The effect of vehicle speed on the stiffness modulus of conventional asphalt and bioasphalt

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Abstract. Stiffness modulus is the ratio between stress and strain found in a layer. The value of the stiffness modulus is related to the performance of the layer in bearing the load. High modulus of stiffness makes the asphalt mixture stiff and resistant to deformation, while a decrease in the modulus of stiffness will make the pavement layer vulnerable to crack. The purpose of this study was to analysis the characteristic differences between damar asphalt mixture and conventional asphalt mixture in term of the stiffness of asphalt mixtures due to the variations in vehicle speed at the specified temperature. Speed variations are 10, 20, 30, 40, 50 and 60 kph and the temperature reference are 20 and 40°C. Data analysis is performed by comparing the stiffness values of damar asphalt mixtures and conventional asphalt mixture. The results of this study indicate that damar asphalt mixes are more resistant to changes in temperature and vehicle speed than conventional asphalt.

1. Introduction
Flexible pavement is pavement that uses asphalt as a binder. The layers of pavement are carrying and spreading the burden of traffic to the compacted soil [1]. Each layer of pavement that is burdened will experience a response to the vehicle load in the form of stress and strain in each layer of pavement. Stiffness modulus is the ratio between stress and strain found in a layer. Stiffness modulus is a value that indicates the stiffness of a material. The higher the stiffness modulus of a material, the more difficult it is to change shape because the strain that occurs is very small.

The theory of linear viscoelasticity states that the relaxation modulus E(t) and complex modulus are constant, thus time and frequency can be interconverted. The stiffness modulus change during the loading time is not a constant function [2]. This theory is supported by the opinion of Van der Poel who mentioned the stiffness modulus as stiffness of bitumen (Sb) which is a comparison between the stresses on asphalt, which is a function of the length of loading (frequency) applied, the temperature difference with T800 and the penetration index. T800 is the temperature when penetration reaches 800 [3]. So determination of the stiffness modulus of asphalt mix is significantly influenced by pavement temperature and time loading period [4][5].

Determination of temperature in this study is based on the results of research conducted Taherkhani et al showed that in dry condition, the resilient modulus increases with increasing loading frequency, while, in saturated condition, a slight increase of resilient modulus with loading frequency was observed only at 40°C. It is also found that, in both the dry and saturated conditions, the effect of
loading frequency on the resilient modulus decreases with decreasing temperature. Therefore, the temperature of 40°C was recommended for investigating the effect of loading frequency on the resilient modulus [6]. The temperature range in research conducted by taherkhani is -5, 5, 20 and 40°C. So the researchers decided to use temperatures of 20 and 40°C as a reference, another consideration because temperatures in Indonesia ranged between these ranges.

Similar research has been conducted by Lubis to determine the AC-WC stiffness modulus with the result that the modulus of stiffness decreased with increasing concrete asphalt temperature [7]. Sjahdanulirwan conducted a literature review on the effect of loading time on the stiffness of concrete asphalt according to direct methods and indirect methods. For the direct methods used Marshall test and for the indirect methods used Brown & Brunton method and Shell Bitumen method [8]. Riwibowo conducted research on service life which in the process alluded to the stiffness of the asphalt mixture. The results of this study concluded that the pavement temperature and loading time can affect the service life of the road, where the loading time variable is more influential than the pavement temperature [9]. Speed is related to the service life of the road because differences in vehicle speed cause variations in the modulus of elasticity of material that affects the design life [10]. The higher the speed of the vehicle, the damage caused by the road will be lower so that the ability of the road to serve traffic will be longer [11]. Therefore, researchers are interested to know the effect of speed on modulus of stiffness, especially on damar asphalt and its differences with conventional asphalt. Researchers through this study will compare the results of vehicle speed variations at temperatures of 20 and 40°C against the mix stiffness of conventional asphalt and bioasphalt using analytical approach to determine the difference.

