THE EFFECT OF DIFFERENT UNTREATED GRANULAR MATERIALS AS BASE COURSE TO THE PAVEMENT LIFE

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Abstract: In mechanistic empirical pavement design method, there are two criteria determined pavement failure, i.e. rut depth and area of cracks. Tensile strain at the bottom of surface course predicts number of load repetitions to reach the limit of area of cracks. Vertical compressive strain on the surface of subgrade indicates number load repetitions to make a particular ruth depth. When modulus of surface course and subgrade are constant, the quality of aggregate base influences both strains. As these strains determines the pavement life, it is possible to investigate the effect of quality of the aggregates on the pavement life.

Poor quality aggregates performs better for thin pavement. Pavement with 150mm surface course, and 200-250mm base course, a poor or moderate quality of subgrade outperforms the performance of good quality subgrade. For pavement with fatigue criterion governs the pavement life, improving the quality of aggregates increases pavement life significantly. The rate of pavement life increament due to the improvement of subgrade quality is higher on pavement structures governed by rutting criterion.

Key Words: mechanistic empiric, flexible pavement, granular material

1. INTRODUCTION

Flexible pavements are the most common pavement structures. Asphalt as a viscoelastic material bind matrix of aggregates to make asphalt mixtures of having viscoelastic properties as well. This mixture is used as surface course. For stress and strain analysis purposes, quasi static approach for the asphalt mixture is used. Base course of the flexible pavement structure is untreated granular material. Resilient modulus of the untreated granular material depends on the state of the stress within the layer, in addition to type of gradation and surface texture of the aggregates.

The effect of three different qualities of untreated granular materials to the pavement life is analysed, i.e. well graded crushed aggregates, partially crushed aggregates, and gravel. The life of pavement in terms of number of standard axle load repetitions is determined based on two pavement failure criteria. The first criterion is fatigue life with apparent cracks on the surface course, and secondly is permanent deformation on both of the wheel tracks (rutting).

Based on this research, pavement designers can determine the quality of untreated granular base course to be used for their particular projects.

2. MECHANISTIC EMPIRICAL APPROACH

There are many pavement design manuals available such as AASHTO (1993) as an improvement of preceeding design guides (AASHTO, 1972, and 1986) still consistent with the empirical approach. Other pavement design manuals use mechanistic empirical approach, such as The Asphalt Institute (1991), Shell (1978), in addition to many other studies such as ILLI-PAVE (Raad and Figueroa, 1980), MICH-PAVE (Harichandran, et al., 1989). Empirical method is easier to use, however its application is limited to the same conditions as where the empirical method is obtained. On the other hand mechanistic empirical approach is easier to understand the mechanism of how pavement fails under traffic load. This approach also enables to incorporate various new pavement materials (such as man made materials, and additives to improve asphalt properties) into pavement design.

Loads on the surface distribute stresses and strains to the pavement layers. There are two kind of strains become the interest in pavement life analysis, i.e. horizontal tensile strain at the bottom of surface layer made of asphalt mixture, and vertical compressive strain at the upper subgrade layer. The tensile strain predicts number of load applications to cause crack on the surface, while vertical compressive strain predicts number of load applications to cause rutting on the wheel tracks. Criteria of pavement failure are: (a) minimum percentage of area with cracks, and (b) minimum rut depth. When either one of these criteria is met (the minimum value is exceeded), the minimum number of load applications for that particular criterion is specified as the pavement life.

3. PAVEMENT LIFE CRITERIA

There are lots of research publications on relationships between strains and number of load applications. In this analysis, the Asphalt Institute's is used. The relationship between tensile strain and fatigue life used for this analysis is based on Finn, et al. (1977), and was modified to accommodate the effect of various asphalt content and air voids after Pell and Cooper (1975) and Epps (1968), as follows:

$$N_f = 18.4\left(10^{4.84*\left(\frac{V_b}{V_b+V_v}\right)-0.69}\right)\left(4.325*10^{-3}\right)\varepsilon_t^{-3.291}E^{-0.854} \qquad \text{............ [1]}$$

where:

N_f = number of load repetitions to have ≥20% of cracks on surface
V_b = percentage of asphalt volume
V_v = percentage of air voids
ε_t = tensile strain at the bottom of asphalt mixture in surface course
E = absolute value dynamic modulus of asphalt mixture in the surface course [psi]

