Overlay Design and Analysis using the Mechanistic and Semi-Analytical Methods. Case Study: Pamanukan-Sewo Section in PANTURA West Java - Indonesia

Bambang Sugeng SUBAGIO[a], Faisal GERARDO[b], Indrayati Tenrijaja SUBAGIO[c]

[a,b] *Graduate School of Civil Engineering, Institute of Technology Bandung, Bandung 40132, Indonesia, E-mail: bsugengs@si.itb.ac.id*
[c] *School of Civil Engineering, Mercu Buana University, Jakarta, E-mail: office@si.itb.ac.id*

Abstract: The purpose of this research is to compare the Mechanistics and Semi-analytical methods in analyzing the flexible pavement structures of the PANTURA National Road in Indonesia, located in North corridor of Java Island and it has a very strategic role in the transportation mobility from West Java to East Java. The objective of this research is to calculate the overlay thickness required, based on the FWD deflection measurement. Using the deflection data, the Resilient Moduli in each layer can be determined by using the the Everseries® Computer Program. These results were then compared to the calculation using the semi-analytical method of AASHTO 1993. 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 using analytical method showed that the overlay needed was slightly higher than that calculated by semi-analytical method.

Keywords: Deflection, Mechanistics, Overlay analysis, Everseries, AASHTO-93 method

1. INTRODUCTION

The purpose of a pavement structure 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 critical stresses and strains at all pavement layers and at the top of subgrade are within the capabilities of the materials. The performance of the pavement therefore related to its ability to serve traffic over a period of time, namely “design life”.

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 the reconstruction or major structural repair is necessitated before the end of design life. The purpose of this research is to compare the 2 (two) methods, namely the Mechanistic and Semi analytical methods in analyzing the existing pavement structure of the National Road (PANTURA), and to calculate the overlays thickness required, based on the deflection-bowl data using Falling Weight Deflectometer (FWD) equipment. Considering the Cumulative Damage theory and the allowable stress/strain in each layer, the overlay thickness needed were obtained.

2. THE EVERSERIES PROGRAM

The EVERSERIES is a series of computer program which consists of 3 (three) “subprograms”, namely: EVERCALC, EVERSTRESS, and EVERPAVE. This program could analyze the flexible pavement structures based on the mechanistic approach (WSDOT, 2005).

The Evercalc program can calculate the “elastic” moduli of pavement layer, determine the coefficient of stress sensitivity of unstabilized materials, stresses and strains at various depths, and optionally normalizes the asphalt mix modulus to a standard laboratory condition. The Everstress program is capable of determining the stress, strains and deflections in a multi-layered elastic system under circular surface loads. This program will also take into account any stress dependent stiffness modulus.

The Everpave program is a flexible pavement overlay design based on the multilayered elastic system. The determination of the overlay thickness is based on the required thickness to bring the damage levels to an acceptable level under a design traffic condition. The damage levels are calculated on two primary distress type, namely fatigue cracking and rutting. This program is also capable of considering the seasonal variations and the stress sensitivity of the pavement materials.

