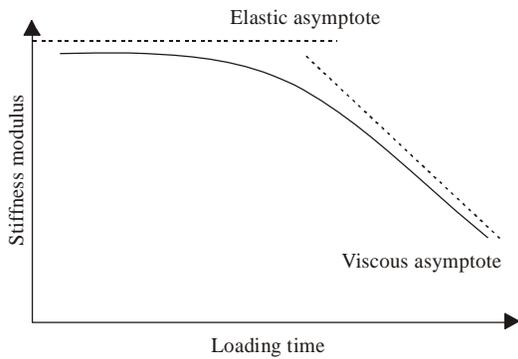
INTRODUCTION

In general, a flexible pavement system consists of an asphalt concrete layer, a base layer and a sub-base layer placed on the subgrade. The strength of the flexible pavement is determined by the quality of the materials used and is usually measured as a modulus (E). The stiffness of flexible pavement is also affected by changes in the weather or season (specifically rain) in the area. Changes in temperature will affect the modulus of the asphalt concrete layer, while changes in rainfall will affect the modulus of a non-asphalt layer such as the subgrade. Environmental factors such as the temperature influence the behavior of flexible pavement layers that use bitumen as a binder (Ullidtz, 1987; Ehrola *et al.*, 1990; AASHTO, 1993). Therefore, this study was conducted to investigate the effect of temperature at different tensile levels on the Soekarno-Hatta and Purwakarta Cikampek roads in Bandung, West Java, Indonesia. Different testing methods were used; namely, a Falling Weight Deflectometer (FWD), Spectral Analysis of Surface Waves (SASW) and a Universal Testing Machine (UTM). The FWD and

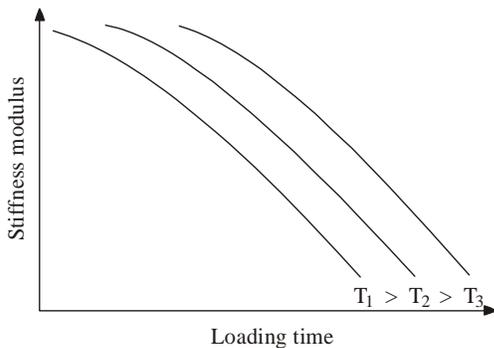
SASW tests represent non-destructive tests and the UTM test is a destructive test.

LITERATURE REVIEW

An asphalt mixture, by definition, is a composite material made up of aggregate particles, bitumen, air and other components such as additives, modifiers, fines and water in either liquid or vapor form (Lytton, 2009). The bitumen, which is black or dark brown in color, acts as an adhesive that glues the aggregates and other components into a dense mass and waterproofs the particles. The mineral aggregate, when bound together, acts as a stone framework to give strength and toughness to the composite system. Asphalt mixture performance is affected by the individual properties of both aggregate and bitumen and the interaction between them. However, bitumen requires special attention, as its characteristics may change dramatically with changes in temperature, loading and/or state of ageing (Reubush, 1999). In general, bitumen plays a vital role in the asphalt mixture at low temperatures. As the temperature increases, particularly at high temperatures,



(a)



(b)

Fig. 1: Stiffness modulus as a function of loading time and at different temperatures (Whiteoak, 1990)

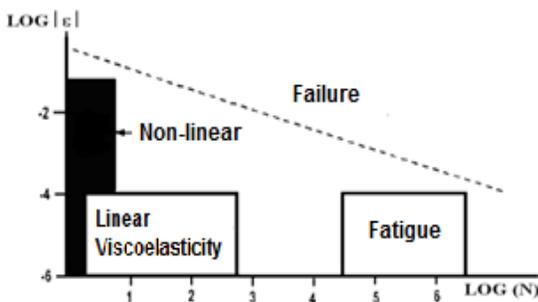


Fig. 2: Typical bituminous mix behavior domain (Di Benedetto and Olard, 2009)

the "stone-on-stone" contact of the aggregates plays a dominant role over that of bitumen.