The prediction of rut depth is entirely based on the vertical compressive strain at the upper layer of subgrade, as being used in the Asphalt Institute (1982).

$$N_d = 1.365*10^{-9}\varepsilon_c^{-4.477} \qquad \text{............ [2]}$$

N_d = number of load applications to cause rut depth of ½" on the wheel track
ε_c = vertical compressive strain on the upper subgrade layer

4. TRAFFIC AND PAVEMENT MODELING

In the analysis of strains in the pavement structures, traffic load is converted into standard axle load. Standard axle load is specified as an 80 kN (18 kips) single axle load dual wheel (with a separation of 345mm) with a uniform and circular contact pressure of 517 kPa (75 psi) for each wheel. No horizontal load is considered.

Pavement structure is modeled of asphalt mixture as surface course, untreatred granular materials as base course, and sugrade course on the bottom. The thickness of pavement structures is varied. Each pavement structure is numerically analysed to obtain number of load applications until failure criteria is met. Strains in the pavement structure are evaluated with assumption that all of pavement materials are homogeneous, isotropic, and linear elastic. For this purpose a computer program ELSYM5 is used.

The modulus of asphalt mixture as a viscoelastic material depends on temperature and time of loading. The temperature of asphalt layer is predicted from mean monthly air temperture (Witczak, 1972). The effect of moving load is taken into account as frequency of loading in Hz. Prediction of absolute value of dynamic modulus of asphalt mixture is obtained from regression analysis of actual test data (AI, 1982), as the following:

$$\log E = 5.553833 + 0.028829\left(\frac{P_{200}}{f^{0.17033}}\right) - 0.03476(V_v) + 0.070377(\eta_{70F,10^6})$$
$$+ 0.000005\left[t_p^{1.3+0.49825\log f}\sqrt{P_{ac}}\right] - 0.00189\left[t_p^{1.3+0.49825\log f}\frac{\sqrt{P_{ac}}}{f^{1.1}}\right] + 0.931757(f^{-0.02774}) \quad \text{..........} [3]$$

where:

E = absolute dynamic modulus of asphalt mixture [psi]

P_{200} = percentage by weight of aggregate passing #200

f = load frequency [Hz]

P_{ac} = percentage by weight of asphalt, it also can be predicted from percentage by volume of asphalt as 0.434 V_b

t_p = temperature of asphalt mixture being analysed [F].

$\eta_{70F,10^6}$ = absolute viscosity of asphalt used in the mixture at 70°F [poises x10^6]. It is predicted from penetration test at 25°C by using the relationship as 29508.2(pen$^{-2.1939}$)

Temperature of asphalt layer depends on the air temperature. Witczak (1972) developed a relationship between mean monthly air temperature (MMAT) and asphalt layer thickness as the following:

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

where:

z = depth below pavement surface [in]. In the analysis, the average temperature of surface layer is at $^1/_3$ of surface layer thickness.

Resilient modulus of untreated granular base depends on the state of the stress of the material. Several models used to predict this parameter, such as a function of bulk stress, confining pressure, deviator stress, or Nataatmadja (1992) with two parameter model involves the first invariant of stress and the repeated deviator stress. It is required to make iterative calculations in order to predict the resilient modulus. Rada and Witczak. (1981) analysed resilient modulus of untreated granular base with bulk stress model. Their analysis shows that the prediction of resilient modulus can be obtain from a simple relationship as the following, to avoid an iterative solution.

$$E_2 = 10.447 h_1^{-0.471} h_2^{0.041} E_1^{-0.139} E_3^{0.287} k^{0.868} \qquad \text{............ [5]}$$

where:

E_2 = resilient modulus of untreated granular base course [psi]
h_1 = surface course thickness [in]
h_2 = base course thickness [in]
E_1 = absolute dynamic modulus of surface course [psi]
E_3 = subgrade modulus [psi]
k = a constant, which depends on the quality of granular material, with a range of k between 1600 to 9000 (according to Hicks,1970; Hicks and Finn, 1970; Allen, 1973; Kalcheff, 1973; Boyce, et al., 1976; Monismith, et al., 1972). Densed crushed aggregate has higher k value compare to the uniform and rounded shape.