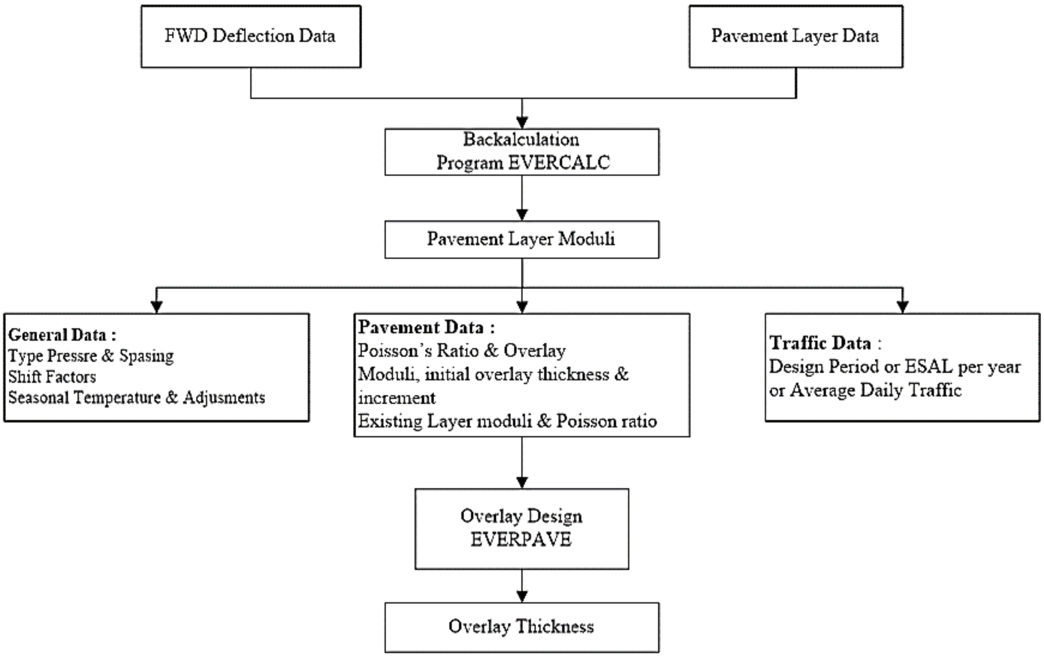


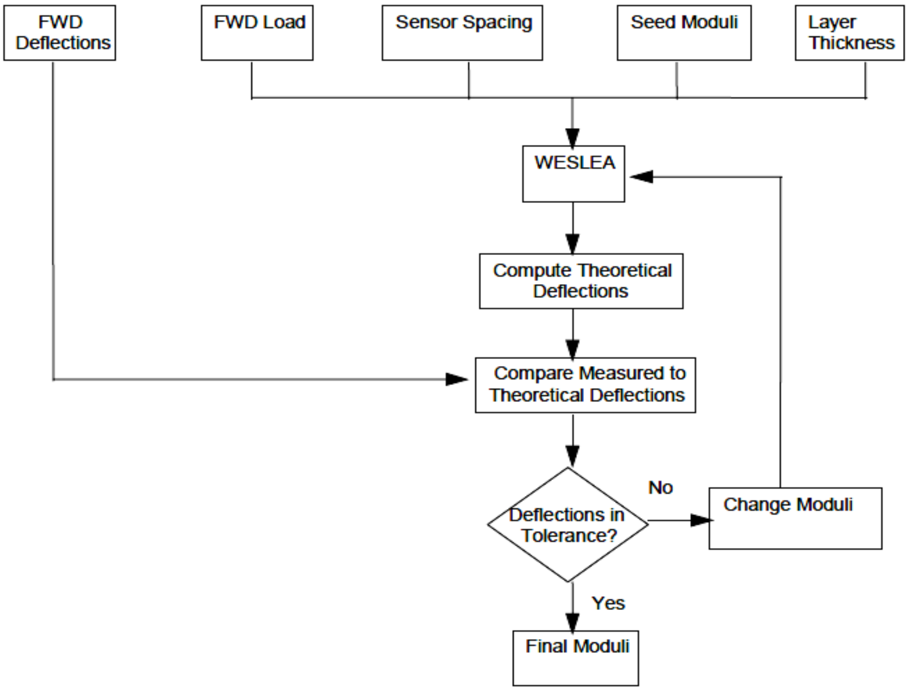
Figure.1 Principles in EVERSERIES Program

A mechanistic overlay design procedure in this program was developed by the Washington State Department of Transportation (WSDOT, 2005) which is based on the back-calculation of material properties and fatigue and rutting failures. Backcalculation method is defined where measured and calculated surface deflection basins are matched (to within some tolerable error) and the associated layer moduli required to achieve that match are determined. In this approach, layer moduli can be calculated for each deflection test point according to the flowchart in the Figure 2. The primary measure of the convergence between measured and calculated surface deflection will be the Root Mean Square (RMS), defined as:

$$RMS\ (\%) = 100\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{dm-dc}{dm}\right)^2}{Nd}} \quad (1)$$

Where,

- RMS : Root Mean Square,
- Dc_i : Calculated Pavement Surface Deflection at Sensor i,
- Dm_i : Meaured Pavement Surface Deflection at Sensor i, and
- Nd : Number of Deflection Sensors used in The Backcalculation Process.