Normally, the bitumen content is relatively small, between 4 and 7% of the total weight of the asphalt mixture. Bitumen is typically viscous at high temperatures and long loading times. At low temperatures and/or short loading times, bitumen is elastic in nature. In between these two extremes,

bitumen is viscoelastic. The modulus as a function of loading time is represented on a graph of logarithmic scales, as illustrated in Fig. 1, in which the asymptotes represent the approximation of the elastic and viscous response at short and long loading times respectively (Whiteoak, 1990). According to Van Der Poel (1954), a simple concept of Young's modulus (S) can be applied to the viscoelastic materials and can be shown as the following:

$$S_b = \frac{\sigma}{\varepsilon}(t, T) \quad (1)$$

where,

S_b = The stiffness modulus of bitumen (Pa) and depends on loading procedure frequency of loading and temperature

σ = Tensile stress

ε = The total strain

Apart from the very thin surface layers, the different asphalt mixture layers have a structural effect. To characterize this effect and its evaluation with time, the mechanical properties of asphalt mixtures have to be modeled considering the following aspects:

- Stiffness and stiffness evaluation with time
- Fatigue and damage law evaluation
- Permanent deformations and accumulation
- Crack initiation and crack propagation, particularly at low temperatures (Di Benedetto and Olard, 2009)

The first aspect is observed for very small strains and corresponds to the linear viscoelastic behavior of the asphalt mixtures. The three other aspects are, respectively, the origin of major distresses: degradation by fatigue, rutting and crack propagation. Each of these properties or distresses appears for a given domain of loading and corresponds to a specific type of mixture behavior. Figure 2 highlights the domains corresponding to typical types of mixture behavior according to the strain amplitude and the number of applied cyclic loadings.

The chemical properties of materials and the stiffness of the asphalt mixture layer can be changed as a result of temperature changes. Park and Kim (2001) used back calculation to study the effect of temperature on the Young's modulus values of the asphalt mixture. It appears that the stiffness modulus values differ depending on the ambient temperature of the asphalt mixture. Therefore, temperature correction for the deflection in testing using equipment such as a Falling Weight Deflectometer (FWD) is required. The test is

normally conducted at temperatures between 0 and 40°C with a vehicle speed of 55 km/h. An empirical equation to determine the elastic modulus of the asphalt layer can be shown as the following:

$$E_1(t) = 15000 - 7900 \times \log(t) \quad (2)$$

where,

$E_1(t)$ = The elastic modulus of the asphalt mixture layer at temperature $t(t \geq 1^\circ\text{C})$

The effect of temperature changes on the elastic modulus of asphalt mixtures in the ELMOD software can be shown using the following temperature correction equation:

$$\frac{E_t}{E_c} = A_s - B_s \log(t_a/c_a) \quad (3)$$

where,

E_t = The elastic modulus of the asphalt mixture layer at a temperature t

E_c = The reference elastic modulus of the asphalt mixture layer

t_a = The temperature of the asphalt mixture layer

c_a = The reference temperature of the asphalt mixture layer and A_s and B_s are constant values

The relationship between the bending and thickness of flexible pavement and temperature from the FWD tests can be shown as Eq. (4) and (5) below (Ehrola *et al.*, 1990):

$$d = A_d \times B_d^T \quad (4)$$

$$d = 0.981 \times h^{0.00726} \quad (5)$$

where,

T = The pavement temperature ($^\circ\text{C}$), A_d and B_d are constants

h = The thickness (mm) and d is the bending (mm)

EXPERIMENTAL DESIGN

In this study, the FWD measurements were carried out on two motorways: the Soekarno-Hatta Road in Bandung and the Cikampek-Purwakarta in West Java. Both motorways are located in Indonesia. In general, these roads consist of an asphalt mixture surface, base,

sub-base and subgrade. First, the FWD tests were conducted on different sites on the Soekarno-Hatta road, followed by the SASW tests. The same procedure was repeated on the Cikampek-Purwakarta road. Drill-hole tests also were carried out on the Soekarno-Hatta road. The samples obtained were taken to the laboratory and tested using the UTM machine to investigate the modulus of the asphalt pavement layer. The results will later be compared with the results obtained using both the FWD and SASW tests.

A total of 16 samples were obtained from the pavements. The modulus of the asphalt mixture layer can be determined using the following equations (Haas and Hudson, 1978; Universal Testing Machine, 2002):

$$S_t = \frac{2F}{\pi LD} \quad (6)$$

$$E_{\text{asfalt}} = \frac{H}{D} \quad (7)$$

$$M_{\text{asfalt}} = \frac{\sigma_d}{E_{\text{asfalt}}} = \frac{F(R + 0.27)}{LH} \quad (8)$$

where,

S_t = The tensile strength (kPa)

E_{asphalt} = The elastic Modulus of the asphalt mixture (MPa)

L = The length of the sample (mm)

D = The diameter of the sample (mm)

F = The maximum peak force given to the load repetitions (N)