5. PAVEMENT STRUCTURE ANALYSED

a. Characteristics of asphalt concrete mixture:

P_{200}	5
V_v	4
V_b	11
pen at 25°C	65

b. Characteristics of untreated granular base material:

Type of Granular Material	k
crushed stone/well graded crushed lime stone	8000
partially crushed aggregate	5000
gravel	2500

c. Typical pavement thickness:

	h_2 [mm]			
h1 [mm]	150	200	250	500
100	x	x	x	x
150	x	x	x	x

d. Modulus of subgrade, E_3 [MPa] are 30, 50, 70, 90, and 110

e. Dynamic modulus of asphalt mixture:

Load frequency which represents a moderate rate of speed as used in AI (1982)	10 Hz
Temperature of asphalt mixture is calculated based on MMAT of [°C]	25

Total pavement structure analyzed is 120. Tensile and compressive strains are evaluated. For each pavement structure, there are three positions evaluated for each tensile strain and compressive strain. The depth of tensile strain evaluations is the same as the surface course thickness. While the depth of compressive strain evaluations is the total thickness of surface and base courses. There are three horizontal positions for both strains, i.e. first, at the center one circular contact pressure; secondly, at mid point between the wheel loads; and finally, at the edge closest to mid point.

The maximum tensile strain from each pavement structure is substituted to equation 1 to obtain fatigue life. The same token is used for compressive strain, by using equation 2 to obtain number of load applications until it causes rut depth of ½". The minimum number load applications is the pavement life. The results are shown on Table 1 and 2 for pavement surface course of 100mm, and 150mm respectively.

The tables also indicate type of failure of the pavement. The figures in bold are for pavement life governed by fatigue, and the others are due to rutting criterion. These tables also show the ratio of number of load repetitions for various quality of granular material to the best base course (i.e. well graded crushed aggregates).

Table 1. Number of Load Repetitions for Different Untreated Granular Base Material with h_1=100mm

	N		N		N		N		N	
k	E_3=30 MPa	%	E_3=50 MPa	%	E_3=70 MPa	%	E_3=90 MPa	%	E_3=110 MPa	%
					h_1=100mm, h_2=150mm					
8000	10,993	100	42,794	100	111,361	100	236,611	100	442,063	100
5000	8,164	74	33,700	79	93,037	84	205,652	87	396,854	90
2500	7,197	65	33,700	79	99,442	89	233,427	99	**381,947**	**86**
					h_1=100mm, h_2=200mm					
8000	19,696	100	77,857	100	202,970	100	428,530	100	798,386	100
5000	13,560	69	56,170	72	155,382	77	341,662	80	659,143	83
2500	10,625	54	50,063	64	149,753	74	**324,383**	**76**	**366,382**	**46**
					h_1=100mm, h_2=250mm					
8000	37,156	100	141,769	100	367,995	100	770,570	100	1,424,220	100
5000	23,079	62	95,643	67	264,089	72	581,040	75	**766,764**	**54**
2500	16,279	44	77,857	55	235,012	64	**319,266**	**41**	**357,438**	**25**
					h_1=100mm, h_2=500mm					
8000	699,968	100	**1,050,351**	**100**	**1,251,735**	**100**	**1,432,435**	**100**	**1,606,355**	**100**
5000	334,215	48	**533,762**	**51**	**633,460**	**51**	**713,742**	**50**	**791,060**	**49**
2500	163,295	23	**232,469**	**22**	**271,393**	**22**	**302,166**	**21**	**332,260**	**21**

Note: 1. Figures in bolds are due to fatigue criterion, others are due to permanent deformation
2. Percentage of number of load repetitions for various granular base material compared to the well graded crushed aggregates (k=8000)

Table 2. Number of Load Repetitions for Different Untreated Granular Base Material with h_1=150mm

	N		N		N		N		N	
k	E_3=30 MPa	%	E_3=50 MPa	%	E_3=70 MPa	%	E_3=90 MPa	%	E_3=110 MPa	%
h_1=150mm, h_2=150mm										
8000	72,341	100	246,485	100	595,714	100	1,191,148	100	2,129,920	100
5000	66,610	92	241,486	98	610,844	103	1,275,795	107	**2,086,915**	**98**
2500	77,446	107	317,598	129	865,600	145	1,192,564	100	**1,364,040**	**64**
h_1=150mm, h_2=200mm										
8000	108,843	100	379,220	100	931,241	100	1,888,562	100	**3,238,592**	**100**
5000	93,551	86	351,909	93	905,935	97	**1,841,228**	**97**	**2,116,795**	**65**
2500	102,846	94	438,631	116	**978,928**	**105**	**1,150,732**	**61**	**1,298,178**	**40**
h_1=150mm, h_2=250mm										
8000	170,627	100	605,749	100	1,498,640	100	**2,942,553**	**100**	**3,401,230**	100
5000	137,559	81	530,881	88	1,395,723	93	**1,892,423**	**64**	**2,147,234**	**63**
2500	141,769	83	626,447	103	**967,976**	**65**	**1,110,793**	**38**	**1,251,480**	**37**
h_1=150mm, h_2=500mm										
8000	1,752,301	100	**2,523,040**	**100**	**2,989,368**	**100**	**3,401,230**	**100**	**3,696,765**	**100**
5000	1,092,174	62	**1,490,170**	**59**	**1,744,135**	**58**	**1,972,751**	**58**	**2,178,247**	**59**
2500	**641,594**	**37**	**803,997**	**32**	**925,730**	**31**	**1,024,389**	**30**	**1,110,793**	**30**