Source: EVERSERIES User's Guide, 2005

Figure 2. Prinsiples of Backcalculation in Evercalc Program

The Evercalc program uses WESLEA as the layered elastic solution to compute the theoretical deflections and a modified "Augmented Gauss-Newton" algorithm for optimization. An inverse solution technique is used to determine the elastic moduli from FWD pavement surface deflection measurements. The deflections calculated using WESLEA is compared with the measured ones at each iteration. When the discrepancies in the calculated and measured deflections falls within the allowable tolerances, or the number of iterations has reached a limit determined, the program terminates.

The determination of the overlay thickness is based on the required thickness to bring the damage levels to an acceptable level under a design traffic condition. The damage levels are based on two primary distress types, fatigue cracking and rutting, which are the most common criteria for mechanistic analysis based on overlay design. The program is also capable of considering the seasonal variation and stress sensitivity of the pavement materials (Subagio, BS, et al., 2011).

For fatigue cracking failure, the Finn's model (Finn, F.N, 1977) is commonly used. The model used linearly shifts Monismith's laboratory model (Monismith, 1969) which is shown below:

$$\log N_f = 14.82 - 3.291 \log(\varepsilon_t) - 0.854 \log(E_{ac}) \quad (2)$$

Where,

N_f : Number of Axle Load Applications to Failure,
ε_t : Horizontal Tensile Strain at The Bottom of The HMA Layer (in/in x 10^{-6}),
E_{ac} : The Stiffness Modulus of The HMA Layer (ksi).

Rutting occurs due to permanent deformation of the asphalt concrete layer and the unbound layers. However, as the deformation of asphalt concrete is not well defined, the failure criteria equations are expressed as a function of the vertical compressive strain at the top of the subgrade. The rutting criterion was adopted from the Asphalt Institute (Asphalt Institute, 1981) which is shown below:

$$\log N_f = 1.077 \times 1018 (\varepsilon_v)^{-4.4843} \quad (3)$$

Where,

N_f : Allowable Number of 80 kN (18,000 lb) Equivalent Single Axles (ESAL) so that Rutting at The Pavement Surface Should Not Exceed 0.5 inch, and

ε_v : Vertical Compressive Strain at The Top of The Subgrade Layer

The properties of the pavement system are significantly affected by climatic conditions. Consequently, the seasonal adjustments for pavement materials are essential for design purposes. The adjustment for asphalt concrete is achieved by the use of a stiffness temperature relationship and that for the unbound materials by applying the seasonal variations of the materials (in terms of Moduli Ratio's).

As the climate condition changes with location and time and its effects vary with the pavement materials, engineering judgment is always needed. As the stiffness of asphalt concrete is significantly affected by temperature, it is important to determine pavement temperature as accurately as possible. The pavement temperature is commonly determined by the relationship between air temperature and pavement temperature. For the pavement design purpose, the Mean Monthly Air Temperature (MMAT) are converted to Mean Monthly Pavement Temperatures (MMPT) (Shook, et al., 1982) as follows:

$$MMPT = MMAT \{1 + 1/(Z + 4)\} - 34/(Z + 4) + 6(12) \quad (4)$$

Where,

MMPT : Mean Monthly Pavement Temperature (°F),

MMAT : Mean Monthly Air Temperature (°F), and

Z : Depth below Pavement Surface (inches).

3. RESEARCH METHODOLOGY

The working plan of this study can be seen in Figure 1 and Figure 4, which is divided into structural analysis programs using the AASHTO 1993 and the Everseries® program method. The Methodology of Structural analysis consists of:

1. The collection of some principal data in the Pamanukan - Sewo section, which consists of traffic data (AADT), the axle-loading data resulted from WIM survey in 2013, the FWD's deflection data, the pavement thickness data and the pavement temperature data.
2. The average Traffic Growth was calculated based on the "time series" AADT data.
3. The Truck Factor for each vehicle type was calculated using the axle-loading data.
4. The cumulative ESAL actual and the "future" cumulative ESAL will be determined considering the AADT data, the average growth factor and the Truck Factor for each vehicle.
5. Hence, the AASHTO-93 method can be applied to obtain the SN_f and SN_{eff} (future and effective values, respectively), and the overlay thickness for several survey sections.

