

DETERMINATION OF EQUIVALENT AXLE LOAD FACTOR OF TRAILER WITH MULTIPLE AXLES ON FLEXIBLE PAVEMENT STRUCTURES

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Abstract: The paper shows how to develop EALF of ten axles 80 tires trailer on flexible pavement structures, which is used to transport segmented concrete girder from fabricator site to project site. Total maximum weight is 175 tons. Trailer is operated between 10 pm – 4.30 am to minimize traffic obstruction. EALF analysis is based on mechanistic empirical method. As air temperature affects modulus of surface layer, Bandung's average minimum temperature is used. The result shows fatigue criterion determined its failure on pavement with high subgrade modulus, otherwise its failure criterion is based on permanent deformation. Thicker pavement has higher EALF when its failure is permanent deformation, otherwise EALF is lower. In general, EALF is within a range of 3.28 to 78.44. The higher the subgrade modulus, the lower trailer's EALF. Trailer's EALFs for subgrade modulus of 50 MPa is higher than subgrade moduli of 100 – 150 MPa. The difference is apparent with surface thickness of 150 – 200 mm.

Keywords: EALF, flexible pavement, mechanistic empirical method, multiple axle

1. INTRODUCTION

Total number of standard axle loads is a parameter used for design of a new pavement structure, or showing its remaining life of in service pavement structures. During the life of pavement, various traffic loadings will pass on design lane. The passage of those vehicles on the design lane will deteriorate pavement structure. It is design that the lanes of pavement structure should not fail before total number of vehicles is reached its designed number of standard axle loads. There are various type of vehicles, total vehicle loads, axle types, and axle loads will pass on the pavement. Damaging effect of those axles on the pavement structure will be different from one to the others. In order to make pavement design simpler, damaging effect of those various axles are converted into of standard axle load. Ratio of damaging effect of non standard axle load to standard axle load is called Equivalent Axle Load Factor (EALF). It is common to define standard axle load as a single axle dual wheels with 80 kN (18 kips, 8.16 ton) such as in Asphalt Institute (1991), Shell (1978), AASHTO (1993), Austroads (1992), and SNI (1989). In each of those design methods, EALF for

various load levels of different axle types such as single axle, tandem, or tridem are usually available.

In Bandung, capital of West Jawa province, there is an elevated highway project above existing pavement structure. One segment of the project which cross a valley is a cable-stayed bridge. The other is concrete structure above existing road with heavy traffic. Construction of elevated highway is prefabricated segmental hollow portland cement concrete. The elevated highway construction is built by assembly those concrete segments with prestressed wire strands. The concrete segments are fabricated outside of the city. Later the concrete segments are transported to the project site. The weight of the segments are vary. It depends on geometry of its cross section. The maximum weight is 158 tons. A special trailer is built for transporting the segments. It is a 10 axles trailer with 8 tires on each axle (as shown in Figure 1). The purpose of this special trailer is to enable transporting those concrete segments through existing culverts and bridges. It is an interesting study to know damaging effect of this fully loaded trailer compared to standard axle load on the current flexible pavement structure.



Figure 1. Trailer Loaded with a Typical Portland Concrete Segment

2. OBJECTIVE

The objective of this paper is to evaluate damaging effect of fully loaded trailer (175 tons including the weight of trailer bed) of 10 axles with 8 tires on each axle on flexible pavements compared to standard single axle dual wheel of 80 kN with mechanistic empirical method.

3. EVALUATION METHOD

The analysis of equivalent axle load is based on mechanistic empirical method as used in the Asphalt Institute. Equivalent axle load is defined as the ratio of number of repetitions of non standard axle load to the standard axle load up to failure. Failure is defined as the minimum number of repetitions that cause of 20 percent fatigue cracking on pavement surface or 13 mm rut depth on the wheel track. Number of repetitions of any axle load to develop cracks or rut depth depends on strains in the pavement structure. Computer program Everstress 5.11 for Windows (developed by N. Sivaswaran, L.M. Pierce, and J.P. Mahoney for Washington State Department of Transportation) is used to analyze strains in the pavement structures. Three layers of flexible pavement structures are analyzed with surface thickness of 100, 150, and 200 mm, untreated granular base 150, 250, and 350 mm, and subgrade resilient modulus of 50, 100, and 150 MPa. The concrete segments are transporting from the fabrication site to the project between 10 pm to 4.30 am. The average air temperature at this period is 18.6 °C. Stiffness modulus of bituminous mixture is evaluated based on this air temperature.

