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ABSTRACT

This paper presents the threshold stress determination to determine the pavement thickness. This design method is based on maintaining the maximum deviator stress induced from traffic loadings on top of the sub-grade below the threshold stress of the subgrade by providing a suitable pavement layer thickness. The design method is intended to achieve a stable deformation behavior of the subgrade soil under repeated loadings, thus limiting plastic deformation. This method has significant advantages over existing ones. It is applicable to the various soil types, different surfaces, base and subbase qualities. The effects of surface and base qualities are isolated from the formation quality, and can be readily presumed and determined. A simple laboratory test procedure for quick evaluation of the threshold stress of the subgrade soil is suggested. A flow chart is given for the systematic formation design along with a suitable example. The importance of drainage conditions for the success of this approach is emphasized. The design method is evaluated by observing the performance of an actual formation under repeated load applications.

Keywords: threshold stress, induced stress, traffic loading

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1. INTRODUCTION

The highway formation can be designed empirically and rationally with different approaches between them. In the empirical design approach, the CBR test method is commonly applied to design the highway construction, which can also be used to determine the Resilient Modulus [9]. The rational approach or mechanistic approach that based on the threshold stress value, seems more realistic in pavement thickness determination [10].

The rational method seems more realistic in design pavement thickness, where traffic moving load considered as repeated loading. The rational method was also used to investigate the reliability in pavement thickness determination [2][6] and has also been developed to determine the pavement thickness for modified subgrade [7].

The design of pavement layer thickness based on the threshold stress of the subgrade soil is developed in this paper. The objective is to develop the design chart to determine the total depth of the highway formation based on the stress induced downwards from overlying layers of the pavement. The induced stress should be less than the threshold stress of the soil. The threshold stress of the soil is the stress level above which the cyclic loading causes rapid permanent deformation [10],[12].

2. BACKGROUND

Pavement layers thickness can be determined by using several methods that are currently available for design thickness measurement. The more commonly used design methods are the AASHTO (American Association of State Highway and Transportation Officials) method, Asphalt Institute method in the United States, and In Indonesia is Pedoman Perencanaan Tebal Perkerasan Lentur method as per Pt T-01-2002-B from Public Works Department [8].

In the Asphalt Institute method, materials are characterized by its resilient modulus, elastic modulus and Poisson's ratio of the soil, are represented in the multilayered elastic system [3]. In addition, the soil was assumed homogeneous, the layer is isotropic with physical properties are different from layer to layer.

Vertical compressive stress occurs at the surface of the subgrade, while horizontal tensile strain develops at the bottom of the asphalt layer. The principal design approach for thickness determination in the Asphalt Institute method is to ascertain the required minimum thickness of the layers that can adequately withstand stresses from the vertical compressive strain and horizontal tensile strain.

In the AASHTO method, the reliability component is used which incorporates some degrees of certainty and serviceability consisting of initial and terminal serviceability to determine the structural number (SN) [4]. The SN is obtained from the structural layer coefficient in equation (1) for the determination of the thickness of each layer.

$$SN = a_1\,d_1 + a_2\,d_2 + a_3\,d_3 \qquad (1)$$

Where,

a_1, a_2, a_3 = structural layer coefficient for surface, base and subbase

d_1, d_2, d_3 = surface, base and subbase layer thickness

Equation (1) has been adopted for use in the Analisa Komponen *Method* (1987) and this method has been updated to Pedoman Perencanaan Perkerasan Lentur in 2002 on Pavement Design thickness in Indonesia [8], which utilized the term correction thickness (T_A') instead of SN. It is designed empirically by using the California Bearing Ratio (CBR) value of the subgrade soil to determine the T_A' from which each pavement layer thickness can be obtained.

The design of pavement layers based on the threshold stress of the soil is applied to determine the pavement thickness. It focuses on keeping induced stresses below the threshold stress level by providing sufficient layers depth.

The induced stress, on the other hand, is the stress due to loads acting on top of the pavement layers. These induced stresses can be lowered, while the magnitude of the threshold stress may be increased by subgrade soil improvement methods [12].

The basic idea of this design is that the stress level induced by traffic loadings should be less than the threshold stress of the subgrade soil of the formation. Threshold stress can be defined as the stress level limit where the induced stress due to traffic loadings should not exceed this limit and the built up cumulative pore water pressure, leading to failure below the static failure value [10][12].

Pavement layers' design encompasses the determination of construction thickness layers consisting of the surface, base and subbase layers overlying the subgrade soil. These layers possess certain thicknesses, characteristics and material specifications.

3. ESTIMATION OF INDUCED STRESSES ON THE SUBGRADE

A key element in the development of the pavement layers design method is the reasonable estimation of induced stresses imposed on top of the subgrade caused by wheel loads from traversing traffic.

The induced stresses generated on top of the subgrade is dependent upon the loads applied on top of the pavement, its thickness and material properties of the layers as a requirement for estimating the required thickness of the pavement structure.

