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MULTI-LAYER PAVEMENT STRUCTURAL ANALYSIS USING METHOD OF EQUIVALENT THICKNESS CASE STUDY: JAKARTA – CIKAMPEK TOLL ROAD.

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Abstract: An analytical method of overlay design has some advantages, such as to take into account the variation of loading types, which will give more exact and accurate results. The purpose of this research is to analyze the existing pavement structure of Jakarta-Cikampek toll road, for analysis period between 1995 to 2003 and to calculate the Residual Life and Overlay Thickness required, based on the deflection data using Falling Weight Deflectometer (FWD) equipment. The deflection bowl was then analyzed by Method of Equivalent Thickness (MET), firstly proposed by ODEMARK-ULLIDTZ and the results were Resilient Moduli in each layer. Considering the Cumulative Damage theory and the allowable stress/strain in each layer, the residual life of pavement and the overlay thickness needed were obtained. These results could be compared to the calculation results using semi-analytical method i.e. AASHTO® 2002 method.
The result of Resilient Moduli in each layer shows that those values could identify the weakness layer in the pavement structure, indicated by the lower value of Moduli. The calculation of Residual Life for each section showed some locations that needed to be overlaid immediately, because of those values are nearly zero or less than 1 year. On the other hand, there were some sections having Residual Life more than 20 years. This means that pavement structure in those sections was strong enough and need not to be repaired in short term. In general, the Residual Life and Overlay Thickness calculated by those two methods i.e. MET and AASHTO method, were indifferent significantly.

Keywords : deflection bowl, method of Equivalent Thickness, Residual Life, Overlay Thickness, AASHTO method.

1. INTRODUCTION.

The purpose of a pavement is to carry traffic safely, conveniently and economically over its extended life. The pavement must provide smooth riding quality with adequate skid resistance and have adequate thickness to ensure that traffic loads are distributed over an area so that the stresses and strains at all levels in the pavement and subgrade are within the capabilities of the materials at each level. The performance of the pavement therefore related to its ability to serve traffic over a period of time.

From the day it is opened to traffic, a pavement will suffer progressive structural deterioration. It is possible that the pavement may not fulfill its intended function of carrying a projected amount of traffic during its design life, because the degree of deterioration is such that reconstruction or major structural repair is necessitated before the end of the design life.

There are two main types of failure, functional and structural, associated with pavement deterioration. Functional failure is that wherein the pavement is unable to carry traffic without causing discomfort to the road users. This failure depends primarily upon the degree of surface roughness. Structural failure, on the other hand, indicates a breakdown of one or more components making it incapable of sustaining the loads imposed upon its surface. In flexible pavements, this failure may result from bituminous surface fatigue, consolidation settlement, shear developing in the subgrade or inadequate performance of the subbase, road base, and surface, as a result of inferior quality materials or poor construction.

The purpose of this research is to analyze the existing pavement structure of Jakarta-Cikampek toll road, for analysis period from 1995 to 2003, and to calculate the Residual Life and Overlay Thickness required, based on the deflection data using Falling Weight Deflectometer (FWD) equipment. The deflection bowl was analyzed by Method of Equivalent Thickness (MET), firstly proposed by Odemark-Ullidtz (Ullidtz, 1987) and the results were Resilient Modulus in each layer. Considering the Cumulative Damage theory and the allowable stress/strain in each layer, the residual life of pavement and the overlay thickness needed were obtained. These results then was compared with the calculation results using semi-analytical method i.e. AASHTO 2002 method.

2. FALLING WEIGHT DEFLECTOMETER

A Falling Weight Deflectometer (FWD) is a device performing dynamic plate loading tests on pavement. A circular loading plate is placed on the surface of the pavement and a pulse load is applied to the plate by means of a falling weight, which is dropped on to a resilient system on the plate. The peak value of the surface is measured in the centre of the loading plate and often in one or several other points in the deflection bowl (Thŏlen, 1992). It is possible either to measure the energy absorbed by the pavement to which a shock from the falling weight has been imparted and the energy which is given back or to measure the resulting deflection that has occurred, on the basis of which the modulus of layers tested can be determined.