4. THEORETICAL BACKGROUND

Mechanistic empirical method in pavement design is a powerful method compared to empirical method. This method uses correlation between strains in the pavement structures to the number of load repetitions which cause distress in pavement structure. Two types of distress are used to define pavement failure, i.e. at least 20% cracks on pavement surface, or 13 mm rut depth on the wheel tracks. The minimum number of repetitions that produces one of those criteria is number of repetitions to the pavement. Maximum horizontal tensile strain at the bottom of the surface layer due to axle load determines number of load repetitions to produce cracks. This number of load repetitions is called fatigue life of the pavement. This part is called as mechanistic method. Fatigue cracking and tensile strain correlation is based on bituminous material properties obtained from laboratory experiments. Load applied to the specimens in laboratory are controlled with a consistent loading mode during the test (either strain controlled or stress controlled). In reality, pavement loading is random in load level, load level sequence, and the time between the loadings. As the result, relationship of fatigue cracking and tensile strain in laboratory requires adjustment in order to obtain similar result to the actual fatigue life in the field. Adjusting laboratory result to the field is the part of empirical method. Similar procedure is applied to number of load repetitions that produces rut depth. Equations to predict fatigue life and life based on deformation are as Equations 1 and 2. These equations are defined by Finn, et al. (1977) and also used by AI (1982). Factor M is used when the bituminous mixture characteristics differs than the one used while developing the equation.

$$N_f = 18.4(10^M)(0.004325\varepsilon_t^{-3.291})(E_t^{-0.854}) \quad \text{.....(1)}$$

$$M = 4.84 \left(\left(\frac{V_b}{V_v + V_b} \right) - 0.69 \right)$$

$$N_d = 0.1365 e^{-0.8 \left[\frac{1}{\varepsilon_c} \right]^{4.477}} \quad \text{.....(2)}$$

Pavement life is either based on fatigue criterion or deformation. It requires state of strains occur in the pavement layers. Information about moduli of each pavement layers are indispensable. Stiffness modulus of the surface layer made of bituminous mixture can be predicted based on Equation 3 (AI, 1982). As the modulus depends on temperature of bituminous layer, the pavement temperature is predicted from the air temperature. It is used Equation 4 for this purpose. Subgrade resilient modulus can be obtained from its CBR value. For this purpose, Equations 5a or 5b is used. Base course resilient modulus which made of untreated granular material is a function of state of the stress in that particular layer. Prediction of resilient modulus of base course requires iteration procedures. Witczak and Smith (1981) found that resilient modulus can be predicted by using Equation 6 in order to simplify the procedure.

$$\begin{aligned} \log E_1 = & 5.553833 + 0.028829 \left(\frac{P_{200}}{f^{0.17033}} \right) - 0.03476 (V_v) + 0.070377 (\eta_{70^\circ F}, 10^6) \\ & + 0.00005 \left[t_p^{(1.3+0.49825 \log f)} P_{ac}^{0.5} \right] - 0.00189 \left[t_p^{(1.3+0.49825 \log f)} \frac{P_{ac}^{0.5}}{f^{1.1}} \right] \\ & + 0.931757 \left(\frac{1}{f^{0.02774}} \right) \end{aligned} \quad \text{.....(3)}$$

$$MMPT = MMAT \left(1 + \frac{1}{z+4} \right) - \frac{34}{z+4} + 6 \quad \text{.....(4)}$$

$$E_3 = 10.3 * (\text{CBR}) \text{ for unit of } E_3 \text{ in MPa} \quad \text{... (5a)}$$

$$E_3 = 1500 * (\text{CBR}) \text{ for unit of } E_3 \text{ in psi} \quad \text{... (5b)}$$

$$E_2 = 10.447 (h_1^{-0.471}) (h_2^{-0.041}) (E_1^{-0.139}) (E_3^{0.287}) (k_1^{0.868}) \quad \text{.....(6)}$$

In addition to the moduli of pavement layers, it also requires the Poisson's ratio of each layers. The Poisson's ratio are not sensitive to the strains. In this particular analysis, the Poisson's ratio for surface and base course are 0.40 while for subgrade is 0.45.

EALF is the ratio of number of load repetitions of standard axle to the non standard axle. Once the number of load repetitions are obtained for both standard axle (single axle dual wheels) and non standard load (trailer with 10 axles and 80 tires), the EALF of that particular non standard axle load can be calculated. There are 27 combinations of pavement structure analyzed. The combinations are shown on Table 1.

There are two load levels applied to every pavement structure. For standard axle load, the 80 kN is distributed equally to the four tires. The contact pressure with uniform and circle shape of tires to pavement surface is 483 kPa. The distance of dual wheels is 345 mm (center to center). Configuration of trailer tires is shown on Figure 2. The maximum load of concrete segment is 158 tons. In this analysis, total weight of loaded trailer is assumed to be 1715 kN (175 tons), and equally distributed to each of 80 tires. The contact pressure of each tires to the pavement surface is 627 kPa, and their shapes are all circles.