Loads acting on the surface surely can be in the form of concentrated load as in Boussinesq's solution or uniform load [4]. Concentrated loads and uniform distributed loads are types of load acting on top of the pavement, which is different in terms of transmission or in load distributions to the underlying pavement layers. Concentrated load is a point load while uniform distributed load takes into account the area of loading. The stresses beneath the centre of the uniform load (on the centreline of the load, i.e., r = 0, τ_{zr} =0) acting on top of the pavement layer can be determined by equations (2) and (3) [4]; and for concentrated load, it refers to the stress components due to a normal force (P) acting on the plane's boundary of a semi-infinite solid which can be determined by equations (4) and (5) [14].

$$\sigma_z = q[1 - \frac{z^3}{(a^2+z^2)^{1.5}}] \qquad (2)$$

$$\sigma_r = -\frac{q}{2}[1 + 2v - \frac{2(1+v)z}{(a^2+z^2)^{0.5}} + \frac{z^3}{(a^2+z^2)^{1.5}}] \qquad (3)$$

$$\sigma_r = -\frac{P}{2\pi}\{ (1-2v)\left[\frac{1}{r^2} - \frac{z}{r^2}(r^2+z^2)^{-\frac{1}{2}}\right] - 3r^2 z(r^2+z^2)^{-\frac{5}{2}} \qquad (4)$$

$$\sigma_z = -\frac{3P}{2\pi} z^3 (r^2+z^2)^{-5/2} \qquad (5)$$

Where,

σ_z = vertical stress

σ_r = radial stress

P = concentrated load

q = uniform pressure

a = radius of the circular wheel load

z = distance below the surface

v = Poisson's ratio

Equations (6) and (7) are used to determine the stress ($\sigma_1 - \sigma_3$) at certain depths in order to see the difference of concentrated load versus uniform load [14].

$$\sigma_1 = \left(\frac{\sigma_z+\sigma_r}{2}\right) + \sqrt{\left(\left(\frac{\sigma_z-\sigma_r}{2}\right)^2 + \tau_{zr}^2\right)} \quad (6)$$

$$\sigma_3 = \left(\frac{\sigma_z+\sigma_r}{2}\right) - \sqrt{\left(\left(\frac{\sigma_z-\sigma_r}{2}\right)^2 + \tau_{zr}^2\right)} \quad (7)$$

Where,

σ_1 = major principal stress

σ_3 = minor principal stress

τ_{zr} = shear stress

Figure 1 presents the comparison between the concentrated load and uniform load with increasing formation thickness.

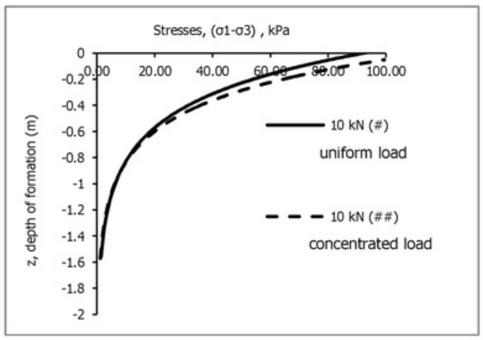

Figure 1 Concentrated load versus uniform load.

As can be seen from Fig. 1, the variation of stresses ($\sigma_1 - \sigma_3$) with depth of the pavement based on the type of loads shows a little gap existing between them. The concentrated load or point load give large calculated stresses values compare to the uniform load or distributed load acting on top of the highway pavement layers.

In this investigation, the solutions at axis of symmetry are utilized to determine the stresses–strains response on top of the subgrade (Fig. 2). It is assumed that the load is applied over a single circular-loaded area and the most critical stress, strain and deflection occur under the centre of the circular area or on the axis of symmetry [10]. Thus, as can be seen in Fig. 2 and 3, the shear stress ($\tau_{rz} = 0$) and radial stress (σ_r) is equal to the tangential stress (σ_t), where the vertical stress (σ_z) and radial stress (σ_r) are the principal stresses which can be calculated by using equations (2) and (3).

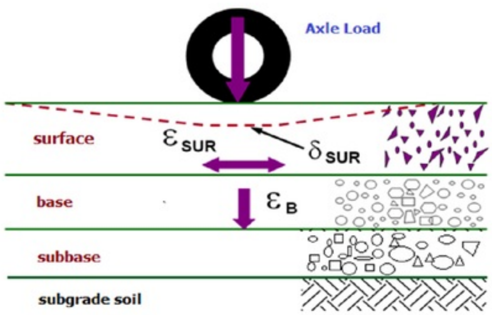

Figure 2 Pavement responses under loads

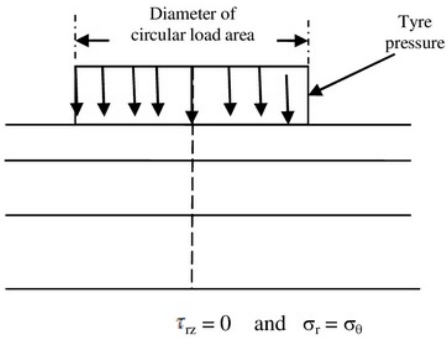

Figure 3 Pavement Response at Axis of Symmetry

Traffic is the most important factor in the pavement design. The key factors include contact pressure, wheel load, axle configuration, moving loads, load, and load repetitions [15].