For a deflection testing device to be used to determine in-situ moduli of the pavement materials, the following requirements should be met:

a. The load must resemble that of heavy wheel passage in terms of both load magnitude and duration.
b. Deflection must be measured extremely accurate, especially at distances from 0.60 meters to 1.50 meters from the centre of the loaded area.

The resulting deflections are used to determine the modulus of subgrade and must therefore be accurate, because the subgrade generally contributes 60 to 80 percent of the total centre deflection. For the same reason, it is also essential to consider any non-linearity of the subgrade.

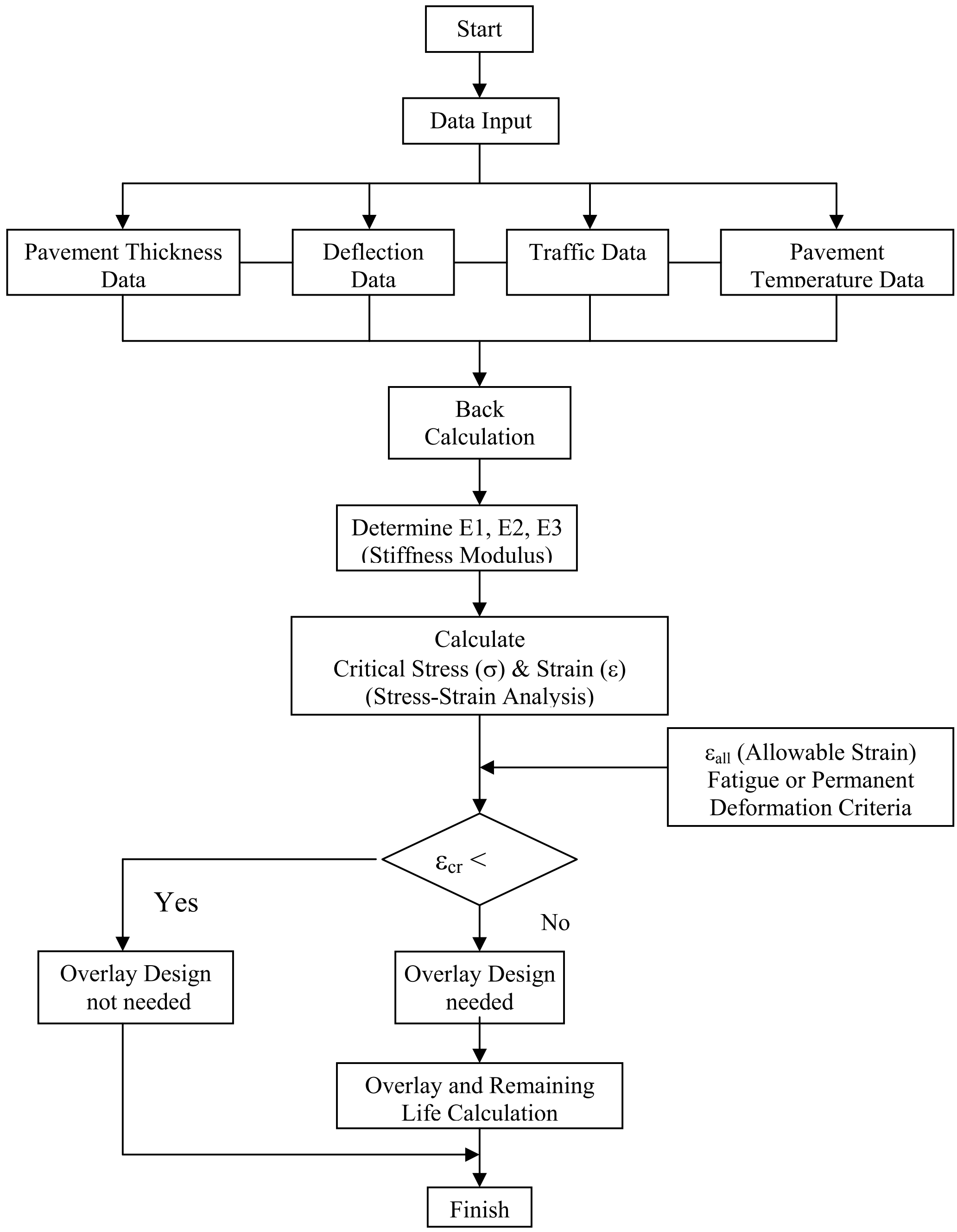

Figure 1
The Algorithm of MODCALC's Program

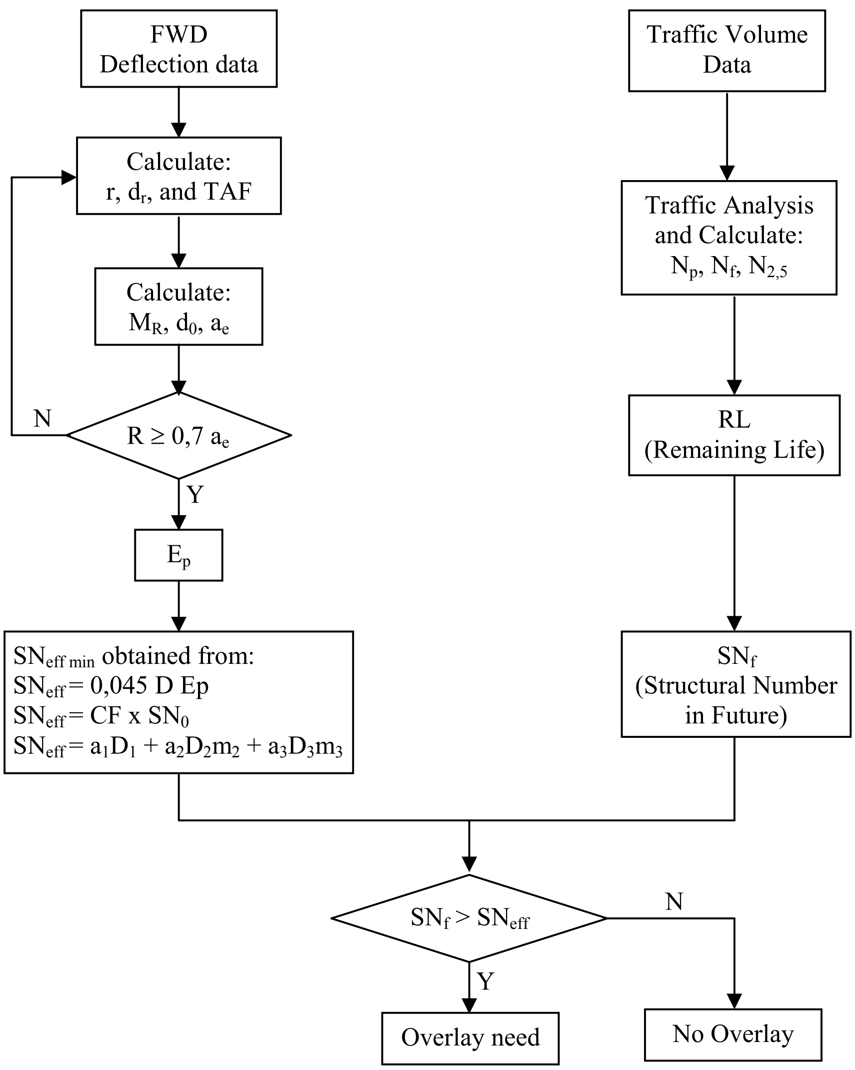

Figure 2
The Algorithm of the AASHTO 1993 Method

3. THE MODCALC PROGRAM

Using FWD-derived load deflection data, structural evaluation of pavement may be carried out with the MODCALC program, which is based on the Method of Equivalent Thickness or M.E.T (Ullidtz, 1987). The equivalent thickness of pavement layers can be calculated using equation :

