CHARACTERIZATION OF ASPHALT LAYER MODULUS FOR INDONESIAN TEMPERATURE CONDITIONS

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Abstract : The response of asphalt pavements to environmental condition is well recognized. Temperature variation is one of the important factors to be considered in modern pavement structural design in view of the in-service modulus of the asphalt layer influenced primarily by temperature. This paper yielded specific information on in-service temperature gradients and time variations at various depths throughout the asphalt pavement structure in Indonesia climatic conditions. Fieldwork carried out included measurement of asphalt temperature gradients up to 24.5 cm depth at selected site in Jakarta area over a three representative months period. The implication of the measured temperature gradient for pavement design was analyzed by assessing the effective modulus of the asphalt layer.

1. INTRODUCTION

As an exposed structure, climatological considerations are of major importance in the design, construction and maintenance of both rigid and flexible pavements. Variation in ambient temperature has no significant influence on the moduli of soils and unbound material, except when frost is present, but temperature governs the modulus of the asphalt layer. A wide range in modulus of an asphalt material may occur as the temperature varies from cool to warm conditions. Load spreading properties are related to the elastic modulus of the asphalt layer and this is reduced significantly in areas such as Indonesia where high temperatures occur. Futhermore, the modulus of asphalt mix will govern the pavement performance given its influence on factors such as fatigue resistance of the asphalt layer, the stress distribution characteristics of the pavement, and subgrade deformation. The fatigue life of a pavement is increased at high temperature. However, higher temperature in the bituminous layer also results in the transference of increased stress to the underlying pavement layers which may ultimately contribute to compaction or distortion in these layers. A reduction in the strength or stability of the bituminous layers occurs at elevated temperature, owing to a decrease in the dynamic elastic moduli of the structure thereby increasing the tendency for permanent deformation and rutting in the pavement surfacing.

In deciding how best to take temperature variations in the asphalt layer into account, due regard must be taken of the nature of the temperatures data that are generally available to engineers. The most accessible information is the 'Mean Monthly Air Temperature' (MMAT) which can be obtained from the meteorological offices, airport authorities or related institutions. From the pavement design point of view, however, it is necessary to have details of asphalt temperature at various depths in the asphalt layer, and the changes that occur during the day. The objectives of the research program were : (i) To determine, at a representative MMAT period, the temperature gradients in the asphalt layer at different times during the day. (ii) To evaluate the implications of the measured gradients for pavement design by assessing the effective modulus of the asphalt layer in Indonesian climatic conditions.

2. METHODOLOGY

2.1 Road Structure Site Conditions

After observing a number of pavement and environmental conditions, it was concluded that the Jakarta - Cikampek Toll Road was the best location for conducting the research. This conclusion was reached in consideration of the following aspects: (i) the road is in the Jakarta area where the climate is representative of the majority of regions in Indonesia, (ii) locating the site of the investigation on a toll road reduces the likelihood of human interference and (iii) the pavement was constructed to a high standard and the road has asphalt layer thickness greater than 250 mm although rutting EDWARD & VALKERING (1974) reported that the top 100 mm of an asphalt concrete structure is of most importance so far as the effect of temperature on structural behavior is concerned

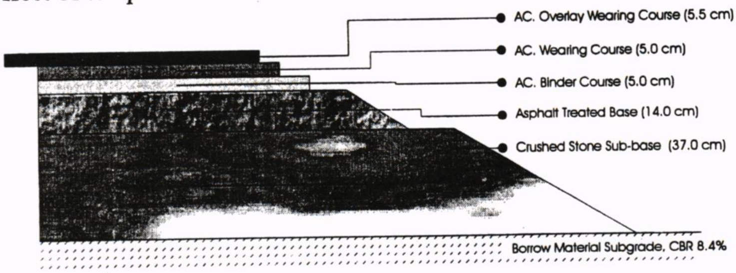

Figure 1. Pavement Structure

On the road authority's recommendation, and taking into account construction quality control data and safety considerations, the site chosen for the investigation was a tapered length at Sta. 33+600 on the South Side of the "Widening of Cawang - Cibitung Toll Road" Project. As shown on Figure 1, the asphalt layer consists of four components. The aggregate gradation and bitumen content determined for each asphalt layer from extraction tests conducted on the cores were found to comply with the job mix formulae for these materials. It is reasonable then to adopt the bituminous mixture parameters of the job mix formula.

2.2 Temperature Measurement Technique and Equipment

At the selected research location nine 8.0 mm diameter holes were made to measure the asphalt temperature. The lay-out and the depth of the observation holes is shown in Figure 2. To prevent water or dirt intrusion, the holes were protected as shown on Figure 3. It was not necessary to protect holes no.1 (≅ 0.25 cm depth) and no.2 (≅ 1.5 cm depth). Pavement temperature measurements were made manually using a glass thermometer type ASTM G-641 (20-102 °C). This equipment was selected to avoid making the larger holes (≅ 13.0 mm diameter) that would be needed if a digital thermometer were used.

On site air temperature was continuously monitored at the same time and place as the pavement temperature measurements. The air temperature measurements were taken at a height of about 1 to 2 meters above the test pavement, following the measurement techniques recommended by the meteorlogical office.