R = The Poisson's ratio is and

H = The change in shape in the horizontal direction

RESULTS AND DISCUSSION

The effect of temperature on the elastic modulus: An empirical equation to describe the relationship between temperature and the elastic modulus of the asphalt has been developed by AASHTO (1993). A relationship between temperature and the elastic modulus of the asphalt mixtures of the motorways can be calculated using Eq. (2). For instance, using pavement temperature (T_p) of 40°C, the elastic modulus (E_1) of the asphalt pavement can be calculated as follows:

$$E_1(40^\circ\text{C}) = 15000 - 7900 \times \log(40) = 2.344 \text{ MPa}$$

Figure 3 shows the relationship between the pavement temperature and elastic modulus (E) for both roads,

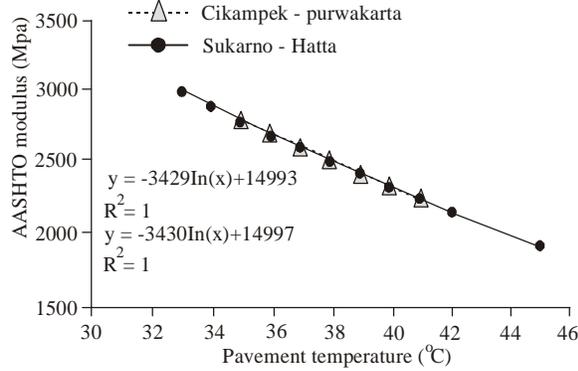


Fig. 3: Moduli versus temperature for the sukarno-hatta and cikampek-purwakarta roads using AASHTO (1993)

Table 1: Different parameters used by Dynatest Engineering (1989) and Puslitbang (1993)

Parameter	Dynatest Engineering (1989)	Puslitbang (1993)
Reference temperature (°C)	25	35
Elastic modulus (MPa)	3000	2000
A_s	1.0	1.0
B_s	2.2	3.5

based on the empirical equation of AASHTO (1993). Both parameters show a good agreement, where R^2 is almost equal to one (ideal conditions). At low temperatures the elastic modulus values increase and at high temperatures the elastic modulus values decrease. This finding is consistent with the rheological properties and viscosity, whereby the asphalt mixture is easily influenced by changes in temperature. It is also deduced that the AASHTO (1993) equation can be used in the study area.

The correction equation was developed by ELMOD/ELCON (Dynatest Engineering, 1989) for the elastic modulus of pavement layers due to the influence of temperature, as shown previously in Eq. (3). The temperature and constants (A_s and B_s) are not the same for each area, as they depend on the climate and temperature range. For example, Dynatest Engineering (1989) and Puslitbang (1993) used different parameter values, shown in Table 1. It is observed that the logarithmic equation in Fig. 3 shows a perfect relationship between the Elastic modulus (E) of the asphalt mixture and pavement temperature ($R^2 = 1$), where the equation is shown as the following:

$$Y = 14.995 - 342.5 \ln(X) \tag{9}$$

Equation (9) can be rewritten in the logarithmic form to represent the elastic modulus of the asphalt layer at a temperature t and by replacing $Y = E_t$:

$$E_t = 14.995 - 7895.56 \log(t) \tag{10}$$

The above equation is used to calculate the elastic modulus at reference temperatures of 35°C (Puslitbang, 1993) and 25°C (Dynatest Engineering, 1989). It is found that the elastic modulus for Puslitbang (1993) and Dynatest Engineering (1989) are 2802 and 3956 MPa, respectively. The observed values are slightly higher compared to the values given in Table 1.

By dividing E_t Eq. (10) with $E_{35} = 2802$ MPa, the following equation is obtained:

$$\frac{E_t}{E_{35}} = 5.35 - 2.82 \log(t) \tag{11}$$

Subsequently, the temperature (t) in the above equation is divided by 35°C:

$$\frac{E_t}{E_{35}} = 0.9957 - 2.82 \log\left(\frac{t}{c}\right) \tag{12}$$

It is observed that Eq. (12) is almost similar to Eq. (3) (ELMOD software), whereby factor $A_s = 0.9957$ (approximately equal to 1) and $B_s = 2.82$. The process was repeated using $E_{25} = 3956$ and $c = 25^\circ\text{C}$ and a new equation can be shown as follows:

$$\frac{E_t}{E_{c35}} = 1 - 2 \log(t) \tag{13}$$

Equation (13) is also in good agreement with ELMOD software; A_s and B_s are 1 and 2 respectively. It is deduced that the A_s values derived from both equations are equal to 1 and in good agreement with Puslitbang (1993) and Dynatest Engineering (1989). However, B_s obtained from the test is smaller compared to the reference values (Table 1). The larger B_s value used in the ELMOD equation yields a smaller value of elastic modulus and vice versa. This finding indicates that the temperature changes will affect the elastic modulus of flexible pavement. In this study, the following values are used with the ELMOD (1989) equation: (i) $A_s = 1.0$, $B_s = 3.5$, $c = 35^\circ\text{C}$ and $E_c = 2000$ MPa, in accordance with the values proposed by Puslitbang (1993). This is done in order to obtain smaller values of Elastic modulus (E_t) and to ensure that pavement stiffness is not too excessive. The result obtained from a combination of Eq. (3) and the Puslitbang (1993) parameters is shown in Fig. 4. In this study, the following values are used with the ELMOD equation.