Note: 1. Figures in bolds are due to fatigue criterion, others are due to permanent deformation

2. Percentage of number of load repetitions for various granular base material compared to the well graded crushed aggregates (k=8000)

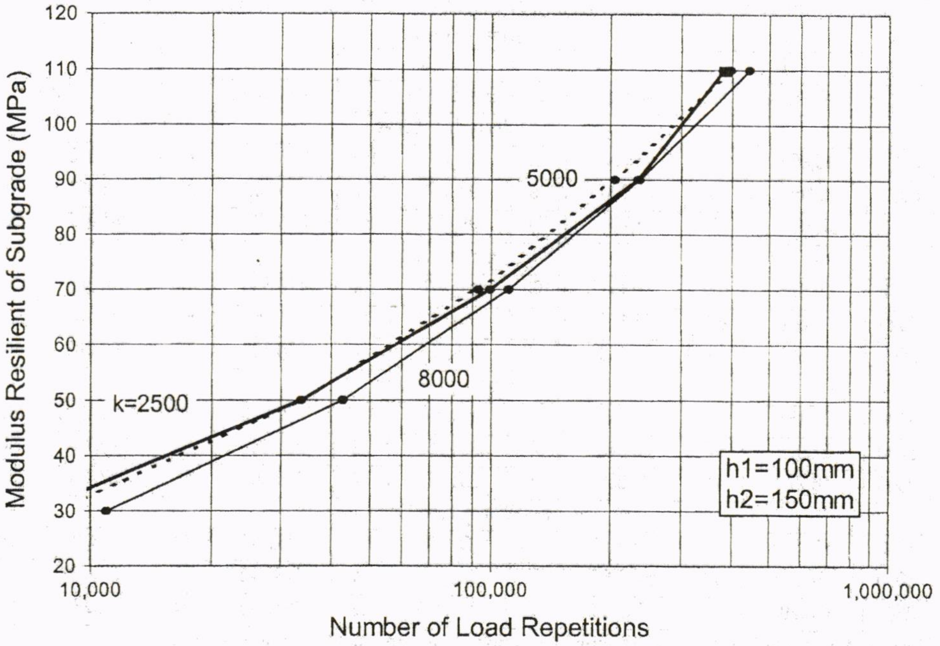

Figure 1. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=100mm and h_2=150mm

