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Review

Effect of stiffness modulus and dynamic loading on pavement subgrade

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An optimum pavement structure design requires characterization of materials under traffic loading. Investigation of stress-strain relationship of materials, under traffic loading is advised to determine the appropriate stiffness modulus. Since stiffness modulus is extensively dependent to loading dynamics, the loading parameters in the laboratory testing condition should simulate the field condition as close as possible. In this paper, the importance of accurate determination of stiffness modulus was discussed. Significant loading parameters including loading waveform, loading time, and rest time were expressed in subgrade layer. It was demonstrated that for subgrade layer; haversine loading waveform can better present what practically occurs in the field compared to the square waveform. Furthermore, for this layer, the effect of loading time is intensified due to the increase in depth and decrease in the quality of materials. In addition, because of elasto-plastic nature of subgrade material, the rest period should be considered in determination of stiffness modulus.

Key words: Stiffness modulus, dynamic loading, subgrade layer.

INTRODUCTION

Subgrade is the foundation layer for supporting highways. Stiffness of this layer is a crucial parameter as it upholds the traffic loadings. Studies conducted on pavements structural design indicated that the input value of stiffness modulus has a dramatic influence on the determined thickness for the subbase, base course, and asphalt layer. Furthermore, numerous studies have indicated that many cases of fatigue or rutting failures refer to inadequate stiffness of soil layers (Jegede, 2000; Xu and Huang, 2011; Cardone et al., 2011; Mulungye et al., 2007; Wright and Paquette, 1987; Barksdale and Itani, 1989; Zakaria and Leest, 1996; Van Zyl and Maree, 1983; Giroud and Han, 2004).

One of the influential parameters on stiffness modulus is dynamic loading characteristics. In investigating the stiffness modulus, dynamic loading components including loading waveform, loading time and rest period should be taken into account.

IMPORTANCE OF STIFFNESS MODULUS OF SUBGRADE

Determination of pavement layer thickness is governed by the stiffness of subgrade and granular layers, thus information on the stiffness modulus of subgrade and granular layers is required before designing any pavement. These parameters are necessary to determine

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the thickness of the pavement layers in order to achieve an optimum economic design. If the stiffness value of base, subbase and subgrade layers is high, it means that these layers have higher stress distribution ability. Accordingly, the required thickness of pavement can be reduced using the stiffer layers. Thus, it gives a considerable cost saving in terms of construction beside the optimum design. In this paper the main focus is on subgrade layer.

Barksdale and Itani (1989) indicated that uncrushed gravels have a lower stiffness modulus than crushed stones making them more susceptible to rutting. In addition, Zakaria and Leest (1996) reported that pavement strain is strongly dependent on aggregate type, fines content, moisture content, compaction and load applications.

Giroud and Han (2004) stated that, bearing capacity failure of the base course or subgrade after repeated traffic loads is the main cause of surface rutting. Xu and Huang (2011) concluded that most rutting is related to the weakness in the middle and lower layers. In addition, in the Mechanistic-Empirical Pavement Design Guide (M-EPDG) the total rut depth in the pavement structure is equal to the sum of rut depths in each layer and the rutting of underlying layers should not be overlooked. Consequently, Jegede (2000) stated that stabilization could improve the California Bearing Ratio (CBR) when facing poor soil properties. This concurs with Van Zyl and Maree (1983) conclusion that increasing density (that is, increased stiffness) significantly reduces plastic deformation. In terms of fatigue failure, Mulungye et al. (2007) stated that even in weak soil layers, fatigue cracking occurred before rutting. Based on the studies done by Cardone et al. (2011), the stiffness of the soil and granular layer must be sufficiently high to avoid fatigue cracking. Finally, a critical overview of the literature indicates the significance of using appropriate stiffness for underlying layers including subgrade.

NECESSITY OF USING STIFFNESS MODULUS FOR DESIGN

Currently, flexible pavements are designed generally based on static properties such as CBR and soil support values. These methods are unable to represent the real response of pavement layers under traffic loading, since they are based on static conditions which are different from actual conditions (dynamic loading). Stochastic dynamic loads are assumed to increase pavement damage about 20 to 30% more than static loads (Divne, 1998; Cebon, 1998; Yongjie et al., 2010). Although, researchers have long been aware of the effect of dynamic loading on road damage (Gillespie, 1992; Lu and Xueju, 1996) the actual pavement design was limited to static loading based on the experience. Recognizing this deficiency, engineers are recommended to use stiffness modulus for design and characterizing the pavement layers (M-EPDG guide and AASHTO, 2002).