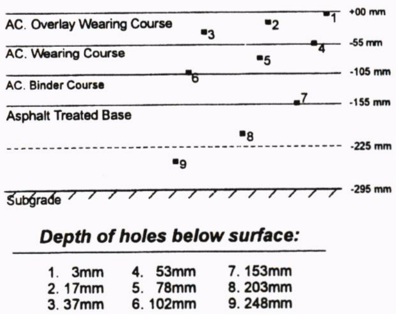

Figure 2. Lay Out and Depth of Observation Holes

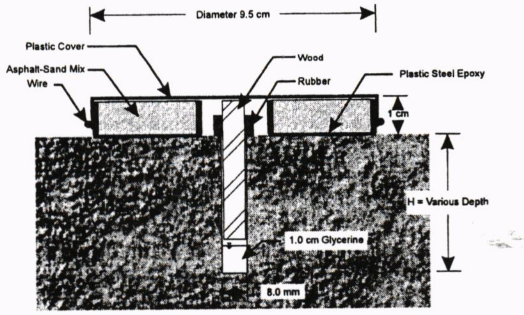

Figure 3. Protection of Holes against Water or Dirt Intrutions

2.3. Method of Analysis

The results of the asphalt temperature measurements made over each month gave the average temperature gradient for a particular time of the day. These temperature gradients were related to the corresponding MMAT. They were analyzed to produce an effective asphalt modulus. The procedure used was as follows:

1. Determination of asphalt modulus gradient corresponding to the pavement temperature gradient using the "S_{mix} - Temperature" relationship for the mix. For this purpose, the predictive equation developed by The Asphalt Institute (1982) was used.
2. Structural analysis of the pavement modeled in accordance with the modulus gradient determined for each period during the day using the BISAR computer program. The analysis was done by dividing the asphalt layer into a number of sub-layers. From the modulus gradient, a modulus value was assigned to each sub-layer and the compressive strain in the subgrade was calculated.
3. The relative damage (inverse of life) associated with the compressive strain was then calculated. These procedures were repeated for other temperature gradients appropriate to other times of the day.
4. Using cumulative damage theory and Miner's hypothesis (MINER, 1945), total relative subgrade damage was computed.

$$\sum_{i=1}^{n} d_i = \sum_{i=1}^{n} 1/N_i \qquad \text{(Eq.1)}$$

   where :
   d_i is relative damage due to strain amplitude ε_i
   N_i is permissible number of repetitions of ε_i
   n is number of temperature gradients

5. An effective subgrade strain of such magnitude that n repetitions will cause the same relative damage as that indicate by Eq.1 was calculated as follows (Van DIJK and VISSER, 1977):

$$\frac{n}{N_{eff.}} = \sum_{i=1}^{n} 1/N_i$$

$$\therefore (\varepsilon_{eff})^4 = \frac{1}{n}\sum_{i=1}^{n} (\varepsilon_i)^4 \qquad \text{(Eq. 2)}$$

6. Working back from the effective strains determined from Eq.2 the effective asphalt modulus was calculated i.e. that modulus which if assigned to the entire asphalt layer would result in the same subgrade damage as if asphalt modulus gradient were taken into account.
7. The procedure was carried out for both the compressive strain in the subgrade and the tensile strain in the asphalt layer.

3. THE RESULTS OF DATA COLLECTION PROGRAM

3.1 Air Temperature Data

To characterize the ambient air temperature of the Jakarta area, secondary data of air temperature were collected from '*Badan Meteorologi dan Geofisika, Departemen Perhubungan Republik Indonesia*' based on temperature measurements at station No. 96745 located at the BMG main office in downtown Jakarta. The maximum and minimum air temperature recorded for each month were shown in Figure 4 and Figure 5 shows the monthly variation in mean monthly air temperature during each year in the period 1986-1996.

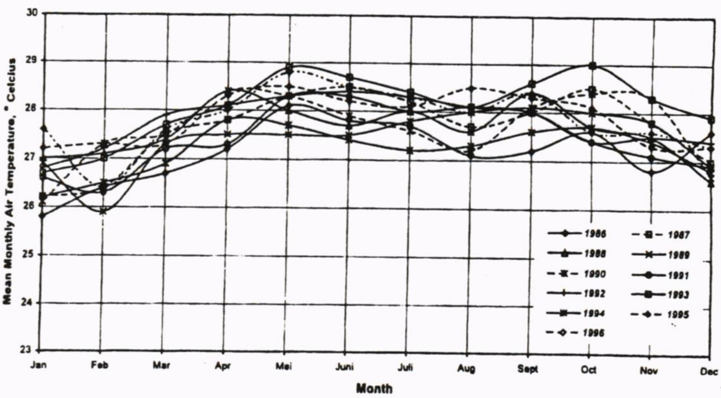

Figure 4. Mean Monthly Air Temperature Variations, 1986 -1996
Source : Badan Meteorologi dan Geofisika, Departemen Perhubungan, Republik Indonesia (1996)

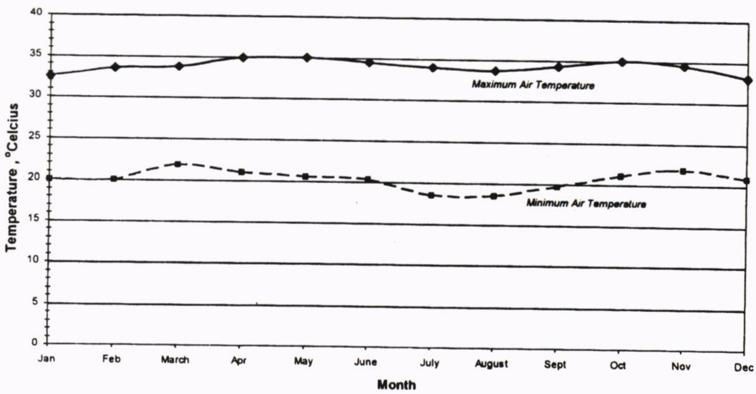

Figure 5. Maximum and Minimum Air Temperature in the Jakarta Area
Source : Badan Meteorologi dan Geofisika, Departemen Perhubungan, Republik Indonesia (1996)

Table 1 : Average Pavement Temperature (°C), May 1998

Depth	06.00am	09.00am	12.00am	15.00am	18.00am	21.00am
-0.3 cm	26.2	35.9	49.8	49.4	34.9	30.0
-1.5 cm	26.9	39.3	56.1	54.9	39.0	32.8
-3.5 cm	28.0	36.4	54.6	53.0	41.5	36.4
-5.0 cm	29.0	33.0	47.7	49.9	45.1	38.5
-7.5 cm	30.2	31.0	42.5	47.3	45.8	41.3
-10.0 cm	30.7	30.3	39.0	44.1	45.1	42.4
-15.0 cm	31.5	30.5	36.3	39.6	40.9	41.5
-20.0 cm	32.0	31.1	34.2	36.3	37.1	39.5
-24.5 cm	32.2	31.9	33.0	34.3	36.3	37.4