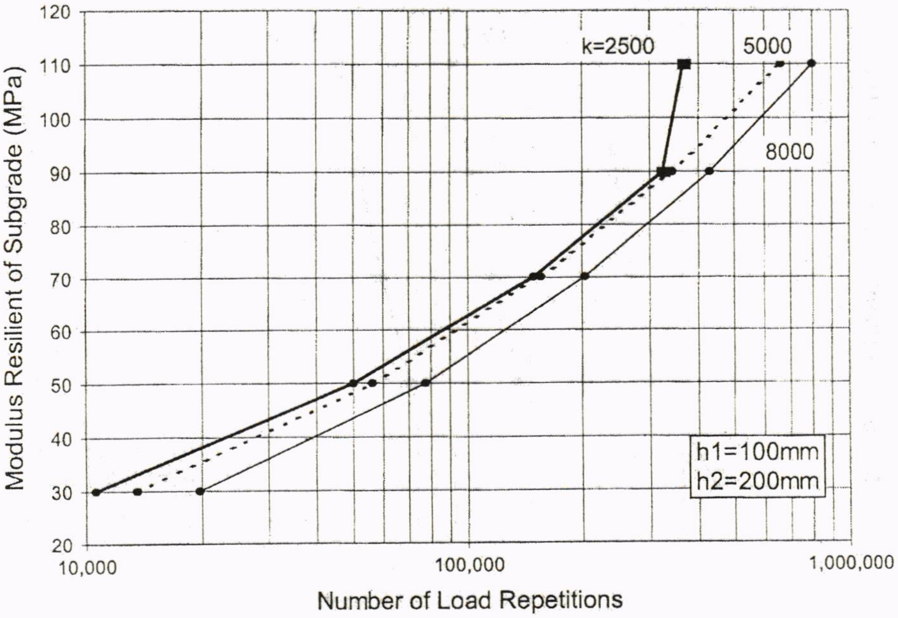

Figure 2. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=100mm and h_2=200mm

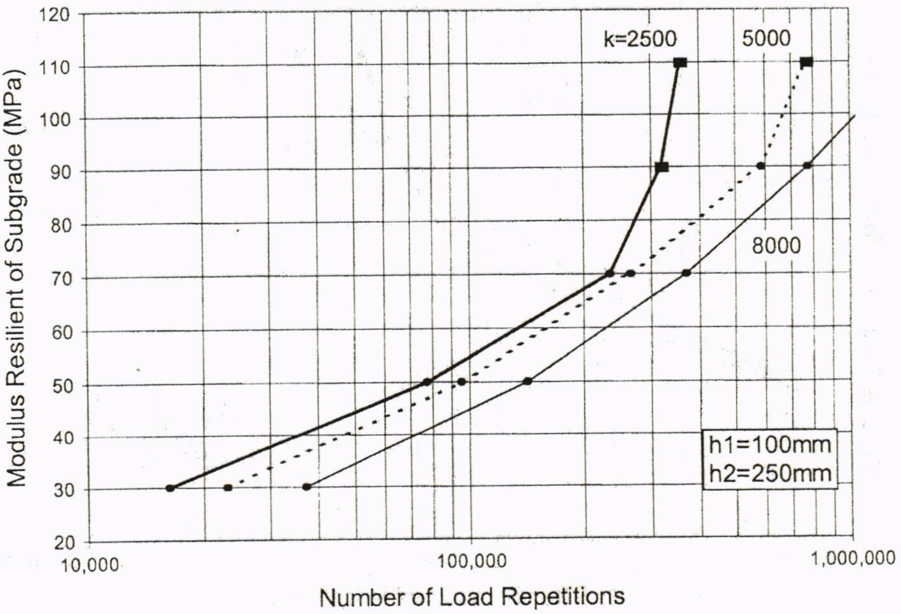

Figure 3. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=100mm and h_2=250mm

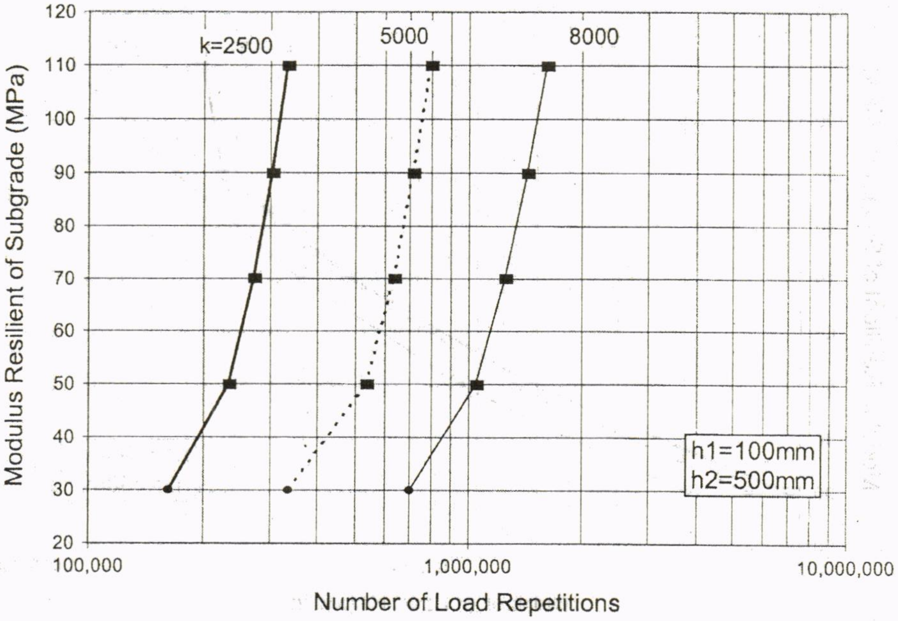

Figure 4. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=100mm and h_2=500mm