2. Experimental

The result from the laboratory test analyzed using the Nottingham design method to obtain the value of asphalt mixture stiffness (SMix) based on an analysis of variations in vehicle speed and temperature. Tests and methods carried out in this study are described in sections 2.1 to section 2.3:

2.1. Bitumen

This research uses two different types of asphalt, the intended asphalt is damar asphalt and conventional asphalt. For research purposes, the two asphalt physical properties are tested, such as penetration, softening points, ductility, specific gravity and flash points.

2.1.1. Damar asphalt is asphalt resin is a binding agent with a mixture of resin, fly ash, cooking oil and latex with a composition of pure resin 100 g is added resin powder 350 g, fly ash 150 g, cooking oil 205 g, and 4% latex. The main physical properties of damar asphalt can be seen in Table 1.

| Type of Testing | Unit | Specification | Test Results |
|-----------------|------|---------------|--------------|
| Penetration     | 0,1 mm | 40-59         | 43           |
| Softening Point | °C   | 51-63         | 57,5         |
| Ductility       | cm   | min. 100      | 115,5        |
| Specific Gravity| g/cm³ | min. 1        | 0,97         |
| Flash Point     | °C   | min. 200      | 260          |

2.1.2. Conventional asphalt used in this research is 60/70 penetration asphalt which is generally used in road engineering in Indonesia. The main physical properties of conventional asphalt can be seen in Table 2.

| Type of Testing | Unit | Specification | Test Results |
|-----------------|------|---------------|--------------|
| Penetration     | 0,1 mm | 60-79         | 61-62        |
| Softening Point | °C   | 48-58         | 50,1-54,5    |
| Ductility       | cm   | min. 100      | 100-140      |
| Specific Gravity| g/cm³ | min. 1        | 1,020-1,031  |
| Flash Point     | °C   | min. 200      | 350,4        |
2.2. Asphalt Mixture
This research uses two different types of asphalt mixture, the intended asphalt is damar asphalt mixture and conventional asphalt mixture. For research purposes, the two asphalt mixture tested are physical properties test (volumetric) to get density, VIM, VMA, VFB and marshall test to get stability and flow from sample. Sample testing was carried out on three samples at room temperature conditions on damar asphalt mixture and conventional asphalt mixture.

2.2.1. Damar mixture is a mixture of road pavement consisting of coarse aggregate, fine aggregate, filler and damar asphalt binding material with a certain ratio and mixed in hot conditions. The damar asphalt mixture used in this study was AC-WC, AC-BC and AC-Base with the main physical properties of each mixture can be seen in Table 3.

| No. | Type of Test          | AC-WC<sup>a</sup> | AC-BC<sup>b</sup> | AC-Base<sup>c</sup> | Spec.    |
|-----|-----------------------|-------------------|-------------------|---------------------|----------|
| 1   | Stability (Kg/cm<sup>2</sup>) | 1181,564          | 1181,564          | 1181,564            | >800 kg  |
| 2   | Flow (mm)             | 4,603             | 4,603             | 4,603               | 2-4 mm   |
| 3   | Density (%)           | 2,410             | 2,410             | 2,410               | -        |
| 4   | VIM (%)               | 3,79              | 3,79              | 3,79                | 3-5%     |
| 5   | VMA (%)               | 12,494            | 12,494            | 12,494              | >15%     |
| 6   | VFB (%)               | 81,033            | 81,033            | 81,033              | >65%     |
| 7   | Marshall Quotient (Kg/mm) | 268,847          | 268,847           | 268,847             | -        |

<sup>a</sup> Asphalt concrete wearing coarse  
<sup>b</sup> Asphalt concrete binder coarse  
<sup>c</sup> Asphalt concrete base coarse

2.2.2. Conventional mixture is a mixture of road pavement consisting of coarse aggregate, fine aggregate, filler and asphalt binder with a certain ratio and mixed in hot conditions. The conventional asphalt mixture used in this study is AC-WC, AC-BC and AC-Base with the main physical properties of each mixture can be seen in Table 4.