Table 2 : Average Pavement Temperature (°C), June 1998

Depth	06.00am	09.00am	12.00am	15.00am	18.00am	21.00am
-0.3 cm	26.3	36.2	48.5	46.2	34.5	30.5
-1.5 cm	26.7	39.2	53.7	52.2	40.6	33.0
-3.5 cm	27.4	36.4	51.4	50.4	44.0	36.2
-5.0 cm	28.5	34.3	46.8	47.9	46.0	38.1
-7.5 cm	29.4	31.4	42.1	44.4	46.1	41.1
-10.0 cm	30.1	30.4	38.9	41.7	44.3	40.8
-15.0 cm	30.7	29.8	35.1	37.3	39.8	39.5
-20.0 cm	31.1	30.5	33.0	34.4	36.3	37.9
-24.5 cm	31.3	30.8	32.2	33.2	35.0	37.6

Table 3 : Average Pavement Temperature (°C), July 1998

Depth	06.00am	09.00am	12.00am	15.00am	18.00am	21.00am
-0.3 cm	25.9	36.5	49.3	44.4	33.7	29.7
-1.5 cm	26.4	38.7	54.0	51.4	37.6	32.4
-3.5 cm	27.5	36.1	50.2	49.7	41.0	35.3
-5.0 cm	28.4	33.9	45.8	47.1	43.2	37.4
-7.5 cm	29.2	31.4	40.2	43.4	43.7	40.0
-10.0 cm	29.7	30.6	37.6	40.9	42.2	41.0
-15.0 cm	30.5	30.4	34.7	36.9	39.2	40.0
-20.0 cm	30.7	30.4	33.0	34.4	35.9	38.2
-24.5 cm	30.9	30.4	32.2	33.6	34.9	36.7

Table 4 : Asphalt Modulus Gradients, May 1998

Depth (cm)	Modulus (Mpa)					
	06.00 am	09.00 am	12.00	15.00 pm	18.00 pm	21.00 pm
-1.50	4,039.25	1,315.20	207.78	238.40	1,344.80	2,419.62
-3.50	3,689.66	1,745.32	247.04	298.55	1,050.34	1,739.72
-5.00	3,390.10	2,394.26	545.41	425.24	718.75	1,418.37
-7.50	3,047.06	2,843.98	946.21	568.14	667.76	1,073.72
-10.00	2,919.98	3,037.12	1,349.12	798.89	723.56	958.12
-15.00	3,189.30	3,471.04	2,119.95	1,578.27	1,390.82	1,311.34
-20.00	3,092.33	3,292.87	2,589.82	2,189.03	2,057.32	1,672.89
-24.50	3,030.62	3,107.17	2,845.87	2,568.85	2,185.02	2,010.47

Table 5 : Asphalt Modulus Gradients, June 1998

Depth (cm)	Modulus (Mpa)					
	06.00 am	09.00 am	12.00	15.00 pm	18.00 pm	21.00 pm
-1.50	4,110.55	1,320.10	276.31	326.63	1,152.12	2,378.01
-3.50	3,879.40	1,730.83	361.20	401.89	809.69	1,774.62
-5.00	3,548.56	2,125.52	603.41	532.08	654.42	1,472.62
-7.50	3,272.42	2,763.49	992.87	779.33	649.15	1,099.50
-10.00	3,073.68	3,007.48	1,364.85	1,030.42	783.46	1,126.25
-15.00	3,415.22	3,657.57	2,347.84	1,934.21	1,549.77	1,584.09
-20.00	3,308.47	3,458.06	2,843.10	2,556.64	2,187.25	1,918.63
-24.50	3,252.57	3,374.66	3,045.22	2,807.30	2,444.47	1,973.30

Table 6 : Asphalt Modulus Gradients, July 1998

Depth (cm)	Modulus (Mpa)					
	06.00 am	09.00 am	12.00	15.00 pm	18.00 pm	21.00 pm
-1.50	4,208.60	1,391.99	265.57	361.20	1,547.85	2,521.90
-3.50	3,847.25	1,783.06	414.00	436.75	1,102.29	1,934.26
-5.00	3,567.37	2,192.72	670.45	580.85	880.41	1,578.09
-7.50	3,321.93	2,757.37	1,194.89	863.36	834.50	1,223.65
-10.00	3,192.39	2,945.69	1,544.10	1,116.33	982.72	1,106.49
-15.00	3,450.02	3,495.69	2,427.87	2,000.01	1,633.99	1,510.82
-20.00	3,409.75	3,467.79	2,845.87	2,546.51	2,266.54	1,869.15
-24.50	3,346.16	3,480.79	3,024.79	2,723.40	2,449.37	2,127.66