Laboratory testing using the Universal Testing Machine (UTM): Figure 5 shows the modulus values

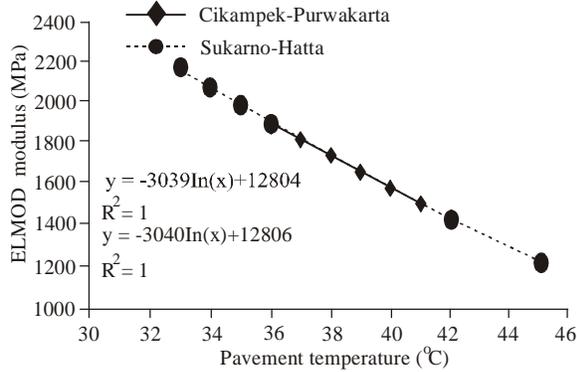


Fig. 4: Moduli versus temperature for the sukarno-hatta and cikampek-purwakarta roads using ELMOD

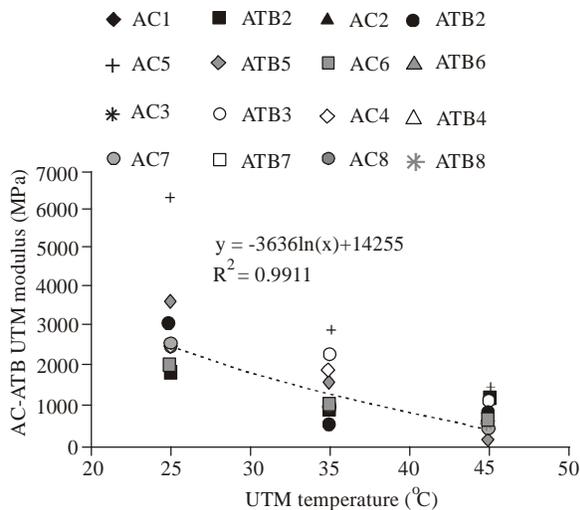


Fig. 5: Moduli of AC-ATB versus temperature from the UTM tests

of core drilled samples (AC) and ATB testing in the laboratory versus temperature (t). The empirical equation in this figure is shown as the following:

$$E_{AC-ATB} = 14225 - 3636 \ln(t) \quad (14)$$

With $R^2 = 0.9911$. This equation indicates that the asphalt modulus is affected by temperature changes. An increase in temperature from the UTM test will decrease the asphalt modulus of the sample and vice versa. A similar study was conducted by Ullidtz (1987) using the SHELL and AASHO methods, where a significant relationship between temperature and asphalt modulus was observed. Figure 6 shows a comparison between different methods (i.e., SHELL,

AASHO, FWD and Eq. (14) used to study the effect of temperature on the asphalt modulus. Results of the FWD and Eq. (14) are in good agreement with the curve obtained using the AASHO method. The curve from the SHELL method also shows a similar pattern but it is not linear.

The following findings are observed using the SHELL method in order to calculate the stiffness modulus (E) of the asphalt layer:

- Air void content in an asphalt mixture should not be larger than 3%.
- The van der Poel's nomograph is used to calculate the asphalt stiffness (MPa) with the following restrictions: t between 0.01 to 0.1 sec; Penetration Index (PI) between 1.0 and +1.0; and temperature difference ($T_{R\&B}-T$) between 0 and 70°C.
- Asphalt mixture stiffness can be calculated using the following equation:

$$E_a = S_b \times \left[1 + \left(\frac{2.5}{n} \right) \times \frac{C'_v}{1 - C'_v} \right]^n \quad (15)$$

where,

E_a = Asphalt stiffness (MPa)

$n = 0.83 \times \log(40000/S_b)$

S_b = The binder stiffness (MPa) from van der Poel's Nomograph

C_v = The volume concentration of aggregate

C'_v = The correction factor where the air void content in the asphalt mixture exceeds 3%

The stiffness moduli calculated using the SHELL method is generally in good agreement with the results obtained from the flexural tests (Ullidtz, 1987). At high temperatures, however, the flexural tests tend to give a lower stiffness modulus. The increase in testing temperature causes the modulus of the asphalt mixture to meet the modulus of the aggregates and subsequently, the moduli approaches zero. Furthermore, Fig. 6 is plotted using the SHELL method and takes the form of a curve. The core drilled samples tested using the UTM machine on the Soekarno-Hatta road are different from the samples tested using the SHELL method; therefore, the results are different.