DYNAMIC AXIAL LOADING AND MECHANISTIC-EMPIRICAL METHOD

Mechanistic-Empirical (M-E) methods have been used for pavement structural design and analysis since early 1960s. Development of the Mechanistic-Empirical Pavement Design Guide (NCHRP 1-37A, 2004) has been the most recent and significant effort in this area. The current M-E pavement design procedure suggests the multi-layer elastic theory for analyzing pavement responses to traffic loading and environmental changes. Within the multi-layer elastic theory framework, the stiffness modulus and the Poisson’s ratio are the two basic material properties.

Numerous studies in the literature have illustrated that the stiffness modulus has the predominant effect in the M-E analysis and the predicted distresses. Consequently, the Poisson’s ratio is often assumed to be constant, while greater attention is paid to the determination of appropriate stiffness modulus for pavement layers (Zhou et al., 2010). Stiffness modulus is extensively affected by the loading conditions. In order to reasonably determine the elastic behaviour of the materials accordingly, dynamic loading characteristics must be recognized. Therefore, this issue has been widely studied in the last several years (Dongré et al., 2005; Al-Qadi et al., 2008). In pavement structures, the selection of appropriate parameters for dynamic loading is still not well established (Zhou et al., 2010).

Three important aspects of dynamic loading include:

i. Loading waveform,
ii. Loading time,
iii. Rest period.

Loading waveform for subgrade layer

Moving traffic applies continuous stress pulses to the material comprising each layer. Type, magnitude, and duration of the induced pulses depend on traffic volume, vehicle type, speed, pavement structure, type of materials, and element position (Huang, 2004). Square loading, haversine and sinusoidal loading waveforms have been used for characterizing the stiffness modulus. In the current MEPDG program, haversine loading waveform is used for testing pavement structure because of its similarity to the field condition.

In a study by Zhou et al. (2010), a three-layered pavement structure consisting of a Hot Mix Asphalt (HMA) surface layer, base layer, and subgrade was analyzed under a standard 18000 lbs (80KN) single axle (dual-tire) load with a uniform contact pressure of 100 psi.

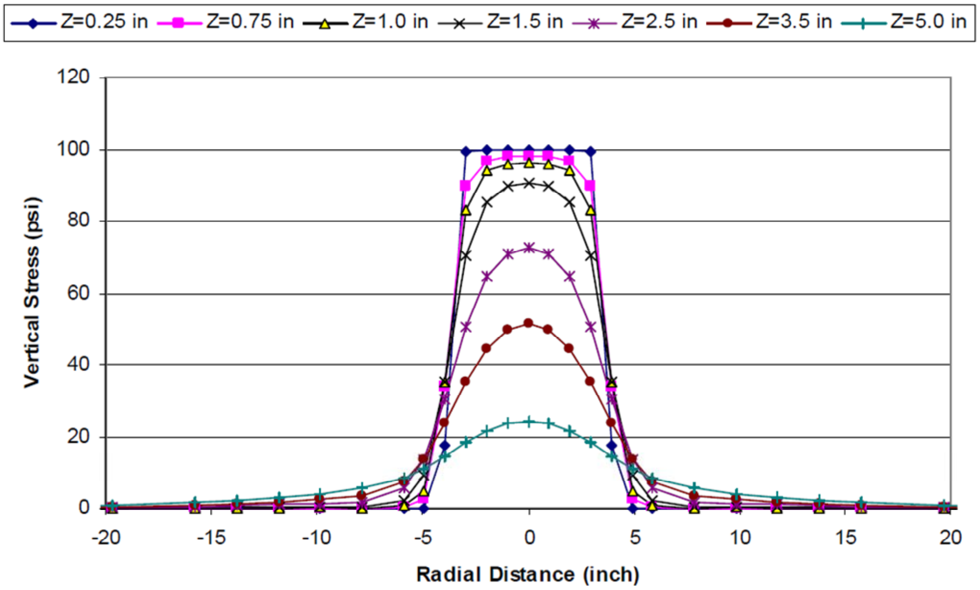

Figure 1. Vertical stress distributions at different depths of pavement (Zhou et al., 2010).

Figure 1 illustrates the computed vertical stress distributions at different depths in this study. They concluded that the square waveform loading represents the vertical stress distribution in the top one inch of pavement structure more realistically. Similar findings were reported in other pavement structures as well.

Consequently, with increase in depth, haversine loading waveform can better present what practically occurs in the field compare to the square waveform. Therefore, for the subgrade layer, haversine loading waveform is recommended.