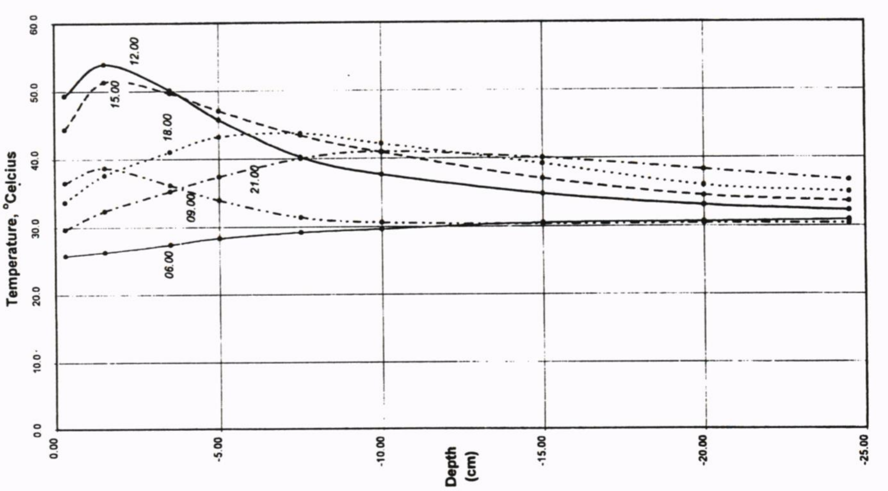

Figure 6 : Average Pavement Temperature Gradient, May 1998

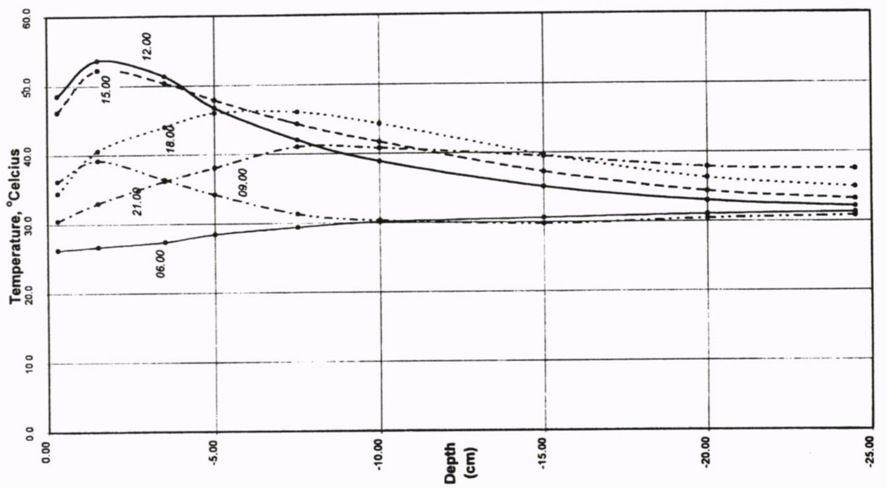

Figure 7 : Average Pavement Temperature Gradient, June 1998

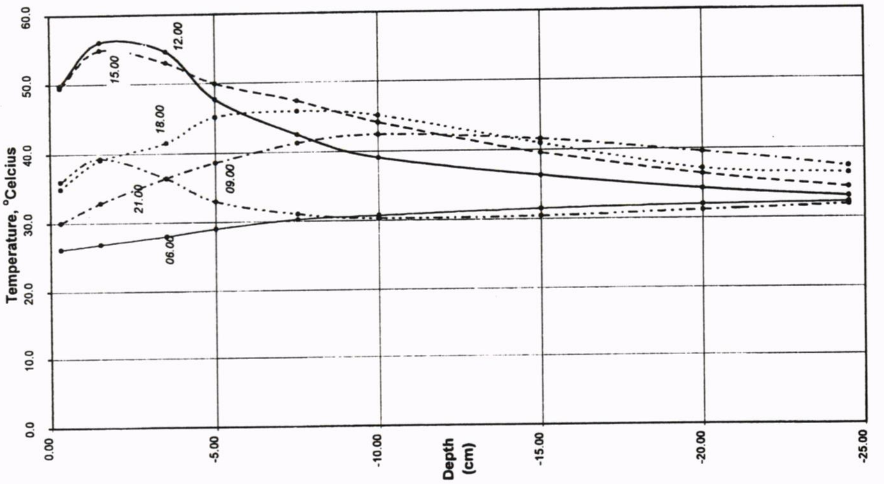

Figure 8 : Average Pavement Temperature Gradient, July 1998

3.2 Pavement Temperature Data

Originally it was intended to measure the pavement temperature gradients 2 days per week during the course of each month. However this was not always possible. The road authority advised against making measurement under or after rainfall, primarily from considerations of safety. However, complete data were collected on 8 days per month during May, June and July.

The average pavement temperature gradients determined at different times during the day for May, June and July are presented in Tables 1, 2 and 3, respectively and shown on Figures 6, 7 and 8. Figures 9, 10 and 11 show the air temperature and pavement temperature conditions over a 24-hour period for May, June and July, respectively.

4. DATA ANALYSIS

Analysis of Air Temperature Data

Since the air temperature data were collected from a meteorological station located about 32 km from the research location, a comparison was made between data taken from Hourly Synoptic Observations Recording Sheets of the meteorological stations and air temperature measured at site. This was done by comparing mean monthly air temperatures calculated from the mean daily temperatures indicated for the two locations on the days when site measurement were made. Average values of mean monthly air temperature for May, June and July are summarized in Table 7.

The mean monthly air temperature at the research location is on average 0.2 °C lower than that at meteorological office. This may be due to the fact that the research location is a very open area whereas the meteorological station is located in downtown Jakarta between many high rise building. However, the result of the comparison indicates that the differences between measurements made at the research location and those made at the meteorological office are not significant. Hence, it may be concluded that air temperature at the reseach location can be used to represent Jakarta conditions and that data from the meteorological office can be applied with confidance, as neccesary, to the research location.

Table 7 : Summary of Air Temperature Comparison

Month	Average Monthly Air Temperature (°C)		
	At Site	Met. Office	Difference
May	28.7	28.4	+0.3
June	27.8	27.4	+0.4
July	27.6	27.7	-0.1

Selection of Temperature Measurement Periods

Form the data collected, Figure 4 shown that air temperature variation in the Jakarta area ranges between 18 °C and 35 °C and Figure 5 shows the annual variation in MMAT during the period 1986 to 1996. Represented the long term of MMAT in above variations, it is important then to decided the periods over which the asphalt temperature measurement were undertaken. The expected periods that usually have a reasonable values of MMAT which are considered equivalent to long term average of MMAT in Indonesia climatic conditions.