Table 1. Combinations of Pavement Structure Analyzed

Thickness of Surface Course (mm)	Surface Course Stiffness Modulus (MPa) ^{*)}	Thickness of Base Course (mm)	Subgrade Resilient Modulus (MPa)
100	3468.2	150	50
150	3565.0	250	100
200	3644.1	350	150

^{*)} Calculated by Eq. 3, with MMAT = 18.6°C

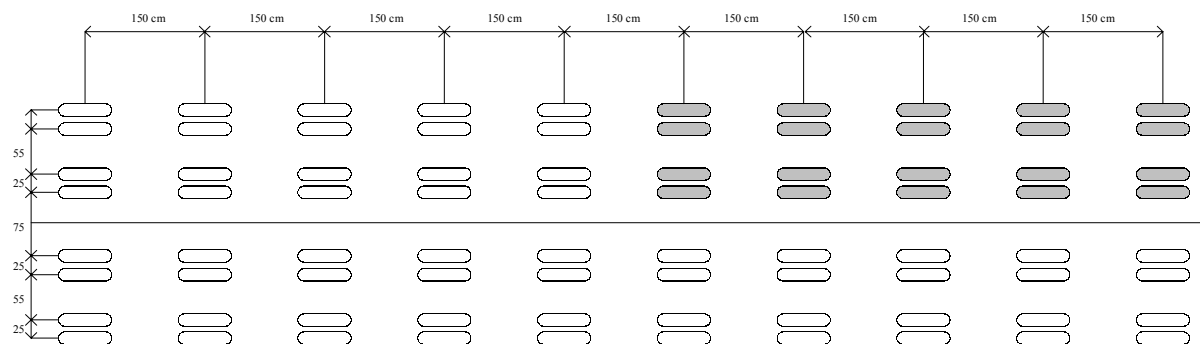


Figure 2. Configuration of Special Trailer with 10 Axles and 80 Tires

5. DETAIL PROCEDURE

The Everstress program is not developed to analyze 80 tires, as it can only handle 20 loaded tires. In order to enable the program to calculate strains due to 80 tires, a quarter system of the trailer is analyzed, i.e. 20 tires (as shown in Figure 2). Strains superposition process from this quarter system is required to obtain strains of the whole system. In the quarter system, there are 20 points evaluated for each of the five axles. The points lined up in a particular axle analyzed. There are additional of 20 points as the mirror of the previous points for the purpose of superposition analysis. Those points are shown in Figure 3.

As an example, it will be describe the process of strains calculation for pavement structure with the thickness of surface and base course is 100 mm and 150 mm respectively, with subgrade resilient modulus of 50 MPa. There are five axles in the quarter system (see Figure 2—the upper right corner). This five axles will be numbered from the left to right as 1st, 2nd, 3rd, 4th, and 5th. For the 1st axle strains evaluation, there are 20 points to be evaluated coincide with the axle, and also 20 additional points as the mirror of them. The results are shown in Table 2. Strain values under X-axis (Positive) are 20 points evaluated under the 1st axle due to the load of 20 tires in the quarter system, while the values under X-axis (Negative) are 20 points as the mirror of the 1st axle. Final horizontal strain ϵ_{xx} at point 1 is 215.35 micro strain as the superposition of 232.43 micro strain (due to the 20 tires in the quarter system), -14.93 micro strain (due to 20 tires on the upper left corner), -0.82 micro strain (due to 20 tires on the lower right corner), and -1.33 micro strain (due to 20 tires on the lower left corner).

The very similar process for other 19 evaluation points, and the results are shown in the last three columns of Table 2. Finally, for the 1st axle, the maximum horizontal tensile strain is 282.18 micro strain, and vertical compressive strain is 783.76 micro strain. These maximum strains are used to calculate maximum number of load repetitions, by using Eq. 1 for fatigue and Eq. 2 for permanent deformation, to determine minimum number of load repetitions to pavement failure. The results are $N_f = 1,008,565$ and $N_d = 109,616$, hence the pavement life is 109,616 of 1st axle repetitions. For standard axle load, the same pavement structure has 67,068 load repetitions. Hence, EALF for the 1st axle is 0.61.

The same procedure is applied to the other 4 axles, i.e. 2nd, 3rd, 4th, and 5th axle and the results are 0.65, 0.77, 0.00, and 0.00 respectively, which are also shown in Table 3. As one passage of this particular trailer, there will be 10 axles passing a particular point of interest, then the total EALFs for one passage of trailer is twice of the sum of each of five EALFs which equal to 4.06. Other trailer's EALFs for the other 26 pavement structures combinations are also calculated. Finally, there are 27 values of trailer's EALFs.

Table 3 shows only six combinations of the pavement structures. In order to make it easier to see the results of all EALF calculations, Figures 4, 5, and 6 are provided. In general, EALF depends on thickness of pavement structures, and subgrade moduli. The range of EALFs are between 3.28 to 78.44. The criterion determined its pavement life depends on subgrade modulus. The table and the rest of calculations (Fung, 2004) shows that failure on pavement with high subgrade modulus (150 MPa) is determined by fatigue cracking. Pavement structure with subgrade modulus of 50 and 100 MPa, its failure is determined by permanent deformation criterion. EALF of pavement which failure is based on fatigue cracking, is lower for thicker pavement structure. Its EALF is higher for thicker pavement structure when permanent deformation criterion governed pavement life. EALF and subgrade modulus has a negative correlation (except for thin pavement structure, i.e. 100 mm surface course), i.e. higher EALF at lower subgrade modulus, no matter what failure criterion governed the pavement life. Pavement with thicker surface course is more sensitive to its EALF value.