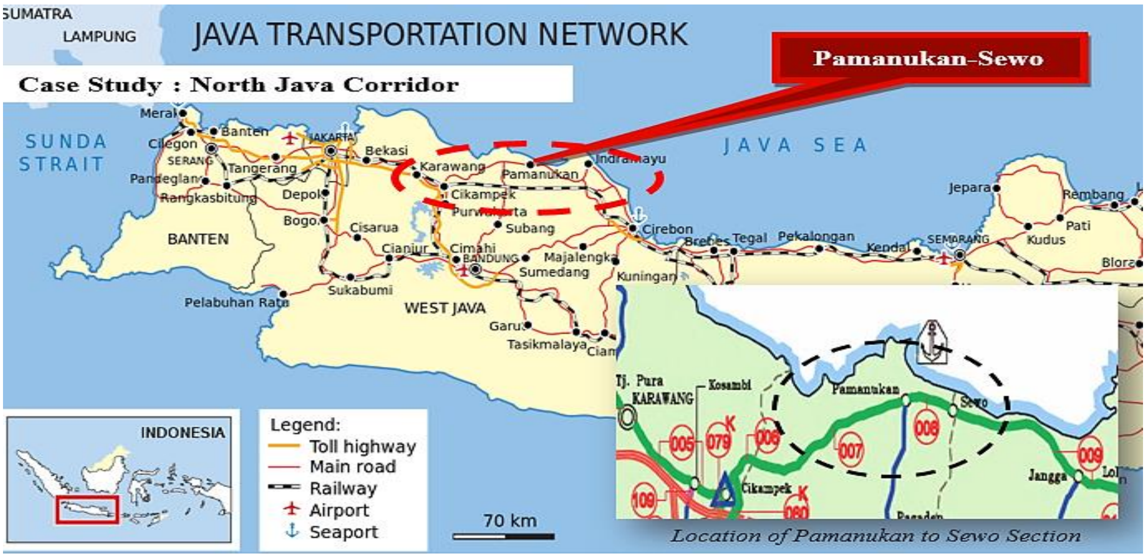
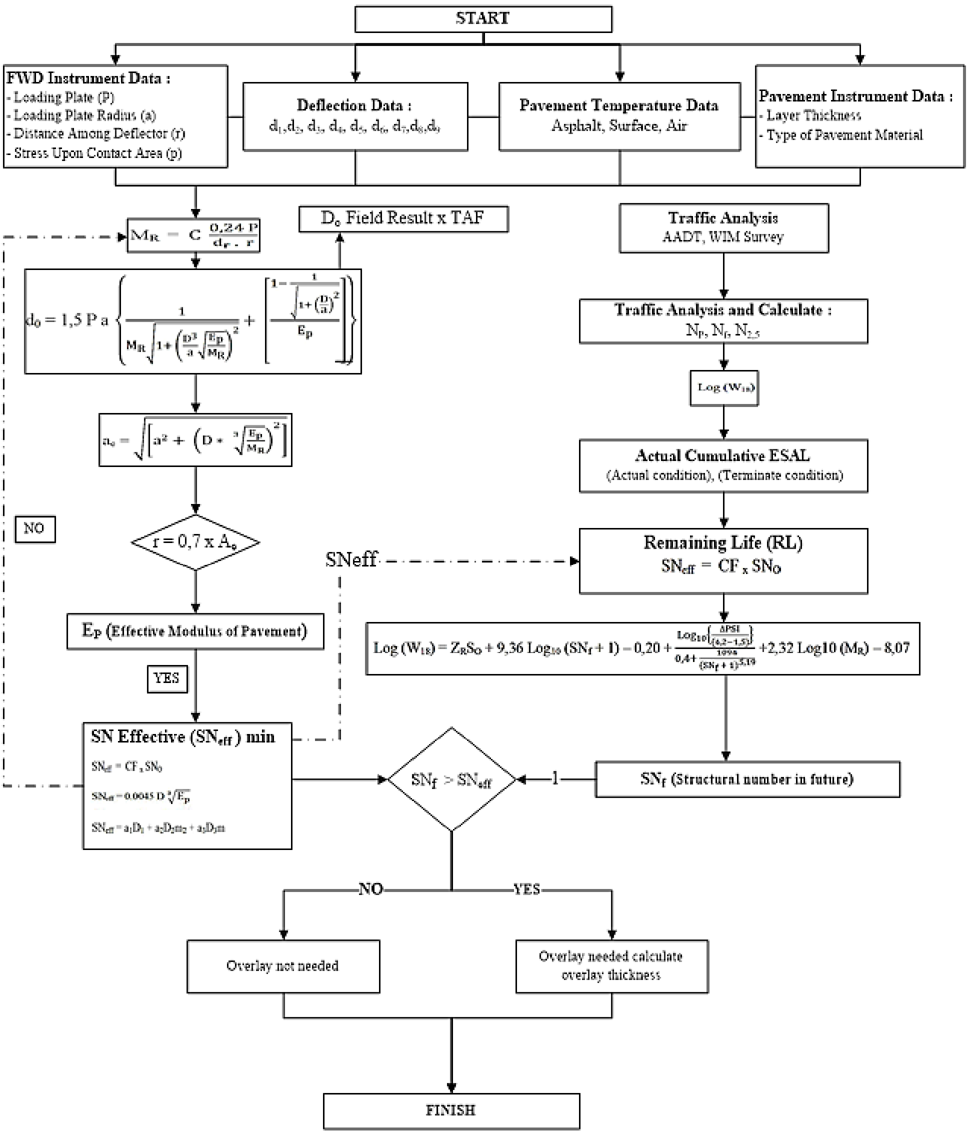