| No. | Type of Test          | AC-WC<sup>a</sup> | AC-BC<sup>b</sup> | AC-Base<sup>c</sup> | Spec.    |
|-----|-----------------------|-------------------|-------------------|---------------------|----------|
| 1   | Stability (Kg/cm<sup>2</sup>) | 1307,36           | 1307,36           | 2143,92             | >800 kg  |
| 2   | Flow (mm)             | 2,05              | 2,05              | 3,15                | 2-4 mm   |
| 3   | Density (%)           | 2,4               | 2,4               | 2,4                 | -        |
| 4   | VIM (%)               | 4,71              | 4,71              | 4,16                | 3-5%     |
| 5   | VMA (%)               | 17,15             | 17,15             | 19,60               | >15%     |
| 6   | VFB (%)               | 72,75             | 72,75             | 78,85               | >65%     |
| 7   | Marshall Quotient (Kg/mm) | 642,21           | 642,21            | 681,17              | -        |

<sup>a</sup> Asphalt concrete wearing coarse  
<sup>b</sup> Asphalt concrete binder coarse  
<sup>c</sup> Asphalt concrete base coarse

2.3. Nottingham Design Method
2.3.1. Calculating Bitumen Stiffness (Sb). Strain depends on the temperature and the length of time the stress is applied, therefore the simple concept of Modulus Young being the ratio of stress to strain and having a fixed value for certain materials clearly does not apply. Van der Poel introduced Stiffness of Bitumen (Sb) as a substitute for young modulus which is a comparison between the stresses on asphalt, which is a function of the length of loading (frequency) applied, the temperature difference with the T800 and the Penetration Index. T800 is the temperature when penetration reaches 800.

The loading time is the length of load received by the road pavement when the wheels of the vehicle cross the road pavement [12]. Vehicles with the same load will produce different levels of damage due to speed differences. The smaller the speed value will result in a longer loading time. Loading time is closely related to the wavelength of vertical compressive stress, depth of interest, and vehicle speed.
The equation between loading time, layer thickness and vehicle speed are presented in equation (1):

$$\log t = 5 \times 10^{-4} h - 0.2 - 0.94 \log v$$

where: $t =$ loading time (s); $h =$ layer thickness (mm) and $v =$ vehicle speed (kph)

The following equation has been derived by Ullidtz for calculating the value of bitumen stiffness under certain conditions [14]:

$$S_b = 1,157 \times 10^7 \times t^{-0.368} \times 2,718^{Plr} (SPr - T)^5$$

where: $S_b =$ bitumen stiffness (MPa); $t =$ loading time (s); $Plr =$ recovered penetration index (0,1 mm); $SPr =$ recovered softening point (°C) and $T =$ design temperature (°C). The limitation for finding the modulus of stiffness of bitumen by Ullidtz is the value of $t =$ 0,01 to 0,10 s; $Plr =$ -1 to +1 and $(SPr - T) =$ 20 to 60°C

The Recovered Penetration Index can be calculated using the following formula:

$$Plr = \frac{27,00 \times \log Pi - 21,65}{76,35 \times \log Pi - 232,82}$$

where: $Plr =$ recovered penetration index (0,1 mm) and $Pi =$ initial penetration (0,1 mm)

The Recovered Softening Point ($SPr$) can be calculated using the following formula:

$$SPr = 98,4 - 26,35 \times \log 0,65 \times Pi$$

where: $SPr =$ recovered softening point (°C) and $Pi =$ initial penetration (0,1 mm)

2.3.2. Calculating Mix Stiffness ($Sme$). Modulus of stiffness of asphalt mixture ($Sme$) can be calculated from asphalt stiffness ($Sb$) and air pore content ($Cv$). The appropriate equation according to Heukelom and Klomp regarding the modulus of stiffness of the asphalt mixture presented in equation (5)[15]:

$$S_{me} = S_b \left[1 + \left(\frac{2.5}{n} \left(\frac{C_v}{1 - C_v}\right)\right)^n\right]$$

$$n = 0.83 \log - \frac{4 \times 10^4}{S_b}$$

where: $Sme =$ stiffness mixture of asphalt concrete (MPa); $Sb =$ bitumen stiffness (MPa); $Cv =$ aggregate volume concentration (%); $n =$ the stiffness constant of an elastic mixture based on bitumen stiffness.

$$C_v = \frac{V_A}{V_A + V_B}$$

where: $Cv =$ aggregate volume concentration (%); $V_A =$ volume of aggregate (%) and $V_B =$ volume of binder (%).