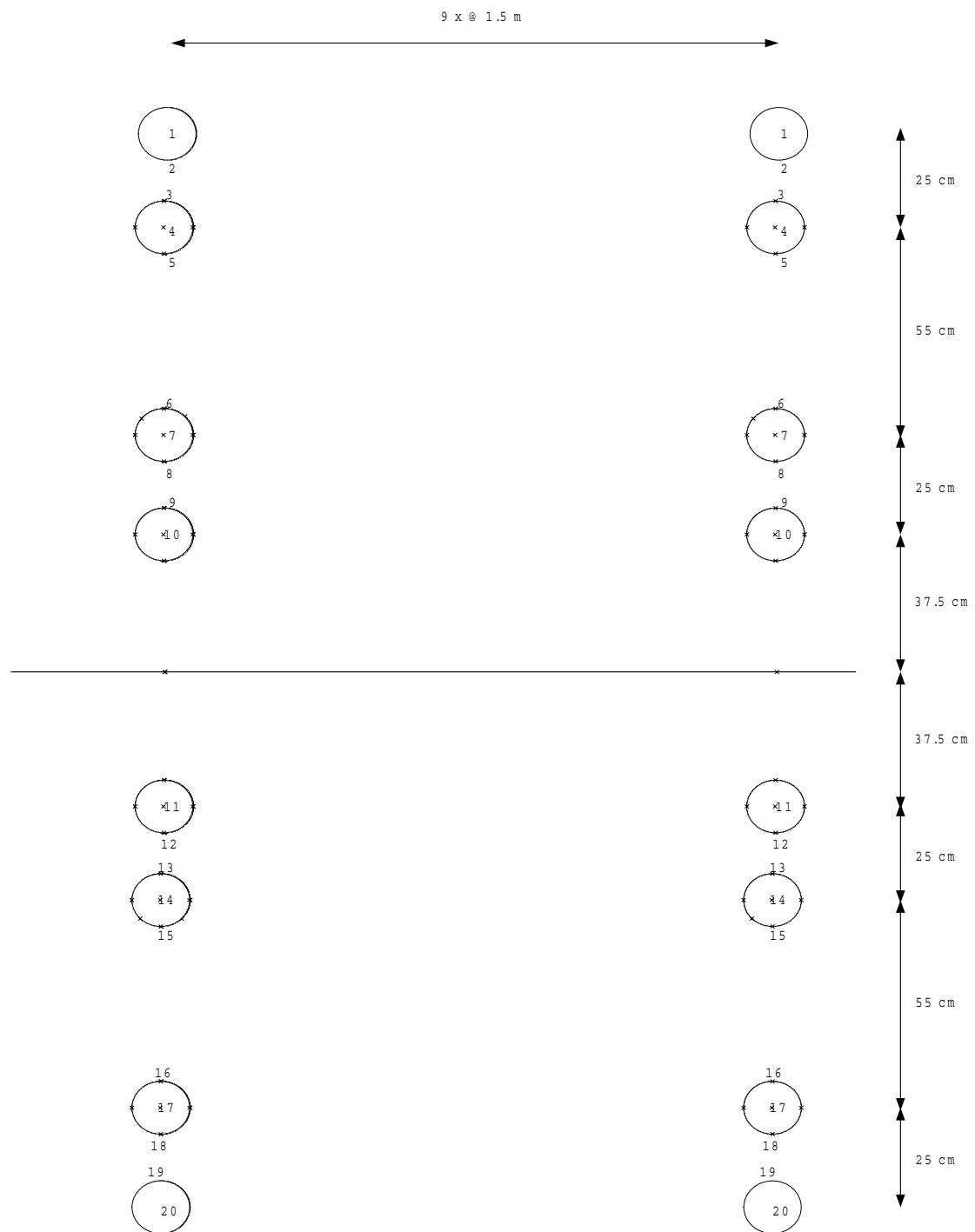


Figure 3. Forty Points for Strains Evaluations

Table 2. Strains Evaluation for 1st Axle

Evaluation Points	X-axis (Positive)			X-axis (Negative)			Total		
	$\epsilon_{xx} (10^{-6})$	$\epsilon_{yy} (10^{-6})$	$\epsilon_{zz} (10^{-6})$	$\epsilon_{xx} (10^{-6})$	$\epsilon_{yy} (10^{-6})$	$\epsilon_{zz} (10^{-6})$	$\epsilon_{xx} (10^{-6})$	$\epsilon_{yy} (10^{-6})$	$\epsilon_{zz} (10^{-6})$
1	232.43	-11.56	-768.3	-14.93	2.3	36.26	215.35	-15.79	-710.61
2	168.99	-100.46	-643.5	-15.1	2.38	36.52	151.72	-105.27	-583.2
3	161.22	-107.36	-625.46	-15.12	2.39	36.55	143.91	-112.55	-563.78
4	192.37	-75.71	-693.36	-15.04	2.35	36.43	175.13	-81.78	-628.89
5	278.33	97.74	-851.28	-14.79	2.24	36.04	261.31	90.56	-783.76
6	297.1	201.22	-845.6	-12.68	1.23	32.89	282.18	187.62	-764.42
7	200.58	18.75	-611.34	-11.8	0.81	31.6	186.6	2.42	-525.28
8	111.16	-64.81	-369.7	-10.84	0.35	30.17	98.24	-84.39	-278.39
9	82.73	-73.98	-268.87	-10.33	0.11	29.38	70.42	-95.46	-174.81
10	48.39	-75.23	-126.12	-9.33	-0.35	27.82	37.37	-100.89	-26.87
11	1.86	-23	55.47	-3.55	-2.31	15.96	37.37	-100.89	-26.87
12	1.15	-19.24	50	-3.13	-2.35	14.68	70.42	-95.46	-174.81
13	0.86	-17.57	47.08	-2.94	-2.36	14.06	98.24	-84.39	-278.39
14	0.43	-14.79	41.56	-2.61	-2.35	12.9	186.6	2.42	-525.28
15	0.1	-12.51	36.42	-2.34	-2.32	11.87	282.18	187.62	-764.42
16	-0.55	-7.32	22.55	-1.68	-2.1	8.93	261.31	90.56	-783.76
17	-0.64	-6.4	19.77	-1.56	-2.02	8.27	175.13	-81.78	-628.89
18	-0.73	-5.64	17.46	-1.46	-1.94	7.67	143.91	-112.55	-563.78
19	-0.76	-5.29	16.38	-1.41	-1.9	7.4	151.72	-105.27	-583.2
20	-0.82	-4.71	14.54	-1.33	-1.82	6.89	215.35	-15.79	-710.61
Maximum							282.18	187.62	-783.76

Table 3. Results of Trailer's EALF for Six Different Pavement Structures

Axle Number	$\epsilon_{xx}(10^{-6})$	$\epsilon_{yy}(10^{-6})$	$\epsilon_{zz}(10^{-6})$	N_f	N_d	N	Note	N_{18}	EALF	
									Axle	Trailer
Total Load = 175 tons, $h_1 = 100$ mm, $h_2 = 150$ mm, $E_3 = 50$ MPa										