$$H_e = \sum_{i=1}^{n-1} \left(f_i \cdot H_i \cdot \sqrt{E_i / E_s} \right) + H_s \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where : H_e = Equivalent thickness
f_i = correction factor (0.8), except for the 1st layer, where it is 0.9 for a two-layer structure and 1.0 for a multi-layer structure.
N = number of layers.
H_i = thickness of layer - i.
E_i = modulus of layer – i.
E_s & H_s are modulus and thickness of subgrade material.

The FWD measures the force applied to the pavement plus the deflection at seven different distances from the loading plate. During testing, these values are stored on magnetic tape and later are read by the MODCALC program. In addition, the thicknesses of the structural layers in the pavement must be given as input to the MODCALC program. A two, three or four layer system may be specified.

The MODCALC program will then automatically determine the layer moduli that will produce the same deflection basin as measured. During this iteration, the program also determines any actual or apparent non-linearity of the subgrade. The lateral variation of subgrade may be treated as single, non-linear elastic layer. This non-linearity is extremely important in facilitating a reasonably accurate determination of both subgrade and overlying structural moduli, and also the remaining life of pavement. (Ullidtz & Stubstad, 1985). The non-linearity of subgrade was calculated using the formula :

$$E_0 = C_0 \times (\delta_1 / \delta')^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

Where : E_0 is the Surface Modulus of subgrade
δ_1 is the Major Principal Stress
δ' is the Reference Stress
C_0 & n are constants, and $n < 0$

The next step in the procedure, when the moduli have been determined, is to calculate the critical stresses or strains. In the calculations, the moduli obtained are those corresponding to the climatic conditions existing during the time of testing, and must therefore first be adjusted to the climatic conditions considered appropriate for each season. For bituminous-bound materials, the moduli are adjusted with respect to the temperature and for unbound materials, including subgrade, with respect to seasons.

The last step in the procedure is to compare the critical stresses or strains to permissible values, which are determined from empirical relationships that may be specified by the user of the program. Bituminous materials are assumed to crack if the strain at the bottom of the asphalt layer exceeds a certain value, which in function of the number of load applications. The rate of functional deterioration is assumed to depend on the maximum vertical stresses or strains in each of the unbound material.

The MODCALC program uses Miner's law to sum the damage of each season and calculates the remaining life expectancy for a given traffic condition, and the needed overlay thickness of a specified material, for a specified design period. The algorithm of the MODCALC program was given in Figure 1.

4. CASE STUDY : JAKARTA-CIKAMPEK TOLL ROAD

4.1 General Information

The Jakarta – Cikampek toll highway is a four-lane highway opened in 1988 to serve transportation needs between Jakarta to Cikampek in West Java. The highway consists of two, two-lane carriageways with the pavement structure designed to carry traffic for twenty years, until 2008. Some assumptions considered in the original design are : initial volume 8950 vehicles/day (two-way), growth factor 7.5%, Truck factor 0.70 and percentage of truck : 20%. (Nurwaida, I.W., 2002). This highway is divided in some sections, marked by the toll-gates e.g. Cikampek-Karawang Timur, Karawang Timur-Karawang Barat, Karawang Barat-Cibitung, etc. In this study, the deflection at slow lane in each direction i.e direction A (Jakarta to Cikampek) and direction B (Cikampek to Jakarta), was measured and analyzed.

4.2 Design vs Actual Truck Factor

The "Design" Truck Factor, defined as the total equivalent damage for each vehicle (TAI,1982) was calculated using the maximum allowable limit of axle load configuration in the vehicle classification data (Jasa Marga, 2003). This data will then be compared to the "actual" Truck Factor, based on the W.I.M (Weight-in-Motion) survey, which is conducted on December 2002. by PT Jasa Marga (Mardiyah, 2004). The comparison of Design and Actual Truck Factor was shown in Table 1.