Based on equation (5) a curve of the relationship between asphalt mix stiffness and vehicle speed can be made, where the stiffness modulus value is the slope of the straight line curve.

3. Results and discussions

3.1. Effects of vehicle speed on the stiffness modulus

This analysis is carried out on variations in vehicle speed which refers to fluctuations in loading time (10, 20, 30, 40, 50 and 60 kph) using the Nottingham design method (equation 1 to 6) at temperatures of 20 and 40°C to the modulus stiffness. The analysis was carried out on two types of mixtures namely damar asphalt and conventional asphalt. Data from the results on damar asphalt and conventional asphalt based on variations in the vehicle speed at 20°C are presented in tables 5 and 6.
The highest ph and less time is found to have more detrimental
condition if the vehicle speed decreases to 20 kph. This is confirmed by the opinion of Pandey et al through his research on fatigue and rutting, from his research it is known that both fatigue and stiffness of the mixture increases with decrease in vehicle speed and they resembles the static loading conditions if the vehicle speed decreases to 20 kph and less time is found to have more detrimental effect on the flexible pavement [16]. The highest stiffness of the mixture drops at a speed of 10 to 20 kph. This is confirmed by the opinion of Pandey et al through his research on fatigue and rutting, from his research it is known that both fatigue and rutting critical strains increase with decrease in vehicle speed and they resembles the static loading conditions if the vehicle speed decreases to 20 kph and less time is found to have more detrimental effect on the flexible pavement [17]. The analysis was then continued at 40°C to determine the effect of vehicle speed on modulus stiffness. Data from the results on damar asphalt and conventional asphalt based on variations in the vehicle speed at 40°C are presented in tables 7 and 8.

Table 5. Damar asphalt stiffness based on variations in vehicle speed at 20°C

| No | v  (kph) | T  (°C) | Sb\(^a\) (MPa) | Sme\(^b\) (MPa) |
|----|--------|--------|----------------|----------------|
|    |        |        | AC – BC\(^c\) | AC – BC\(^d\) |
| 1  | 10     | 20     | 38,551        | 38,879        |
| 2  | 20     | 20     | 48,997        | 49,414        |
| 3  | 30     | 20     | 56,375        | 56,854        |
| 4  | 40     | 20     | 62,273        | 62,803        |
| 5  | 50     | 20     | 67,271        | 67,843        |
| 6  | 60     | 20     | 71,650        | 72,260        |

\(^a\) Bitumen stiffness
\(^b\) Asphalt mix stiffness
\(^c\) Asphalt concrete wearing coarse
\(^d\) Asphalt concrete binder coarse
\(^e\) Asphalt concrete base coarse

Table 6. Conventional asphalt stiffness based on variations in vehicle speed at 20°C

| No | v  (kph) | T  (°C) | Sb\(^a\) (MPa) | Sme\(^b\) (MPa) |
|----|--------|--------|----------------|----------------|
|    |        |        | AC – BC\(^c\) | AC – BC\(^d\) |
| 1  | 10     | 20     | 24,444        | 24,652        |
| 2  | 20     | 20     | 31,067        | 31,331        |
| 3  | 30     | 20     | 35,745        | 36,049        |
| 4  | 40     | 20     | 39,485        | 39,782        |
| 5  | 50     | 20     | 42,653        | 43,016        |
| 6  | 60     | 20     | 45,430        | 45,817        |

\(^a\) Bitumen stiffness
\(^b\) Asphalt mix stiffness
\(^c\) Asphalt concrete wearing coarse
\(^d\) Asphalt concrete binder coarse
\(^e\) Asphalt concrete binder coarse