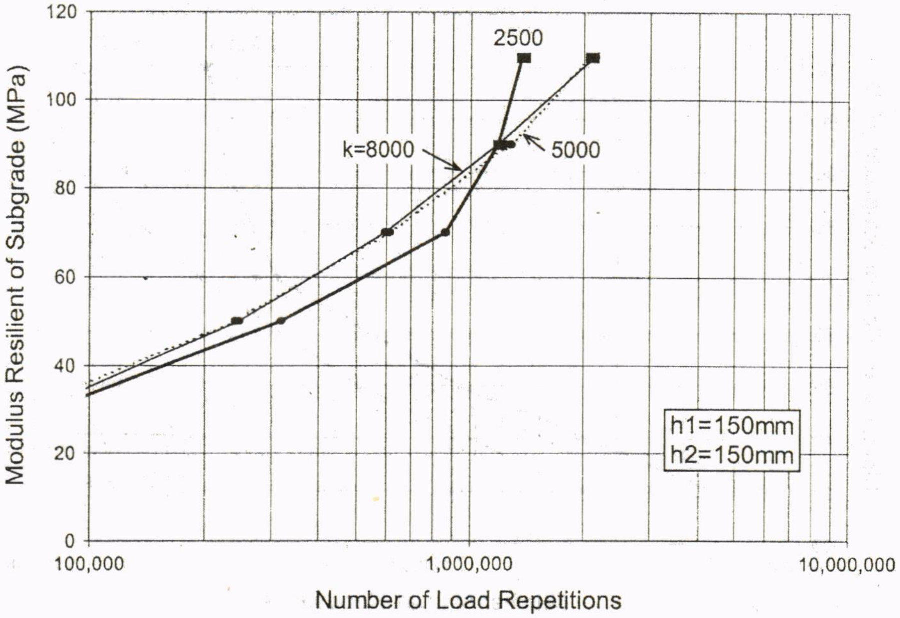

Figure 5. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=150mm and h_2=150mm

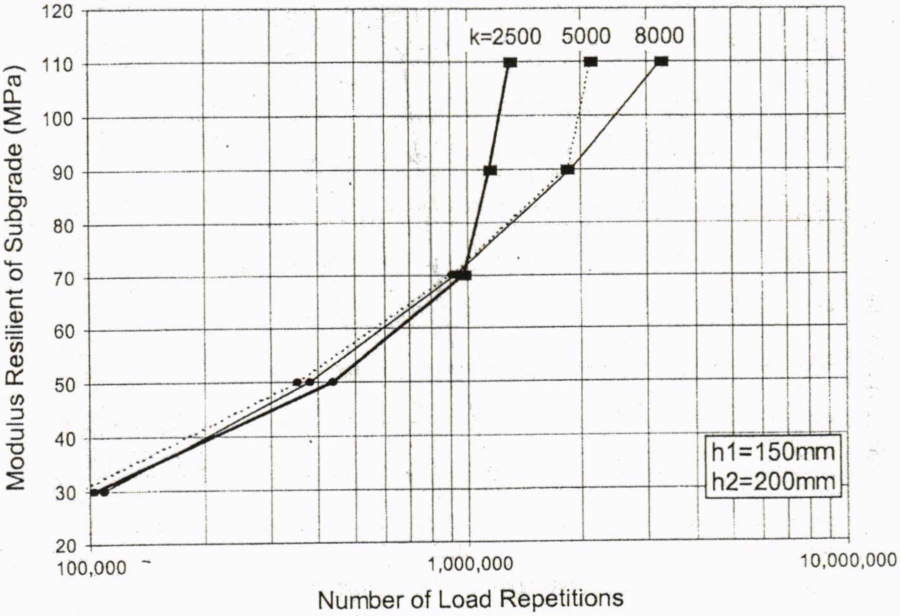

Figure 6. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=150mm and h_2=200mm