Figure 3. Location of Section: Pamanukan to Sewo



Source: AASHTO 1993

Figure. 4 Flow Chart of Structural Analysis Using the AASHTO 1993 Method

4. CASE STUDY : PAMANUKAN TO SEWO SECTION

4.1. Traffic Data

PANTURA is a National ArteriAL road, located in the North corridor of Java Island. It can be said that the heavy vehicles in PANTURA National Road prefer to use fast lane rather than slow lane. However, this phenomenon is contradictive with the regular lane distribution in the arterial road in Indonesia. The actual traffic data was classified into ten vehicle categories, based on Bina Marga's Classification, i.e. vehicle category 2 until vehicle category 7C. For example, the distribution of traffic data for Sewo-Pamanukan direction is shown in Table 1 (Subagio, B.S., et al., 2013)

Table.1. Traffic From Pamanukan to Sewo

No	Year	AADT (Vehicle/Day)										Total Vehicles
		Light Vehicles			Heavy Vehicles							
		2	3	4	5A	5B	6A	6B	7A	7B	7C	
1	2009	6067	7491	4413	741	65	2894	3651	1217	142	478	27159
2	2010	6371	7866	4634	779	69	3039	3834	1278	150	502	28522
3	2011	6674	8241	4855	816	72	3184	4017	1339	157	526	29881
4	2012	7281	8990	5296	890	79	3473	4382	1461	171	574	32597
5	2013	7866	9712	5722	961	85	3752	4734	1578	185	620	35215

Source: Bina Marga's, 2013

4.2 Design and Actual Truck Factor

The "Design" Truck Factor, defined as the total equivalent damage for each vehicle was calculated using the maximum allowable limit of axle load configuration in the vehicle classification data. This data then will be compared to the "actual" Truck Factor, based on the WIM (Weight-in-Motion) survey. The vehicle axle load data that was obtained from WIM (Weight-in-Motion), is similar to a gross weight survey for moving vehicle, and the weight proportion for each vehicle tires was determined by analyzing the dynamic pressure of each tires. The vehicle axle load data used in this research are resulted from WIM Survey at Cirebon-Losari section in 2013. The comparison of Design and Actual Truck Factor was shown in Table 1 and Figure 2.

Table 2. Comparison of Design and Actual Truck Factor

Truck Factor	Vehicle Class			
	6B	7A	7B	7C
Design (Bina Marga's)	3,779	4,452	8,290	6,130
Actual (WIM)	5,651	5,778	10,277	12,312

Source: Bina Marga's, 2013

The cumulative ESAL value can be determined by multiplying the AADT value for one year with the lane distribution factor and the average Truck Factor (TF) for each vehicle. The prediction of cumulative ESAL from 2013 to 2018 is calculated using the AASHTO 1993 and the EVERSERIES program. This value is important in order to obtain the remaining life (RL) and the overlay thickness of that section. The actual Cumulative ESAL predicted from 2013 to 2018 is shown in Table 3.