Based on tables 5 and 6 it is known that increasing speed affects the decrease in the loading time value and when the vehicle speed decreases the loading time becomes high. High loading time causes the strain that occurs to be even greater and result in reduced value of material stiffness [16]. The highest stiffness of the mixture drops at a speed of 10 to 20 kph. This is confirmed by the opinion of Pandey et al through his research on fatigue and rutting, from his research it is known that both fatigue and rutting critical strains increase with decrease in vehicle speed and they resembles the static loading conditions if the vehicle speed decreases to 20 kph and less time is found to have more detrimental effect on the flexible pavement [17]. The analysis was then continued at 40°C to determine the effect of vehicle speed on modulus stiffness. Data from the results on damar asphalt and conventional asphalt based on variations in the vehicle speed at 40°C are presented in tables 7 and 8.

Table 7. Damar asphalt stiffness based on variations in vehicle speed at 40°C

| No | v  (kph) | T  (°C) | Sb\(^a\) (MPa) | Sme\(^b\) (MPa) |
|----|--------|--------|----------------|----------------|
|    |        |        | AC – BC\(^c\) | AC – BC\(^d\) |
| 1  | 10     | 40     | 1,248         | 1,259          |
| 2  | 20     | 40     | 1,587         | 1,600          |
| 3  | 30     | 40     | 1,826         | 1,841          |
| 4  | 40     | 40     | 2,017         | 2,034          |
| 5  | 50     | 40     | 2,178         | 2,197          |
| 6  | 60     | 40     | 2,320         | 2,340          |
Based on Table 7 and 8 the effect of vehicle speed on modulus of stiffness at 40°C is not different from the temperature of 20°C it is known that increasing vehicle speed impacts on increasing the modulus stiffness value. What makes it different is the modulus stiffness value which decreases at all speed variations because the temperature increases from 20 to 40°C.

Asphalt mixture stiffness modulus values generated from the Nottingham design method calculations in tables 5 to 8, then entered into the Cartesian diagram to find the relationship between vehicle speed and stiffness modulus for temperatures 20 and 40°C are distinguished between damar asphalt and conventional asphalt divide into AC-WC, AC-BC and AC-Base. The relationship of the modulus of stiffness and vehicle speed at temperatures of 20 and 40°C is illustrated in Figures 1 to 6.

**Table 8.** Conventional asphalt stiffness based on variations in vehicle speed at 40°C

| No | V (kph) | T (°C) | $S_b^a$ (MPa) | $S_m^e$ (MPa) |
|----|---------|--------|----------------|---------------|
| 1  | 10      | 40     | 0.445          | 394,946       |
| 2  | 20      | 40     | 0.566          | 466,414       |
| 3  | 30      | 40     | 0.651          | 513,784       |
| 4  | 40      | 40     | 0.719          | 550,142       |
| 5  | 50      | 40     | 0.777          | 580,020       |
| 6  | 60      | 40     | 0.827          | 605,573       |

Based on Table 7 and 8 the effect of vehicle speed on modulus of stiffness at 40°C is not different from the temperature of 20°C it is known that increasing vehicle speed impacts on increasing the modulus stiffness value. What makes it different is the modulus stiffness value which decreases at all speed variations because the temperature increases from 20 to 40°C.

Asphalt mixture stiffness modulus values generated from the Nottingham design method calculations in tables 5 to 8, then entered into the Cartesian diagram to find the relationship between vehicle speed and stiffness modulus for temperatures 20 and 40°C are distinguished between damar asphalt and conventional asphalt divide into AC-WC, AC-BC and AC-Base. The relationship of the modulus of stiffness and vehicle speed at temperatures of 20 and 40°C is illustrated in Figures 1 to 6.

**Figure 1.** Comparison of stiffness of damar asphalt mixture with conventional asphalt based on variations in vehicle speed at a temperature of 20°C in the AC-WC layer.
Figure 1 shows that vehicle speed has a linear relationship with modulus stiffness in the AC-WC layer at 20°C. The correlation value between the speed and stiffness of damar asphalt modulus (0.9573) and conventional asphalt (0.9569) is high, so it can be said that they have a strong correlation.