5	-2.41	-3.19	9.99	infinite	infinite	infinite	N_f	67,068	0.00	4.06
4	-12.93	-1.05	45.21	infinite	infinite	infinite	N_f	67,068	0.00	
3	296.51	186.85	-824.90	856,848	87,177	87,177	N_d	67,068	0.77	
2	253.20	195.47	-793.82	1,440,743	103,533	103,533	N_d	67,068	0.65	
1	282.18	187.62	-783.76	1,008,565	109,616	109,616	N_d	67,068	0.61	
Total Load = 175 tons, $h_1 = 100$ mm, $h_2 = 150$ mm, $E_3 = 100$ MPa										
3	257.52	158.83	-522.09	1,362,720	675,751	675,751	N_d	470,174	0.70	3.61
2	230.28	162.85	-488.33	1,968,794	911,513	911,513	N_d	470,174	0.52	
1	251.01	158.34	-503.66	1,482,526	793,713	793,713	N_d	470,174	0.59	
Total Load = 175 tons, $h_1 = 100$ mm, $h_2 = 150$ mm, $E_3 = 150$ MPa										
3	237.81	145.23	-400.05	1,770,974	2,225,702	1,770,974	N_f	1,640,336	0.93	4.99
2	217.86	147.62	-373.47	2,362,889	3,027,916	2,362,889	N_f	1,640,336	0.69	
1	233.65	144.47	-388.47	1,876,876	2,538,512	1,876,876	N_f	1,640,336	0.87	
Total Load = 175 tons, $h_1 = 100$ mm, $h_2 = 250$ mm, $E_3 = 50$ MPa										
5	-1.61	-3.55	14.97	infinite	infinite	infinite		179,839	0.00	6.20
4	-10.65	-2.08	52.66	infinite	infinite	infinite		179,839	0.00	
3	278.92	172.19	-714.73	1,047,881	165,630	165,630	N_d	179,839	1.09	
2	245.09	178.40	-733.20	1,603,670	147,751	147,751	N_d	179,839	1.22	
1	266.81	172.27	-667.15	1,212,703	225,468	225,468	N_d	179,839	0.80	
Total Load = 175 tons, $h_1 = 100$ mm, $h_2 = 250$ mm, $E_3 = 100$ MPa										
3	249.00	151.52	-416.98	1,522,276	1,848,744	1,522,276	N_f	1,251,619	0.82	4.36
2	225.58	154.50	-403.10	2,107,042	2,151,293	2,107,042	N_f	1,251,619	0.59	
1	243.32	150.67	-393.23	1,642,383	2,403,807	1,642,383	N_f	1,251,619	0.76	
Total Load = 175 tons, $h_1 = 100$ mm, $h_2 = 250$ mm, $E_3 = 150$ MPa										
3	233.72	141.54	-300.20	1,875,026	8,049,428	1,875,026	N_f	2,486,518	1.33	7.20
2	215.47	143.40	-282.50	2,450,245	10,566,303	2,450,245	N_f	2,486,518	1.01	
1	230.01	140.54	-284.96	1,976,410	10,164,011	1,976,410	N_f	2,486,518	1.26	