It is shown that the highest Truck Factor obtained was Articulated 3-Axle with 3-Axle Trailer in the direction A, and Heavy Truck in the direction B. The differences between Design and Actual Truck Factor are significant for Heavy Truck, Rigid 3-axle with Trailer and Articulated 3-axle with 3-axle Trailer. This actual data from WIM survey could predict the "overloading" that would happen in the toll road in Indonesia. If the Actual Truck Factor in 2002 and 1992 were calculated and compared each other, those values tend to decrease (Rachman 2004).

4.3 Axle Loading Analysis

The "actual" average daily traffic (ADT) was calculated from traffic count data that was collected in each toll-gate, for the period of 24 hours per day. Those data should be calibrated in order to predict the actual traffic loading in some sections considered. The Truck Factor of each vehicle category or axle configuration was calculated using the "design" and "actual" Truck Factor. The average traffic growth in the period 1990-2001 was assumed to be 7.5% per annum. The results of the calculation of "design" and "actual" cumulative traffic loading were shown in the Table 2.

It is shown that there is no important difference between Design and Actual Cumulative ESAL in the direction A. But inversely, the significant difference was occurred in direction B. This difference could come from higher volume of traffic, higher percentage of heavy truck or "overloading effect" (i.e. Truck Factor of Heavy Truck in Direction B is very high).

Table 1
Comparison of Design and Actual Truck Factor

No.	Vehicle Type	Vehicle Classification	Design Truck Factor	Actual Truck Factor Direction A	Actual Truck Factor Direction B
1	Passenger Car	01	0.0004	0.0007	0.0012
2	Bus	12	0.1593	0.1153	0.0940
3	Light Truck	02	0.3500	1.3810	1.6465
4	Medium Truck	02	1.0648	1.3810	1.6465
5	Heavy Truck	03	1.0375	3.1650	5.4165
6	Rigid 3 Axle with Trailer	06	1.3195	4.1485	3.2480
7	Artic. 3 Axle with 3 axle Trailer	11	2.8877	4.2310	4.2310

Source: Rachman, A., 2004

Table 2
Comparison of Design and Actual Cumulative ESAL per lane

No	Year	Design Cum. ESAL Direction A & B	Actual Cum. ESAL Direction A	Actual Cum. ESAL Direction B
1	1995	1.26×10^6	1.47 x 10^6	3.28 x 10^6
2	1996	2.60×10^6	3.04 x 10^6	6.83 x 10^6
3	1997	4.06×10^6	5.10 x 10^6	11.6 x 10^6
4	1998	5.61×10^6	6.78 x 10^6	15.5 x 10^6
5	1999	7.29×10^6	8.78 x 10^6	19.7 x 10^6
6	2000	9.09×10^6	11.1 x 10^6	24.9 x 10^6
7	2001	11.0×10^6	13.7 x 10^6	30.3 x 10^6
8	2002	13.1×10^6	16.4 x 10^6	33.5 x 10^6
9	2003	15.4×10^6	19.5 x 10^6	37.4 x 10^6

Source: Mardiyah, S., 2004

4.4 Deflection Analysis and Resilient Moduli

The deflection of a pavement system is a response of the pavement to the axle loading. It therefore depends on the condition of the pavement system, on the magnitude, on the location and concentration of loads, and on many environmental factors. Pavement thickness, Resilient

Modulus, Poisson's Ratio and Subgrade Modulus are important parameters which determine the pavement deflection. The effect of these parameters on deflection varies, however, in magnitude and importance. (Majidzadeh, 1982).

Since the resilient modulus of most road materials tends to decrease with load application, the "elastic" deflection of a pavement will tend to increase during the design life. It should therefore be possible to estimate the future life of a pavement of known construction from standardized measurement of elastic deflection. The deflection measurement using FWD equipment was conducted in June 2004 for both lanes i.e. Jakarta to Cikampek and vice versa. The results for any section considered in this analysis, were presented in Figure 3.