![Graph of Figure 1](image1.png)

\[ y = 45,764x + 5190,6 \]
\[ R^2 = 0,9573 \]

\[ y = 43,745x + 5097,7 \]
\[ R^2 = 0,9569 \]

Figure 2. Comparison of stiffness of damar asphalt mixture with conventional asphalt based on variations in vehicle speed at a temperature of 20°C on the AC-BC layer.

Figure 2 shows that vehicle speed has a linear relationship with modulus stiffness in the AC-BC layer at 20°C. The correlation value between the speed and stiffness of damar asphalt modulus (0.9573) and conventional asphalt (0.9569) is high, so it can be said that they have a strong correlation.

![Graph of Figure 2](image2.png)

\[ y = 51,405x + 6362,6 \]
\[ R^2 = 0,9557 \]

\[ y = 45,565x + 5164,1 \]
\[ R^2 = 0,9573 \]

Figure 3. Comparison of stiffness of damar asphalt mixture with conventional asphalt based on variations in vehicle speed at a temperature of 20°C on the AC-Base layer.

Figure 3 shows that vehicle speed has a linear relationship with modulus stiffness in the AC-Base layer at 20°C. The correlation value between the speed and stiffness of damar asphalt modulus (0.9573) and conventional asphalt (0.9557) is high, so it can be said that they have a strong correlation.

![Graph of Figure 3](image3.png)
Figure 4. Comparison of stiffness of damar asphalt mixture with conventional asphalt based on variations in vehicle speed at a temperature of 40°C in the AC-WC layer.

Figure 4 shows that vehicle speed has a linear relationship with the modulus stiffness in the AC-WC layer at 40°C. The correlation value between the speed and stiffness of damar asphalt modulus (0.9624) and conventional asphalt (0.9624) is high, so it can be said that they have a strong correlation.

Figure 5. Comparison of stiffness of damar asphalt mixture with conventional asphalt based on variations in vehicle speed at a temperature of 40°C on the AC-BC layer.

Figure 5 shows that vehicle speed has a linear relationship with the modulus stiffness in the AC-BC layer at 40°C. The correlation value between the speed and stiffness of damar asphalt modulus (0.9624) and conventional asphalt (0.9624) is high, so it can be said that they have a strong correlation.
Figure 6. Comparison of stiffness of damar asphalt mixture with conventional asphalt based on variations in vehicle speed at a temperature of 40°C on the AC-Base layer.

Figure 6 shows that vehicle speed has a linear relationship with the modulus of stiffness in the AC-Base layer at 40°C. The correlation value between the speed and stiffness of damar asphalt modulus (0.9624) and conventional asphalt (0.9615) is high, so it can be said that they have a strong correlation.

Based on figures 1 to 6, if the modulus stiffness value between damar asphalt and conventional asphalt in all layers at 20°C (Figure 1 to 3) is compared with conventional asphalt and asphalt modulus stiffness values in all layers at 40°C (Figure 4 to 6), there will be a shift in the line equation that widens the range of modulus stiffness values between damar asphalt and conventional asphalt due to the influence of temperature. The decrease in modulus stiffness value from damar asphalt is smaller compared to conventional asphalt. So that the ability of damar asphalt to withstand the weight of moving vehicles according to variations in speed is better than conventional asphalt.

4. Conclusion

Based on the analysis of the effect of vehicle speed and pavement temperature on the elastic mixture stiffness using the Nottingham Design Method it is known that the vehicle speed increased from 10 to 60 kph resulting in decreased loading time and an increase in elastic mixture stiffness in all types of asphalt mixtures. The stiffness of damar asphalt mixture due to variations in speed from 10 to 60 kph in AC-WC and AC-BC layers at a temperature of 20°C is higher than in conventional asphalt but in the AC-Base layer is lower than in conventional asphalt. Entering at 40°C all types of damar asphalt mix have a greater stiffness than conventional asphalt at all types of vehicle speed variations. Decreasing the stiffness of all types of damar asphalt mixture is slower than conventional asphalt mixtures from 20 to 40°C so that the damar asphalt mixture is more resistant to changes in temperature and vehicle speed than conventional asphalt.

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