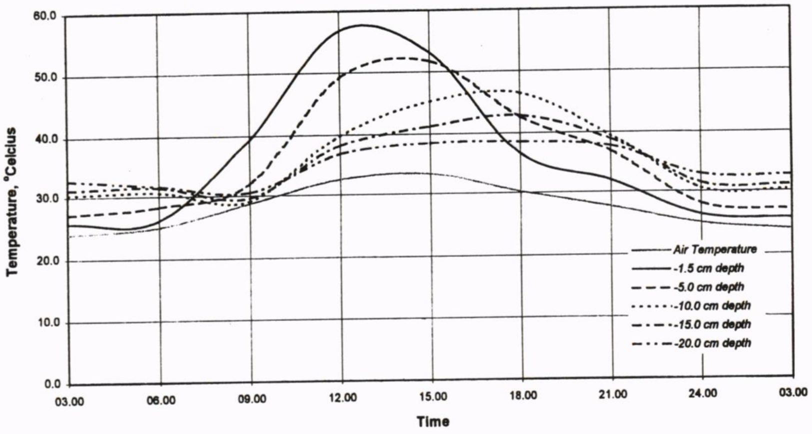

Figure 9 : Hourly Variations of Air and Pavement Temperature, May 17/18, 1998

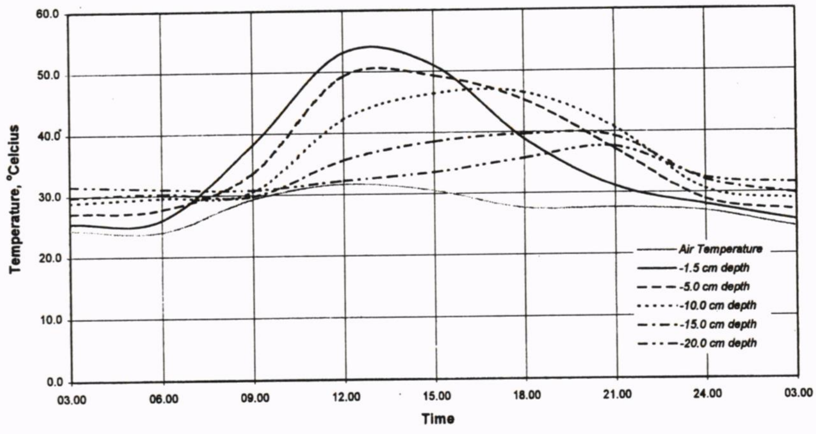

Figure 10 : Hourly Variations of Air and Pavement Temperature, June 13/14, 1998

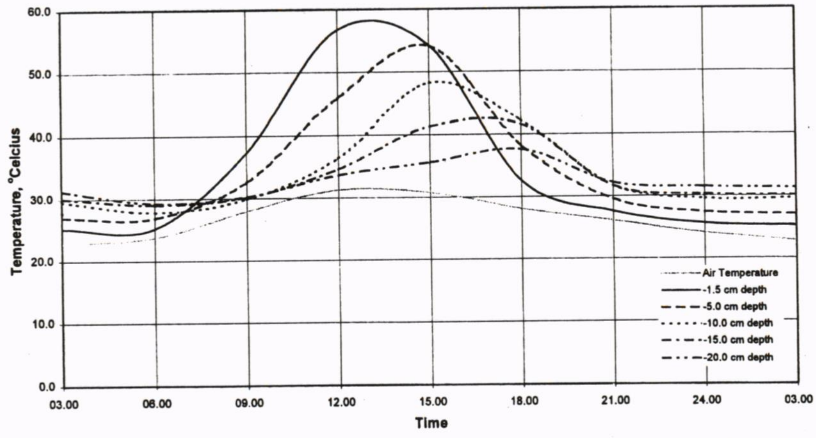

Figure 11 : Hourly Variations of Air and Pavement Temperature, July 19/20, 1998

For this purpose an analysis of MMAT values of the Jakarta area published by the meteorological office was made. Due to the fact that there are only two season in Indonesia climatic condition, the hot periods should be more considered in evaluate the effect of temperature of the asphalt pavement. With reference to Figure 5 the 'hot' months are those between April and October, with MMAT ranging from 27.1 °C to 29 °C. Outside this period the MMAT is usually lower, reaching a minimum value between November and February. After analyzing the MMAT values for cold months during the period 1961-1996, it was found that average MMAT ranges from 26.4 °C (January and February) to 27.8 °C (May). During the 'hot' months, April to October, average MMAT ranges from 27.4 °C (July) to 27.8 °C (May).

These data indicate that the MMAT varied only slighty during the year. The average for the period May to July (27.6 °C) is marginally higher than the average for the year (27.3 °C). It was concluded that the May to July period was most suitable for making measurements of pavement temperature to represent the long term of MMAT in Indonesia climatic conditions.

Analysis of Air Temperature and Pavement Temperature Relationships

Theoretically, the daily variation of pavement temperature gradient is dependent primarily on the amount of solar radiation reaching the pavement surface. As shown on Figures 9, 10 and 11 the pavement "surface" temperature (measured at 1.5 cm depth) starts to increases at 06.00 in the morning reaching the maximum value at the mid day (about 12.00 to 13.00) than decreases following the pattern of solar radiation intensity.

From the above figures it can be seen that there is a time lag between the occurance of maximum temperature at the surface and at a given depth in the asphalt layer; The time lag increases with increased depth and is attributable to the relative low thermal conductivity of asphalt. Hence, it may be concluded that the pavement surface is subjected to a greater range of temperature than any other part of the pavement structure.

The results of the pavement temperature measurements shows that in almost all cases the 'surface' temperature measured at 3 mm, appears to be lower than that measured at 1.5 cm depth. To some extent, this may be due to the fact that when measuring at 3 mm depth the bulb of the thermometer can be influenced by the wind or affected by the air temperature. It should also be noted, that at this depth the pavement temperature may also be influenced by wind which has a cooling effect by increasing the rate of heat loss from the pavement surface by forced convection or, to a lesser extent, by rain which could further cool the pavement surface. For these reasons the temperature at 3 mm depth was not included in the modulus gradient determination. The surface temperature was assumed to have a temperature equal to that measured at 1.5 cm depth.