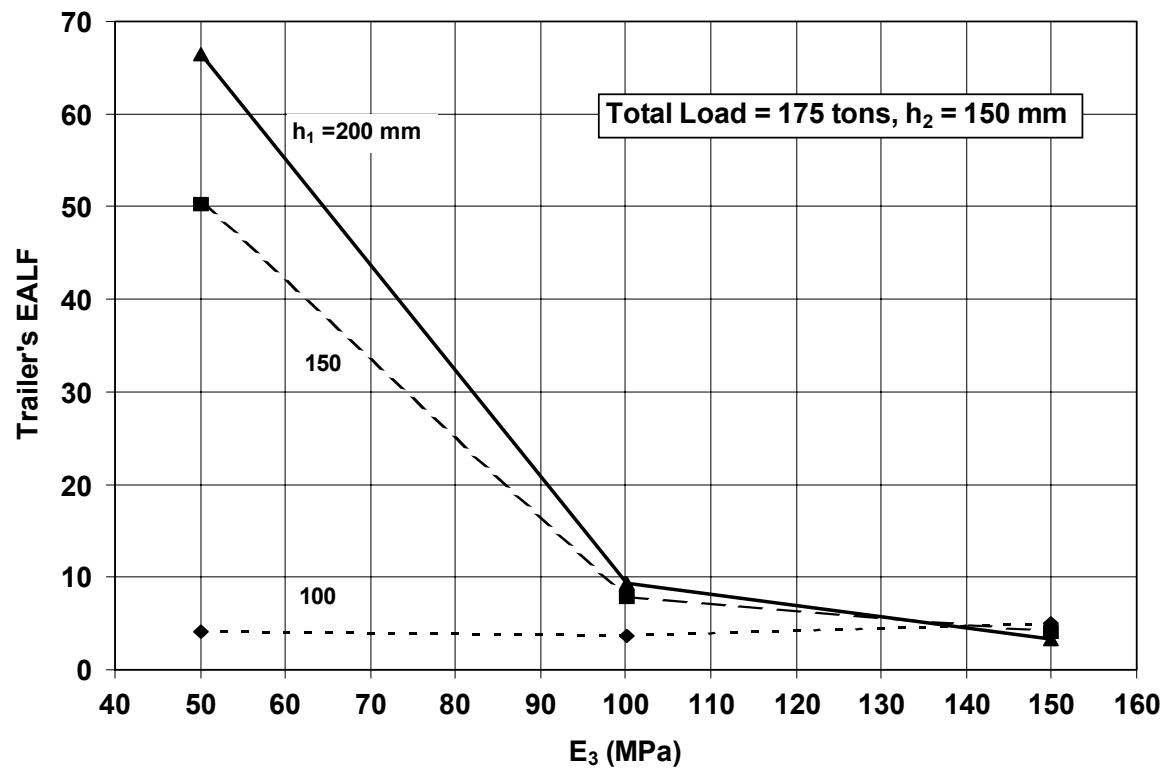


Figure 4. Trailer's EALF at Flexible Pavement with 150 mm Untreated Granular Base Course