It is shown that maximum deflection using FWD equipment, for one section examined, was greater than or equal to 100 x 0.001 = 0.10 mm. In fact, there four points which its maximum deflection was greater than 0.20 mm. Those values could be analyzed either by empirical method (Rachman, A.,2004) or analytical method (Mardiyah, S.,2004).

The MODCALC program used 3(three) or more deflections to calculate the resilient modulus of each layer. Depending on the system considered i.e. 3(three) layer, 4(four) layer, or more, the MODCALC program will carry out an iteration until the difference between the assumed and calculated deflection was minimum or optimum. The results of MODCALC computer program in analyzing the Stiffness Modulus are shown in Table 3.

Table 3 : Percentage of Resilient Modulus in each layer

E_1(MPa)	**$E_1<1000$**	**$1000<E_1<3000$**	**$3000<E_1<5000$**	**$E_1>5000$**
Lane A	3.55%	49.68%	30.32%	16.45%
Lane B	1.29%	36.45%	40.65%	21.61%
E_2(MPa)	**$E_2<100$**	**$100<E_2<500$**	**$500<E_2<1000$**	**$E_2>1000$**
Lane A	17.10	46.45	24.52	11.94
Lane B	22.58	60.00	13.55	3.87
E_3(MPa)	**$E_3<100$**	**$100<E_3<150$**	**$150<E_3<200$**	**$E_3>200$**
Lane A	3.87	41.61	40.97	13.55
Lane B	1.29	23.87	49.35	25.48

It was shown that for the direction Jakarta to Cikampek, the highest percentage of E_1 laid between 1000 to 3000 MPa, while for E_2 laid between 100 to 500 MPa, and for E_3 laid between 100 to 150 MPa. For the direction Cikampek to Jakarta, the highest percentage of E_1 laid between 3000 to 5000 MPa, while for E_2 laid between 100 to 500 MPa, and for E_3 laid between 150 to 500 MPa. By taking a rapid conclusion, it seems that the direction Cikampek to Jakarta had a "better" performance of Stiffness Modulus than the direction Jakarta to Cikampek.

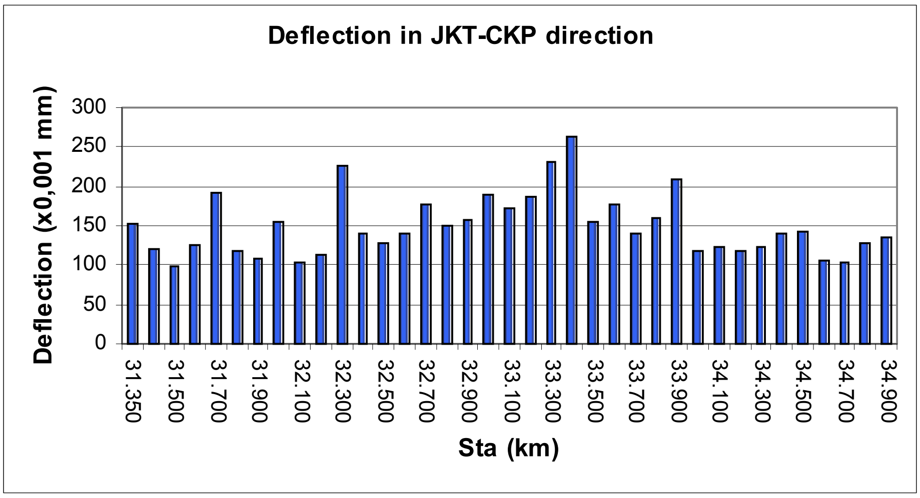

Figure 3
FWD Deflection (δ_{max}) of Jakarta to Cikampek

4.5 Remaining Life and Overlay Thickness

The remaining life was calculated automatically in the MODCALC program, as a difference between the allowable number of cycles, using fatigue of permanent deformation criteria, and the "actual" number of cycles, based on historical traffic-count data. The result of MODCALC program in analyzing remaining life value was shown in table 4 below.