While the progressions of "surface" temperatures were found closely following the pattern of solar radiation intensity and hence air temperature, at lower depths different ascension of pavement temperature were obtained. This is futher illustrated on Figures 9, 10 and 11. The pavement temperature at a depths of more than 10 cm was found start to increasing rapidly between 09.00 to 10.00 and reach the maximum value between 12.00 to 18.00 it then start to decrease until reaching the minimum value between 21.00 PM and 24.00. After that, the pavement temperature remain relatively constant up untill 06.00.

In addition to the fact that the time lag of the occurance of maximum temperature at different depths which increases with increase in depth, the maximum temperature occurred were decreased with increase in depth. This is also can be attributable to the relative low thermal conductivity of asphalt.

4.1 Asphalt Modulus Gradient Determination

Based on the results of pavement temperature measurements and the pavement structural data provided, the asphalt modulus gradient corresponding to the pavement temperature gradient was determined using an established relationship. For this purpose, the predictive equation developed by the Asphalt Institute (1982), Eq.II.7 was used. Since temperature and material varied with depth, modulus was calculated at each point where the temperature was measured. The results of asphalt modulus calculations are summarized in Tables 4,5 and 6 for May, June and July respectively and also shown on Figures 13, 14 and 15.

As shown on these figures, a wide range of pavement modulus occurs during a one day period. Similar to the temperature gradient, the pavement 'surface' have the widest range of modulus, ranging from 207.78 Mpa at 12.00 to 4,200.60 Mpa at 06.00 while at a depth of 24.5 cm the pavement modulus ranges between 1,973.30 and 3,480.79 Mpa. From these modulus gradients, an average modulus value was assigned to each layer for each period during the day. The average was determined from the modulus values determined at various depths in the layer.

4.3 Development of Effective Asphalt Modulus

For purpose of structural analysis the pavement structure shown on Figure 1 was modeled as a layered, linear-elastic system. However, since the BISAR computer program can deal only with up to 4 layers, a more simplified pavement structural model was used, as shown on Figure 12.

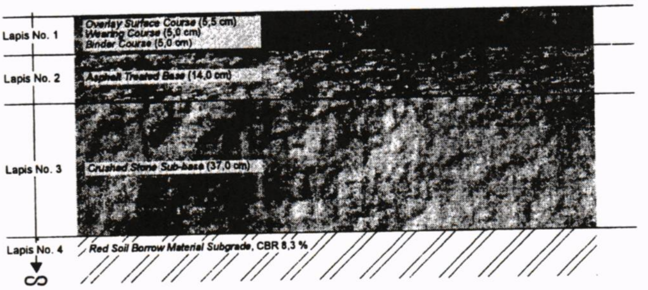

Figure 12 : Pavement Modelling

The wearing course, binder course and overlay were treated as one layer. The same material and job mix formula were used for the wearing course and overlay. Although the composition and the type of bitumen used in the binder course was different from the wearing course and overlay layer, it was assumed that the consequences of combining this course together with the layers above it would not be significant.