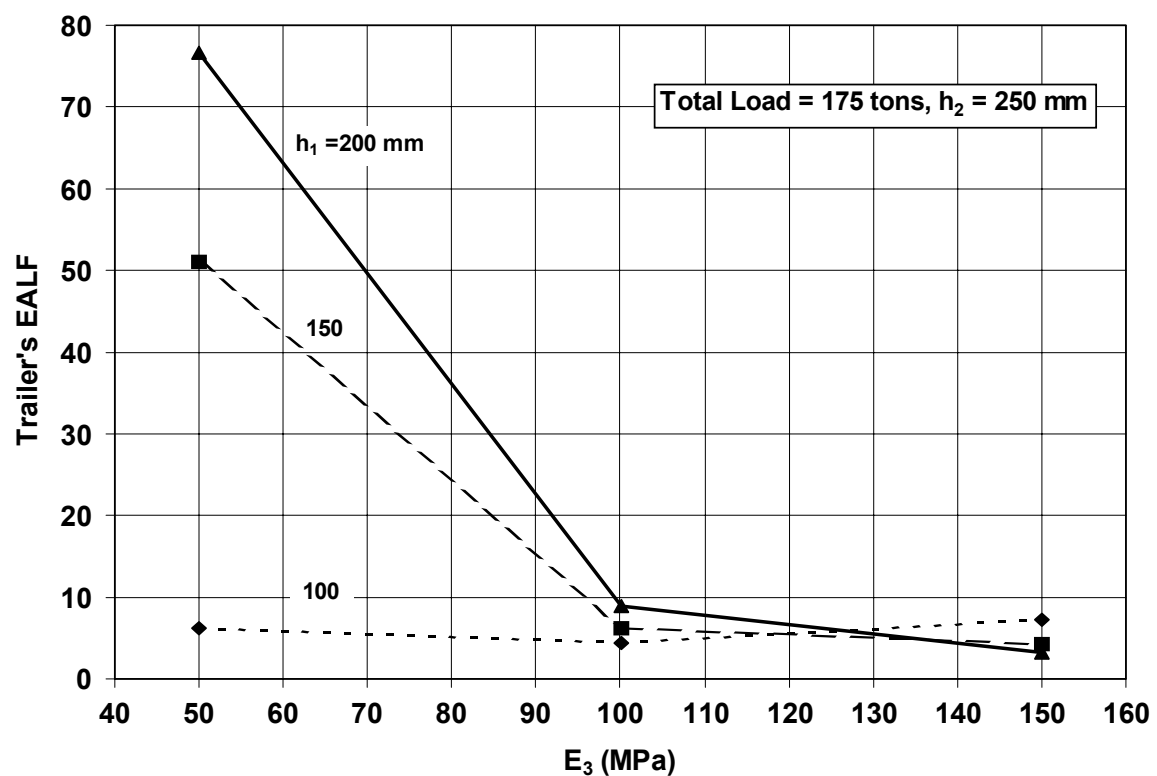


Figure 5. Trailer's EALF at Flexible Pavement with 250 mm Untreated Granular Base Course

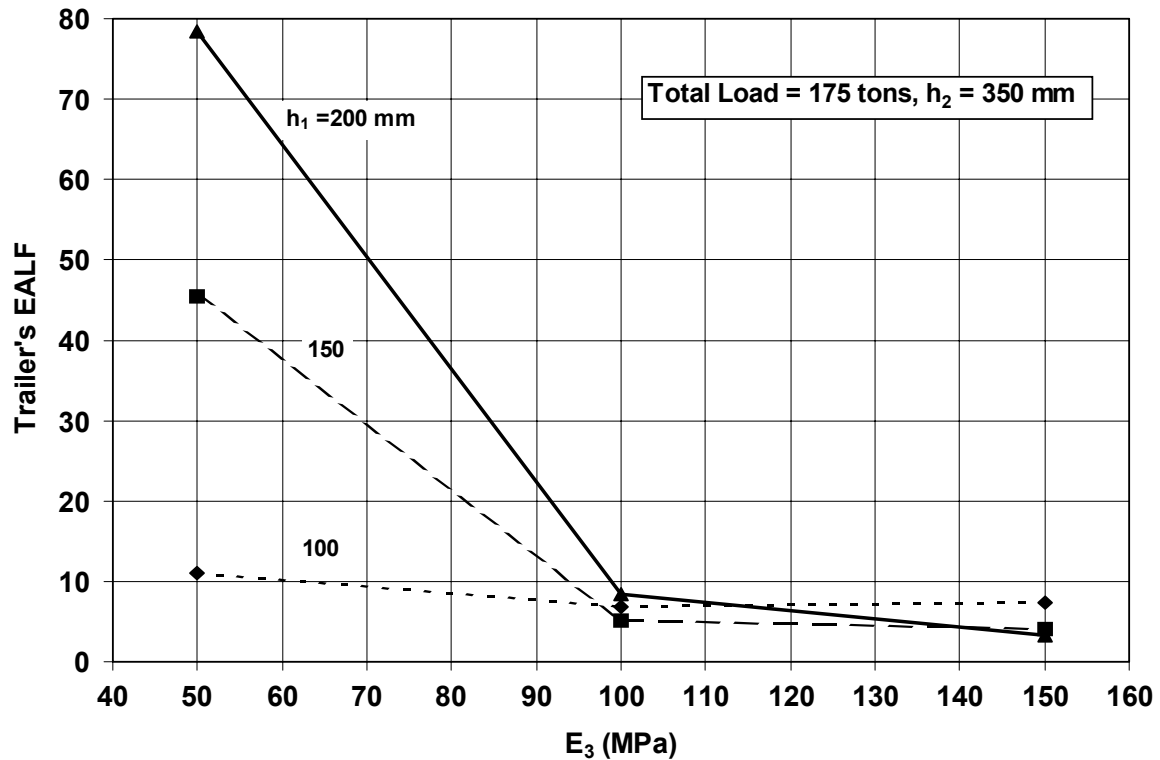


Figure 6. Trailer's EALF at Flexible Pavement with 350 mm Untreated Granular Base Course