In contrast, the AASHTO (1993) equation shows reliable asphalt mixture modulus results at high temperatures. This is shown in Fig. 6, where the line is in good agreement with the results obtained from the FWD and UTM tests. Temperatures below 20°C for the AASHO and below 27°C for this study show mixed results, with the modulus being greater than that obtained from the SHELL method. This is because the low-temperature flexural test in the laboratory (UTM) gives lower tensile values compared to those obtained

from the FWD tests in the field. Asphalt is a viscoelastic linear material and its stretch levels decrease at a certain increase in the modulus

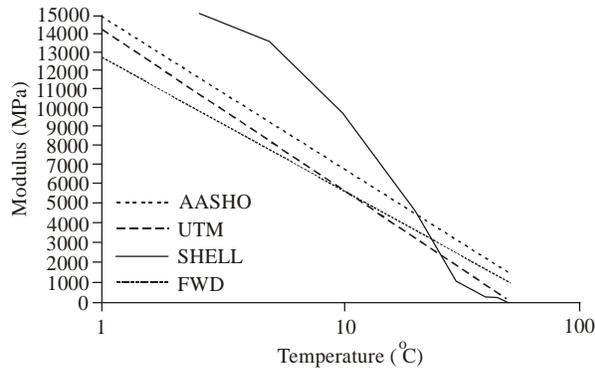


Fig. 6: Asphalt moduli versus temperature

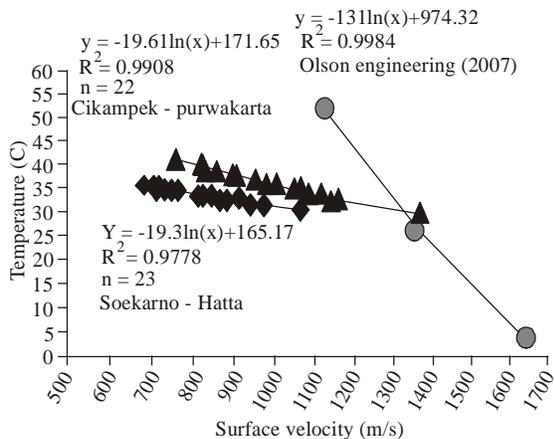


Fig. 7: The relationship between surface velocities versus temperature

Bohn *et al.* (1977) However, the difference in modulus values at low temperatures is vital for pavement performance. For temperatures above 20°C, the modulus of the mixture obtained by the SHELL method falls rapidly compared to the UTM and AASHO methods. At temperatures above 40°C, the SHELL method shows lower modulus values compared to the modulus of aggregates. At temperatures above 30°C, the asphalt modulus values are medium for both the SHELL and AASHO methods.

The influence of temperature in the SASW test: Other important pavement material properties are its viscoelastic properties as a function of temperature. Viscoelastic properties are closely related to the changes of stiffness with changes in temperature. However, only an asphalt mixture layer shows viscoelastic behaviour. Figure 7 shows the relationship

between temperature versus surface wave velocity observed in this study (the Cikampek-Purwakarta and Soekarno-Hatta roads) and Olson Engineering in 2007. A study done by Olson Engineering found that an increase in temperature in pavement with a thickness of 16.764 cm will decrease the surface wave velocity. It is observed that the surface wave velocity values at 4.44, 26.66 and 52.22°C are 1645.9, 1371.6 and 1143.0 m/s, respectively. This finding indicates that the higher the temperature the lower the surface wave velocity values. It was also found that the strain in the SASW is less than 10³% and lower compared to the tests conducted using the FWD and UTM. Since the wave velocity decreased along with an increase in asphalt pavement temperature, the elastic modulus will decrease (Sentot, 2012).

CONCLUSION

In general, the higher the temperature applied to the flexible pavement layer the lower the elastic modulus value will be. In contrast, the elastic modulus of the pavement layer increases as the temperature increases. It is also observed that different tests (i.e., FWD, SASW and UTM) are affected by the changes in temperature.

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