Loading time for subgrade layer

The duration of loading pulse used for stiffness modulus determination should simulate the existing traffic condition in the field. Based on the literature (NCHRP 1-37A, 2004; Zhou et al., 2010; Huang, 2004), it has been well established that the loading time duration depends on the vehicle speed and the depth of the desirable point below the pavement surface. Based on studies by Zhou et al. (2010); they emphasized and recommended the use of modulus ratio (the modulus ratio between each desired layer and the underneath layer) in order to characterize the loading time more realistically. They stated that even if the vehicle speed and the depth beneath the pavement surface are the same, the loading times may differ significantly. A lower value of modulus ratio (R) indicates stiffer underneath materials and higher load distributing ability of the layer.

As it can be seen from Table 1, the calculated loading times at different depths of the pavement structure match reasonably well to the measured values in the field by Loulizi et al. (2002) at the Virginia Smart Road project.

Therefore, the loading time is mostly dependent on the depth, vehicle speed, and the stiffness modulus of the underneath layers. Loading time increases with depth and reduces with high speed traffic volume and stiffer underneath material. Consequently for subgrade layer, the effect of loading time is intensified due to the increase in depth and decrease in the quality of the materials.

Determination of rest period for subgrade layer

Traffic loading is not continuously applied to a pavement structure in the field but a rest period occurs corresponding to the traffic volume. Lytton et al. (1993) reported the rest period (t rest), between traffic loading passes as the number of seconds in a day divided by daily traffic (N) in Equivalent Standard Axle Loads (ESALs) (t rest = 86400/N). For pure elastic material, the rest period has no effect on the stiffness modulus (stress-strain relationship). Therefore, for subgrade material with elasto-plastic response, significant influence of the rest period on the layer stiffness modulus should be considered and AASHTO T307 has approved this statement.

BOUNDARY OF STIFFNESS MODULUS FOR VARIOUS SOILS

The preferred method for characterizing the stiffness of unbound pavement materials is the resilient modulus (M_r). The AASHTO Design Guides 1986 have recommended the resilient modulus for characterizing

Table 1. The measured vs. the predicted loading times at the Virginia Smart road.

Truck speed (Km/h)	Depth (mm)	Measured loading time (sec)-Smart road by (Loulizi et al., 2002)	Modulus ratio (R)	Predicted loading time by (Zhou et al., 2010)
75	40	0.019	1	0.015
	190	0.031	2.66	0.036
	267	0.054	0.17	0.046
	419	0.113	36	0.121
	597	0.142	1.18	0.144
25	40	0.06	1	0.046
	190	0.09	2.66	0.119
	267	0.14	0.17	0.120
	419	0.33	36	0.335
	597	0.42	1.18	0.402

Table 2. Default M_r values for unbound granular and subgrade materials at optimum moisture content and density conditions (NCHRP 1-37A, 2004).

AASHTO soil class	Resilient modulus range (psi)	Typical resilient modulus (psi)
A-1-a	38,500 - 42,000	40,000
A-1-b	35,500 - 40,000	38,000
A-2-4	28,000 - 37,500	32,000
A-2-5	24,000 - 33,000	28,000
A-2-6	21,500 - 31,000	26,000
A-2-7	21,500 - 28,000	24,000
A-3	24,500 - 35,500	29,000
A-4	21,500 - 29,000	24,000
A-5	17,000 - 25,500	20,000
A-6	13,500 - 24,000	17,000
A-7-5	8,000 - 17,500	12,000
A-7-6	5,000 - 13,500	8,000

subgrade stiffness for flexible and rigid pavements.

The resilient modulus test applies a repeated axial cyclic stress with fixed magnitude, load duration and cycle duration to a cylindrical soil specimen. While the specimen is subjected to this dynamic loading, it is also subjected to a static confining stress provided by a triaxial pressure chamber. It is essentially a cyclic version of a triaxial compression test.

Resilient modulus can be estimated from soil classification and soil unit weight. Table 2 summarizes the resilient modulus of different soils depending on soil classification for subgrade applications.

CONCLUSION

In many cases, fatigue or rutting failure in pavements occur due to inaccurate determination of stiffness modulus in subgrade layer. Improper stiffness modulus may rise from the difference between loading parameters in the laboratory testing condition and the field condition. In this paper, significant loading parameters including loading waveform, loading time, and rest time was expressed in subgrade layer. It was concluded that haversine loading waveform can better present what practically occurs in the field compare to the square waveform for subgrade layer. Furthermore, for this layer, the effect of loading time is intensified due to the increase in depth and decrease in the quality of the materials. In addition, because of elasto-plastic response of subgrade material, the rest period should be considered in determination of stiffness modulus.

Conflict of Interests

The authors have not declared any conflict of interests.

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