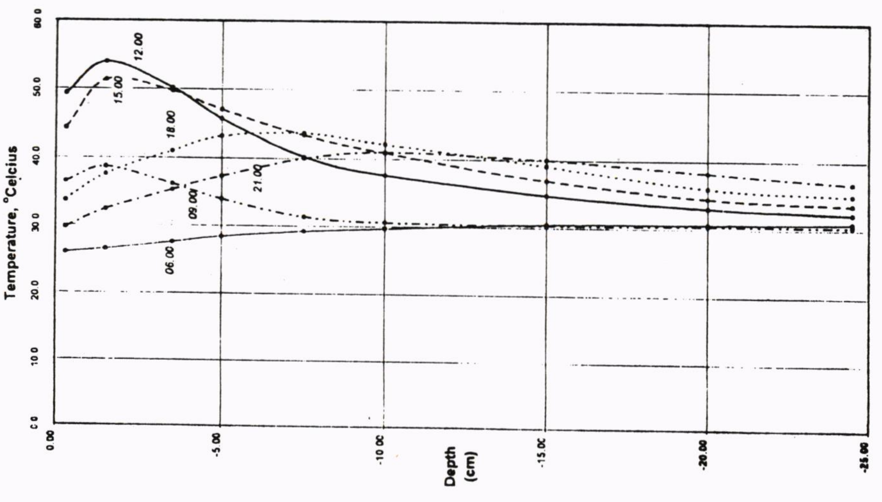

Figure 6 : Average Pavement Temperature Gradient, May 1998

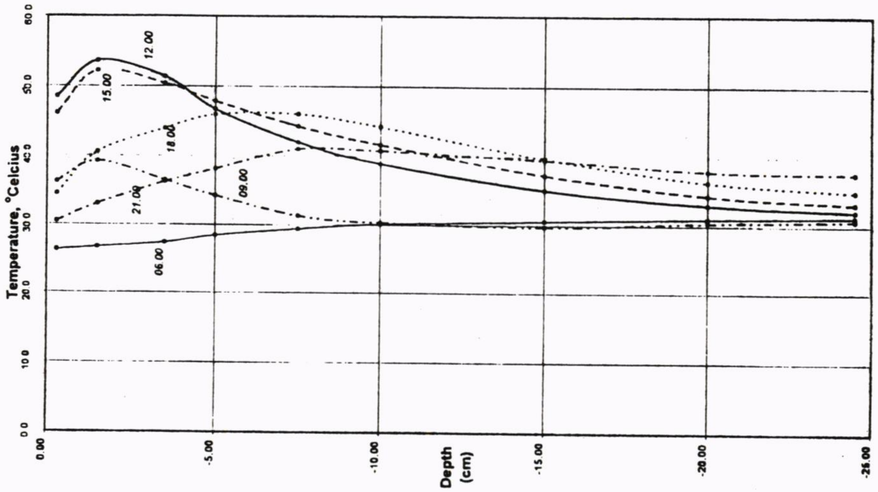

Figure 7 : Average Pavement Temperature Gradient, June 1998

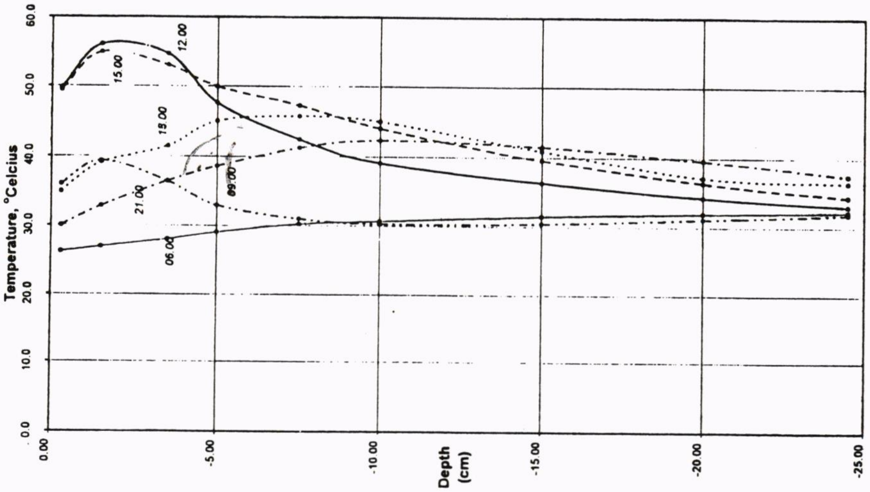

Figure 8 : Average Pavement Temperature Gradient, July 1998

In characterizing the crushed stone subbase layer, the AASHTO (1986) procedure for assigning a modulus value to an unbound granular layer was used. The material used in the subbase was of roadbase quality and the following relationship to estimate the layer coefficient, a_2 for a granular roadbase material was used;

$$a_2 = 0.249(\log_{10} E_{BS}) - 0.977 \qquad \text{(Eq.3)}$$

Assuming the layer structural coefficient a_2 to be 0.14, the elastic (resilient) modulus of the unbound granular material is found to be ≅ 211.2 MPa. The assumption that a_2 equals 0.14 is reasonable given the soaked CBR values determined for the material. The result above is slightly lower than if the SHELL procedure were used.

In the SHELL procedure subgrade modulus is estimate by using the empirical relationship between CBR value and the dynamic subgrade modulus after HEUKELOMP & KLOMP (1962);

$$E_{sg} = 10 \times CBR\,(\%) \qquad \text{(Eq.4)}$$

$$E_{sg} = subgrade\ modulus,\ MPa$$

From the subgrade density data of the road section which can be converted into CBR value, it was found that the subgrade has an average CBR of 8.4 %, then subgrade modulus value can be determined to be 84 Mpa. The unbound granular layer modulus may also be estimated using the Shell design procedure by the modular ratio given as follows;

$$\frac{E_{U/B.gran}}{E_{sg}} = k \qquad \text{(Eq.5)}$$

CLAESSEN et al., (1982) define 'k' as follows:

$$k = 0.206 \times (h_2)^{0.45}; 2 < k < 4 \qquad \text{(Eq.6)}$$

where h_2 is the thickness of unbound granular base and sub-base thickness, mm. By taking the modulus of the subgrade mentioned earlier, then:

$$k = 0.206 \times (370)^{0.45} = 2.948$$

$$\text{and , } E_{U/B.gran} = 2.948 \times 84 = 247.6 \text{ MPa} \qquad \text{(Eq.7)}$$

In this study, as recommended by Shell (CLAESSEN et.al.,1982), a value of 0.35 was selected for bituminous material. The same value of 0.35 has been adopted for the unbound base material and crushed stone subbase. A constant poisson's ratio of 0.45 was chosen for subgrade since a cohesive materials were used in this layer.

Based on Subgrade Compressive Strain Criterion

Structural analysis of the pavement modeled in accordance with the modulus gradients determined for each period during the day was done using the BISAR computer program. Applying a dual-wheel, 80 kN standard axle at the pavement surface, the compressive strain at the top of the subgrade and the horizontal strain at the bottom of the asphalt layer were calculated. The maximum vertical subgrade strain was generally found to occur at the mid-point between the dual wheels and values calculated at this location were used in determining the effective subgrade strain.

In these determinations, the subgrade strain criterion developed by SANTUCCI, (1977), which applies also in the DAMA design procedure, was used. The criterion is expressed as follows:

$$N_d = 1.365 \times 10^{-9} (\varepsilon_c)^{-4.477} \qquad \text{(Eq.8)}$$

Eq. 8 was used also to develop the Asphalt Institute design charts. As long as good compaction of the pavement component layers is obtained and the asphalt mix is well designed, the use of Eq. 8 should not result in rutting greater than 0.5 inch (12.7 mm) for the design traffic (HUANG, YANG. H, 1993). Applying Eq. 2, effective subgrade strains were calculated. Working back-calculations from the effective subgrade strains determined, again using the BISAR computer program, the effective asphalt modulus based on the vertical subgrade strain criterion was determined.

Based on Asphalt Tensile Strain Criterion

The same procedure was followed in determining the effective asphalt modulus based on the horizontal tensile strain criterion. The maximum horizontal tensile strain in the asphalt layer was found at the mid-point of the dual tyre system and values at this location were used in the calculation.