Table 3. The Cumulative ESAL calculated from 2013 to 2018

Year	Pamanukan Sewo (cumulative)
2013	6.404.098
2014	13.239.065
2015	20.533.845
2016	28.319.436
2017	36.628.753
2018	45.469.099

4.3 Deflection Analysis and Resilient Moduli

The deflection data were obtained from survey in 2013 using the Falling Weight Deflectometer (FWD) equipment. The instrument is supported with 25 inch dish load, 200 kg ballast load and 26 inch high falls. Each deflectometer is placed among 0, 200, 300, 450, 600, 900, 1200, 1500 and 1800 mm for pavement with total thickness more than 700 mm. These FWD's deflection data will be used in the structural analysis and will be combined with the AADT data, axle load (WIM) data and pavement thickness. For example, the d_1(maximum deflection) of FWD deflection data for Pamanukan direction in the fast lane is shown in Figure 5.

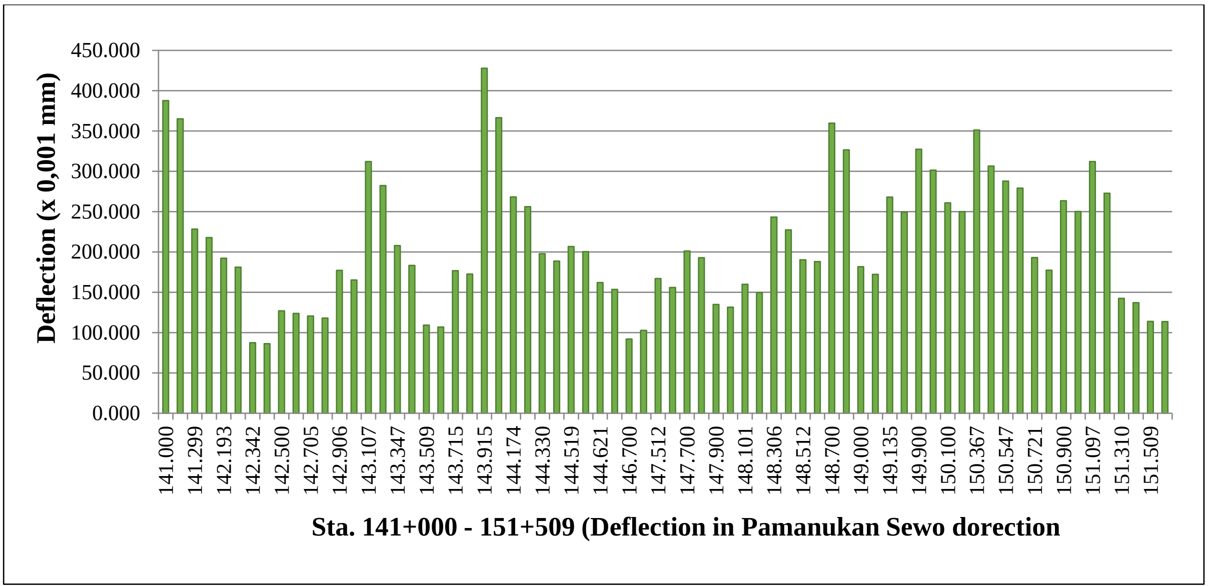


Figure 5. FWD Deflection data from Pamanukan to Sewo.

The EVERSERIES program used 3 (three) or more deflections to calculate the resilient modulus of each layer. Depending on the system considered i.e. 2 (two) layer, 3 (three) layer, 4 (four) layer, or more. The EVERSERIES program will carry out an iteration until the difference between the assumed and calculated deflection was minimum or optimum. The assumptions in analyzing the "existing" Stiffness Modulus using the EVERSERIES program are shown in Figure 6, which compare the 2-layer, 3-layer and 4-layer models.

The results showed that, for the direction of Pamanukan to Sewo, the highest percentage of E1 was laid between 3000 to 5000 MPa, while for E2 it was laid between 100 to 500 MPa, and the value of E3 was more than 200 MPa. For the direction from Sewo to Pamanukan, the highest percentage of E1 laid between 1000 to 3000 MPa, while for E2 the value was less than 100 MPa, and for E3 the value was more than 200 MPa (Gerardo, 2015).