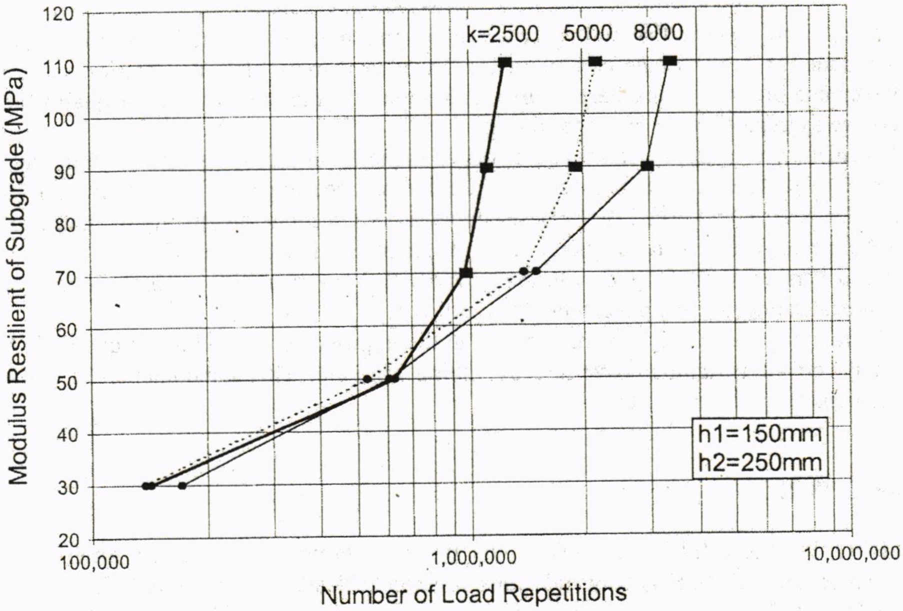

Figure 7. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=150mm and h_2=250mm

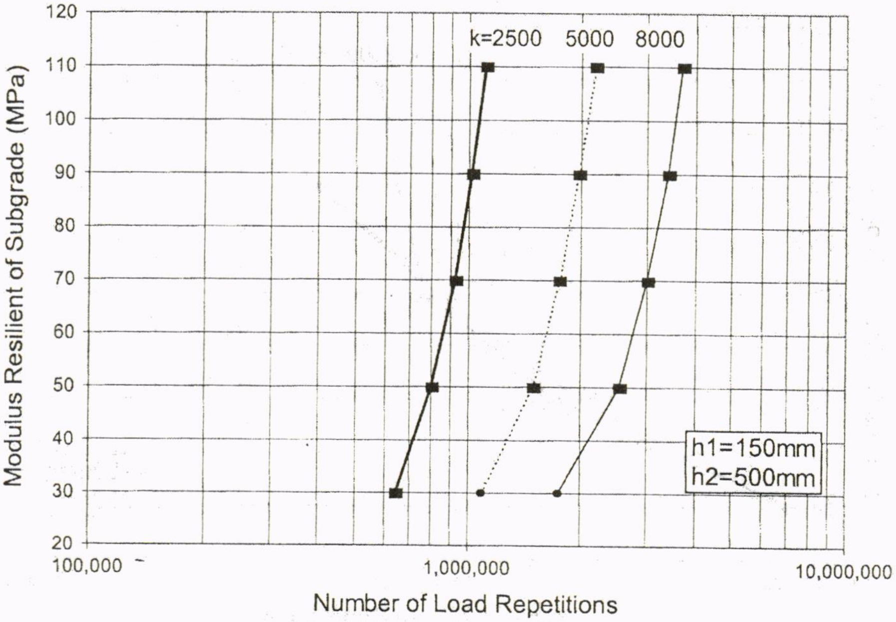

Figure 8. The Effect of Various Untreated Granular Material Base at Flexible Pavement with h_1=150mm and h_2=500mm

6. CONCLUSIONS

a. Table 1 and 2 show that rutting criterion governs thin base courses and poor quality of subgrade, as one extreme condition. On the other extreme, fatigue criterion governs the pavement life with thick base course, and good subgrade quality. Good quality of base course aggregates more prone to rutting.

b. Pavement life of poor quality aggregates is higher than the better one for thin pavement (100mm surface course, and 150mm base course), see Figure 1. Pavement with 150mm surface course, and 200-250mm base course, a poor or moderate quality of subgrade has a better performance than the good quality subgrade. See Figures 6 and 7.

c. For pavement with fatigue criterion governs the pavement life, using a better quality aggregates improve the pavement life significantly.

d. The rate of pavement life increment due to the improvement of subgrade quality is higher on pavement structures governed by rutting criterion. This phenomenon is shown on gradient of the Figures 1 to 8.

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