6. CONCLUSIONS

- Failure on pavement structure with high subgrade modulus (i.e. 150 MPa), is determined by fatigue criterion, while pavement with lower subgrade modulus (i.e. 50 or 100 MPa) is determined by permanent deformation (rutting).
- Thicker pavement structure will have lower EALF when its failure is based on fatigue cracking, otherwise, its EALF will be higher.
- Figures 4, 5 and 6 show the effect of subgrade modulus to the trailer's EALF. The higher the subgrade modulus, the lower the trailer's EALF. Trailer's EALFs for subgrade modulus of 50 MPa is higher than for subgrade moduli 100 – 150 MPa and extremely true for surface course thickness 150 – 200 mm.
- 175 tons of trailer's EALF depends on thickness of pavement layers and subgrade modulus. Trailer's EALF for the analyzed pavement structures has a range from 3.28 to 78.44.

NOTATIONS

- $\eta_{70^{\circ}\text{F}, 10^6}$ = Absolute viscosity of the bitumen used at 70°F (poises $\times 10^6$). It can be predicted from penetration value = $29508.2 * (\text{pen}_{77^{\circ}\text{F}})^{-2.1939}$. In this case η is 1.52 million poise
- 10^M = Adjustment factor due to mixture characteristics
- CBR = California Bearing Ratio of the subgrade (%)

E_1	=	Stiffness modulus of bituminous mixture (psi)
E_2	=	Resilient Modulus of base layer made of untreated granular material (psi)
E_3	=	Subgrade resilient modulus (psi)
f	=	Loading frequency (Hz). In this case f is 10 Hz
h_1	=	Thickness of surface layer (inch)
h_2	=	Thickness of base layer (inch)
K_1	=	A constant depends on the quality of untreated granular material used. Its value within the range of 4,000 to 9,000
MMAT	=	Mean monthly air temperature ($^{\circ}$ F)
MMPT	=	Mean monthly pavement temperature ($^{\circ}$ F) and equal to t_p
N_d	=	The total number of load repetitions to produce rut depth on the wheel tracks
N_f	=	Total number of load repetition to produce at least 20 percent fatigue cracking on the surface of pavement
P_{200}	=	The percentage in weight of aggregate passing sieve number 200 to the total mix. In this case P_{200} is 5%.
P_{ac}	=	The percentage in weight of bitumen to total mix (%). P_{ac} can be calculated as $P_{ac} = 0.483 V_{be}$ or $P_{ac} = 0.434 V_b$
t_p	=	Average temperature of surface layer ($^{\circ}$ F) and equal to MMPT
V_b	=	The percentage of volume of bitumen to the total volume of the mixture. In this case V_b is 11%
V_{be}	=	The percentage in volume of effective bitumen to total mix (%)
V_v	=	The percentage of voids volume to total volume of the mixture. In this case V_v is 4%.
Z	=	The position where the average temperature of surface layer, $1/3h_1$ (in)
ϵ_c	=	Vertical compression strain at the surface of subgrade layer
ϵ_t	=	Maximum horizontal strain at the bottom of surface layer due to a particular load level

REFERENCES

- AASHTO (1993) **AASHTO Guide for Design of Pavement Structures**. American Association of State Highway and Transportation Officials, Washington, DC
- Asphalt Institute (1982) **Research and Development of The Asphalt Institute's Thickness Design Manual (MS-1) 9th Edition**. The Asphalt Institute, College Park, MA.
- Asphalt Institute. 1991. Thickness Design – Asphalt Pavements for Highways and Streets, **Manual Series No. 1**. Lexington, KY.
- Austrroads (1992) **Pavement Design – A Guide to the Structural Design of Road Pavements**. Austrroads, Sydney, Australia.
- Fung, C. (2004) Angka Ekuivalen Kendaraan dengan 10 Sumbu dan 80 Roda Pada Proyek Pasupati Bandung. **Undergraduate Thesis**. Fakultas Teknik Program Studi Teknik Sipil, Universitas Katolik Parahyangan. Bandung.
- Finn, F.N., C. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah (1977) The Use of Distress Prediction Subsystems for the Design of Pavement Structures, **Proceedings of Fourth International Conference on the Structural Design of Asphalt Pavements – Vol. I**. University of Michigan, Ann Arbor, MI.
- Shell (1978) **Shell Pavement Design Manual – Asphalt Pavements and Overlays for Road Traffic**. Shell International Petroleum Company Limited, London, UK.

- SNI (1989) Petunjuk Perencanaan Tebal Perkerasan Lentur Jalan Raya dengan Metode Analisa Komponen. **SNI-No. 1732-1989F**. Departemen Pekerjaan Umum, Jakarta, Indonesia.
- Witczak, M.W. and B.E. Smith. 1981. Prediction of Equivalent Granular Base Moduli Incorporating Stress Dependent Behavior in Flexible Pavements, **Journal of Transportation**. American Society of Civil Engineers.