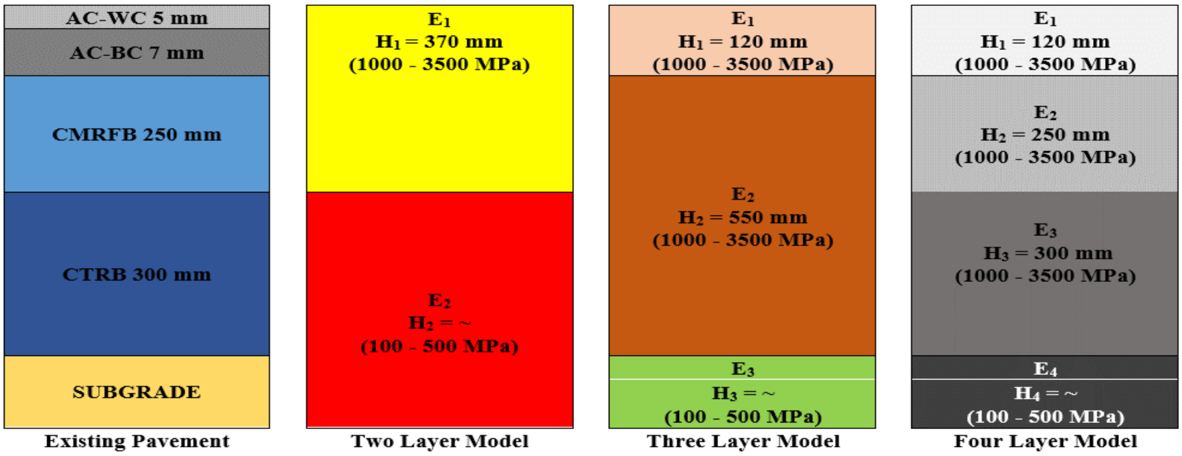


Figure 6. Assumption of Layer pavement models

4.4 Overlay Thickness

The overlay thickness was calculated based on fatigue cracking and rutting failure criteria, which are both commonly used for the Mechanistic analysis. A pavement system under dual tire loads is analyzed by a multilayered elastic program which can consider the stress sensitivity of unbound materials. The analysis produces the two failure criterion parameters, which are the horizontal tensile strain at the bottom of the asphalt concrete layer and the vertical compressive strain at the top of the subgrade for fatigue and rutting failures, respectively. In general, the algorithm of AASHTO 1993 method for determining the overlay thickness was shown in Figure 6 (AASHTO, 1993).

Using the same input as the calculation above, the remaining life and overlay needed were obtained. The summary of overlay thickness calculation was presented in table 4 and table 5 below (Gerardo, 2015).

Table 4. Overlay thickness resulted from the Everseries Program
Direction from Pamanukan to Sewo

$D_{everseries}$ (cm) 2 Layer	$D_{everseries}$ (cm) 3 Layer	$D_{everseries}$ (cm) 4 Layer
11,50	15,00	18,33
15,73	17,00	18,00
14,42	24,00	29,57
12,19	29,00	33,56

Table 5. Overlay thickness resulted from the Everseries Program
Direction from Sewo to Pamanukan

$D_{everseries}$ (cm) 2 Layer	$D_{everseries}$ (cm) 3 Layer	$D_{everseries}$ (cm) 4 Layer
11,20	32,60	33,10
11,08	31,50	32,42
11,00	31,88	32,50
11,21	32,43	32,57
12,86	27,64	33,43
12,58	31,00	28,00
11,64	32,43	33,43
13,07	34,14	34,00

The two tables above showed that the overlay thickness calculated by the EVERSERIES program is greater than calculated by the AASHTO 1993 method. It is shown that the EVERSERIES program gives the highest overlay thickness compared to the others, meaning that the analytical method considers all the "damage" obtained in the flexible pavement structure.