The major difference in models used by the various design methods to relate the asphalt tensile strain to the allowable number of load repetitions is the transfer functions. In this study, the fatigue model developed by FINN et al. (1977) and modified by the Asphalt Institute in developing the DAMA computer program was used.

$$N_f = 18.4 \cdot (C)\left[4.325 \cdot 10^{-3} (\varepsilon_t)^{-3.291} (E_i)^{-.854}\right] \qquad \text{(Eq.9)}$$

Since the maximum tensile strain occurs at the bottom of the asphalt base, the factor C was calculated on the basis of the composition taken from the job mix formula of this layer i.e. Vb = 8.7 % and Vv = 4.3 %, therefore;

$$N_f = 63.1365 \cdot 10^{-3}\left[(\varepsilon_t)^{-3.291} (E_i)^{-.854}\right] \qquad \text{(Eq.10)}$$

Subtitute the modulus values of asphalt-base layer of each modulus gradients, and again applying Eq.2. the effective modulus (E_{eff}) and effective strains (ε_{eff}) at the bottom of asphalt layer were determined simultaneously, using the BISAR computer program practicing trial and errors continously. After a number of trials it was found that (E_{eff})-*assumption* and (E_{eff}) relationship were converging, and the procedure were carried out until (E_{eff})-*assumption* = (E_{eff}) were found.

4.4. The Effective Asphalt Modulus Related to MMAT data

The results of above structural analyses are summarized in Table 8. It was found that the effective modulus is not significantly different for the two criteria, the largest difference being observed for the month of May. An average value of the modulus obtained after considering the subgrade deformation criterion and asphalt fatigue criteria was then considered as the effective asphalt modulus.

Figure 16 shows the relationship between calculated effective asphalt modulus and the MMAT of the month when the pavement temperature measurements were undertaken. From Figure 16, a simple conclusion is obtained: the effective asphalt modulus decreases as the MMAT increases. An estimate of effective asphalt modulus is obtained by a 'best fit' line connecting the MMAT values obtained.

Table 8 : Effective Asphalt Modulus, MPa

Criteria	May	June	July
	MMAT=29.1°C	MMAT=28.0°C	MMAT=27.7°C
Permanent Deformation	1563	1718	1817
Asphalt Fatique	1513	1710	1791
Average Effective Modulus	1538	1714	1807

It is realized that the values of effective asphalt modulus listed in Table 8 are based on a limited range of the MMAT values recorded for Indonesia climatic conditions, i.e. between 27.7 °C and 29.1 °C. Statistical data for the Jakarta area, shows that from 431 MMAT values recorded (1961 – 1996), only 117 are in this range. It should be noted however, that this range includes of the hottest months recorded.

The MMAT in May 1998, 29.1 °C was extremely high. The previous maximum MMAT ever recorded in the Jakarta area for any month was 29.0 °C. For that reason, the effective asphalt modulus determined this month should be used carefully to avoid overdesign of the pavement structure, except as an indication of the extreme pavement conditions that can occur.

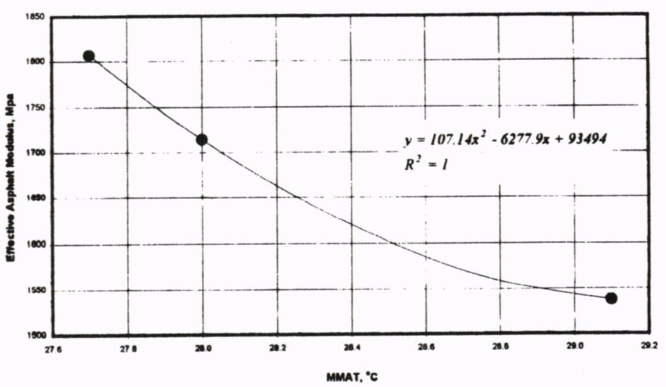

Figure 16: Effective Asphalt Modulus vs MMAT

As discussed earlier, in Jakarta area the 'hot' months are between April and October with average MMAT ranging from 27.4 °C (July) to 27.8 °C (May). The MMAT in July 1998, 27.7 °C, is slightly higher than the average MMAT value of the 'hot' period 27.6 °C. Moreover, the MMAT value of 27.6 °C occurs most frequently in these data. This leads to the conclusion that the effective asphalt modulus determined for July may be the most appropriate for use in the design of asphalt pavements in Indonesian climatic conditions

5. CONCLUSIONS AND RECOMMENDATIONS

From the results of the research and analysis described above, conclusions can be drawn as follows:

1. While the variation of pavement surface temperature closely followed the pattern of solar radiation intensity and hence air temperature, at lower depths a time lag between the occurance of maximum temperature at the surface and at depth in the asphalt layer was observed. The time lag increases with increase in depth. This phenomena may be attributed to the relatively low thermal conductivity of asphalt.
2. Based on measured pavement temperature gradients, the asphalt modulus gradient was determined for each of the three months considered. It was found that a relatively wide variation in pavement modulus occurs during a day. The pavement surface shows the widest range of modulus values, from 207.78 Mpa at 12.00 to 4,200.60 Mpa at 06.00 while at a depth of 24.5 cm the pavement modulus ranges between 1,973.30 and 3,480.79 Mpa.
3. After structural analysis of the pavement model used in this research, it was found that the effective asphalt modulus calculated on the basis of the subgrade strain and asphalt strain design criteria are very similar, with a maximum difference of 50 Mpa.
4. A mean monthly air temperature of 27.6 ^{o}C may be taken as the representative temperature for the design of asphalt pavements in the Jakarta area. If the MMAT value of 27.6 ^{o}C is taken as the representative temperature, the effective asphalt modulus in July, 1807 Mpa, may be most appropriate for structural analysis.

Based on the results of this study, some recommendations are suggested for further research: (i) To determine a representative temperature for different regions in Indonesia in order to estimate the stiffness modulus of the pavement as a function of the temperature conditions in these regions. (ii) To make continuous pavement temperature measurements using possibly more precise equipment such as thermocouples. (iii) To assess pavement modulus in more detail in pavement structural analysis using an advanced computer program such as SAP-90.

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