Table 4 : Percentage of Remaining Life Calculation

RL (years)	**RL=0**	**0<RL<3**	**3<RL<10**	**10<RL<20**	**RL>20**
Lane A	0.65%	4.19%	10.00%	7.42%	77.74%

It is shown that the highest percentage of remaining life achieved for both lanes (A and B) was greater than 20 years. It means that, pavement in both lanes was in good condition and the low percentage of section only which needed an overlay.

The overlay thickness was calculated based on allowable value of stress or strain in surface layer and/or subgrade, as shown in the algorithm in figure 1. The iteration processes was conducted until the critical strain/stress decrease and achieve the allowable values. The calculation results for both lanes were presented in table 5.

Table 5 : Percentage of Overlay Thickness needed.

D_{ov} (cm)	$D_{ov}=0$	$0<D_{ov}<4$	$4<D_{ov}<7$	$7<D_{ov}<11$	$D_{ov}>11$
Lane A	91.94	2.90	3.23	1.61	0.32
Lane B	90.61	3.56	1.29	2.59	1.94

It was shown that almost all section considered does not need an overlay, i.e. 92% for lane A and 91% for lane B. Only a small percentage of section analyzed which needed an overlay thickness.

In general, the algorithm of AASHTO-1993 method for determining the overlay thickness was shown in figure 2 (AASHTO, 1993). Using the same input as the calculation above, the remaining life and overlay needed were obtained. In fact, the remaining life of all sections considered is zero and the overlay thickness is needed in all sections. The summary of overlay thickness calculation was presented in table 6 below.

Table 6 : Summary of overlay thickness using AASHTO 1993 method
Lane A : Jakarta to Cikampek

STA	SN_f	$SN_{eff\,(min)}$	SN_{ov}	D_{ov} (cm)
31.350 – 32.200	4.68	2.54	2.14	12.22
32.300 – 33.900	5.08	2.54	2.54	14.54
34.000 – 37.200	4.78	2.54	2.24	12.83
37.300 – 40.000	3.91	1.55	2.36	13.50
40.100 – 41.900	4.66	2.54	2.12	12.13
42.000 – 44.200	4.98	2.54	2.45	13.97
44.300 – 47.000	5.20	2.54	2.66	15.19

It is shown that for all sections considered, the overlay thickness is required and this value is greater than than 10 cm. Comparing with the MODCALC program, the result of AASHTO 1993 method tends to estimate a "weaker" condition of pavement structure.

5. CONCLUSIONS.

Considering all results presented above, some conclusions could be drawn :

a. Comparing the Design Truck Factor with the Actual Truck Factor, for some types of commercial vehicle e.g. Heavy Truck, Rigid 3-axle and Articulated 3-axle, a significant difference was obtained.
b. Comparing the Design and the Actual Cumulative ESAL, during the period 1995 to 2003, a significant difference occurred in Cikampek to Jakarta direction, not for Jakarta to Cikampek

direction. This is due to either higher volume of traffic, higher percentage of heavy truck or higher Truck Factor.

c. The MODCALC program could give a better and faster calculation of Stiffness Modulus in each layer, and the remaining life and overlay thickness in each section, compared to the empirical method i.e. BINA MARGA method.
d. In some sections of Jakarta – Cikampek toll road, a case study in this research, the Stiffness Modulus in each layer, the Remaining Life and the Overlay needed were calculated and analyzed. In general, the pavement condition in two directions was in good performance, indicated by a high value of Stiffness Modulus and Remaining Life, and almost no overlay is needed.
e. Comparing the output of MODCALC program to the AASHTO method, an important different of structural condition was obtained, for both directions. This is due to the AASHTO method tends to "under estimate" the structural capacity of pavement. In fact, a more detail analysis was needed before using those methods in Indonesia.

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