Table 6. Summary of overlay thickness using AASHTO 1993 method and EVERSERIES Program From Pamanukan to Sewo

STA	SNf	Sneff(min)	SNov	Dov (cm)	Deverseries (cm)
141+000 - 142+300	5,471	3,58	4,739	12,036	11,50
142+300 - 148+442	5,691	3,58	5,288	13,431	15,73
148+442 - 149+900	5,954	3,58	5,946	15,104	14,42
149+900 - 151+000	6,060	3,58	6,210	15,773	12,19

Table 7**.** Summary of overlay thickness using AASHTO 1993 method and EVERSERIES program From Sewo to Pamanukan

STA	SNf	Sneff(min)	SNov	Dov (cm)	Deverseries (cm)
152+000 - 150+773	6,078	3,58	6,255	15,888	11,20
150+773 - 149+165	6,128	3,58	6,382	16,211	11,08
149+165 - 147+985	5,660	3,58	5,211	13,237	11,00
147+985 - 146+187	5,883	3,58	5,769	14,653	11,21
146+187 - 145+017	5,483	3,58	5,253	13,343	12,86
145+017 - 144+000	5,318	3,58	4,878	12,391	12,58
144+000 - 142+791	5,276	3,58	4,250	10,795	11,64
142+791 - 141+405	5,738	3,58	4,875	12,382	13,07

Source: D_{ov} (cm) AASHTO 1993 Method calculation (two layer pavement)
$D_{everseries}$ (cm) EVERSERIES Program calculation (two layer pavement)

5. CONCLUSIONS

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

1. The high value of Truck Factor indicates the "overloading" effect in the road section, which was shown in the case study i.e. Pantura road, section Pamanukan to Sewo. A detail observation and monitoring system was still required actually to overcome this problem.
2. The overlay thickness calculated by the EVERSERIES program, was higher than the results calculated by the AASHTO-93 method. In fact, the mechanistic method analyzes the "total" pavement structure and considers all the "damage" occurred in each layer.
3. The EVERSERIES program, represented one of the Mechanistic method for pavement evaluation, gives a faster method of analysis to calculate the Stiffness Modulus of pavement layers, when it is compared to the Semi-mechanistic method i.e. the AASHTO-93 method.

REFERENCES

AASHTO. (1993), *Guide for Design of Pavement Structures 1993*, American Association of State Highways and Transportation Officials, Washington DC, USA.

Bina Marga. (2013), *Collection Data*, Ministry of Public of Works and Housing, (Direktorat Jenderal Bina Marga; In Indonesia), Jakarta, Indonesia.

Finn, F.N., et al. (1977), *The Use of Distress Prediction Subsystems for the Design of Pavement Structures*, Proceedings, 4th International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Harbor, USA.

Gerardo, F. (2015), *Comparison Overlay of Flexible Pavement Analysis using AASHTO 1993 Method and Everseries Program, (Case Study: Pantura Road Section : Pamanukan - Sewo)*, Highway Engineering Program, ITB, Bandung, Indonesia.

Monismith, C.L., Epps, J.A. (1969), *Asphalt Mixture Behavior in Repeated Flexure*, Institute of Transportation and Traffic Engineering, Univ. Of California Berkeley, USA.

Shook, J.F., Finn, F.N., Witczak, M.W., Monismith, C.L. (1982), *Thickness Design of Asphalt Pavements-The Asphalt Institute Method, Proceedings, 5th International Conference on the Structural Design of Asphalt Pavements*, The Delft University of Technology, The Netherlands.

Subagio, B.S., Wibowo, S.S., Ferdian. T., Sufanir. A.M.S. (2011), *Comparison of Overlay Design Analysis using Mechanistic and Semi-Analytical Methods, case study: Jakarta-Cikampek Toll Road*, Proceedings of the Eastern Asia Society for Transportation Studies, Vol.8.

Subagio, B.S., RAMC, F., Rahman, H., Kusumawati, A. (2013). *Structural and Functional Evaluation of Flexible Pavement in Indonesia Case Study: Ciasem-Pamanukan Section,* Proceedings of 9th Conference EASTS.

The Asphalt Institute. (1981), *Thickness Design-Asphalt Pavement for Highways and Streets,* Manual Series No.1 (MS-1), 9th Edition, College Park Maryland 20740.

WSDOT. (2005), *EVERSERIES © USER'S GUIDE: Pavement Analysis Computer Software and Case Studies*, Washington, USA.