Figure 4 presents the conversion of the dual wheel loads into an equivalent single-wheel load used for stress determination. It also shows that a single circular wheel load area acting on top of the pavement for calculating the stresses–strains responses as in the solution at axis of symmetry.

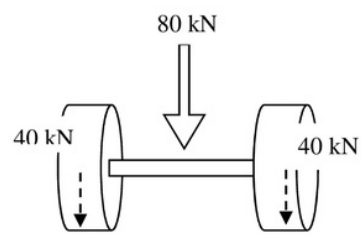

Figure 4 Wheel load for stresses–strains determination.

The application of multiple wheel load characteristics on the pavement layers is simulated in the form of a single circular load. The superposition principle may be taken into account for the multiple wheel configurations [5].

The normal practice is to convert dual wheel into an equivalent single wheel load so that the analysis is made simpler [15]. The wheel load of 80 kN standard axle load is equal to 40 kN in a single wheel.

4. DESIGN METHODOLOGY

The determination of pavement thickness using the proposed design method is based on keeping the stresses below the limits of the bearing failure capacity to prevent excessive layers settlement. The design method works on the basis of ensuring that the maximum deviator stress induced by traffic loadings on top of the subgrade does not exceed the threshold stress of the subgrade soil [10].

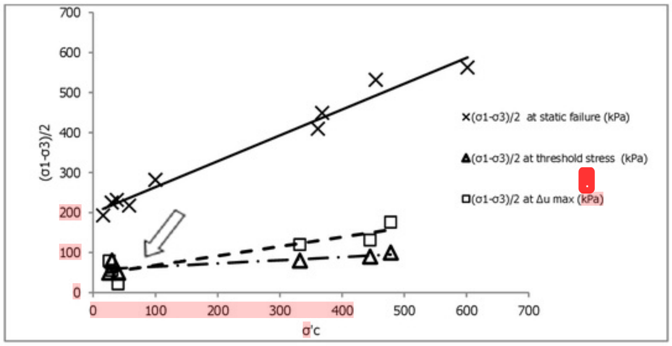

Figure 5 Shear stress versus confining effective stress relationship

Figure 5 has been developed to obtain the threshold stress line which is subsequently used for the development of highway formation design and to present the variations of shear strength {(σ_1-σ_3)/2} with confining effective stress (σ_c'). In the absence of any detailed investigation at low σ_c' values, a straightline relationship is suggested on the basis of this threshold stress value as given below:

$$(\sigma_1 - \sigma_3)_{TS} = 0.235\sigma'_c + 88.68 \text{ (kPa)} \quad (8)$$

It is known that as the depth of formation increases, the confining effective stress is increased, and as the initial confining effective stress increase, the threshold stress also increases.

The density and thickness of the surface, base and subbase layers are first assumed to develop the line of variation of static effective stress with depth as shown in Fig. 5. The density of the surface (Asphalt Concrete) is 23.0 kN/m^3 (~ 150 pcf) to ensure it contains enough air voids to prevent rutting due to plastic flow, but with low enough air voids to prevent permeability of air and water [1]. The density of the base (Recycled Asphalt Pavement base) is 21.0 kN/m^3 and subbase is 19 kN/m^3 based on the NCHRP Report 598 [11], while the assumption of the required minimum thickness of each layer is based on Guidelines for flexible pavement thickness determination [8] in the Manual on Pavement Design, namely, 10 cm and 20 cm for the surface and base, respectively.

Figure 5 shows the variation of shear strength at static failure {(σ_1-σ_3)/2)$_f$}, at maximum pore water pressure {(σ_1-σ_3)/2)at ΔU_{max}}, and shear strength {(σ_1-σ_3)/2} corresponding to the threshold stress level, with σ_c'. The equations for the three relationships are shown in Table 1.

Table 1 Stresses versus Thickness Relationships

Constant value	Slope	Equation	Remarks
b= 199.37	a= 0.6454	y = 0.6454x + 199.37	At static failure
b= 57.05	a= 0.079	y = 0.079x + 57.05	At threshold stress
b= 44.34	a= 0.235	y = 0.235x + 44.34	At ΔU_{max}

As can also be observed from Fig. 5 (see arrow), the shear stress based on the development of pore pressure is higher than the shear stress based on cyclic stress level. However, at lower effective stress ($\sigma'_c \leq 80$ kPa), the shear stress based on pore pressure measurement is lower than the shear stress based on cyclic stress level. It means that the strength of the compacted subgrade is more affected by pore water pressure changes [10].

Thus, from the safety design point of view, the line of the threshold stress is converted to the line of the shear strength at maximum pore water pressure development for $\sigma'_c \leq 80$ kPa as shown in Fig. 6. The relationship of the threshold stress line for effective stress below 80 kPa is {y = 0.235x + 44.34}, while for effective stress of more than 80 kPa is {y = 0.079x + 57.05}. Fig. 6 shows the results at low σ_c' as well as Shahu's result for comparison [12].

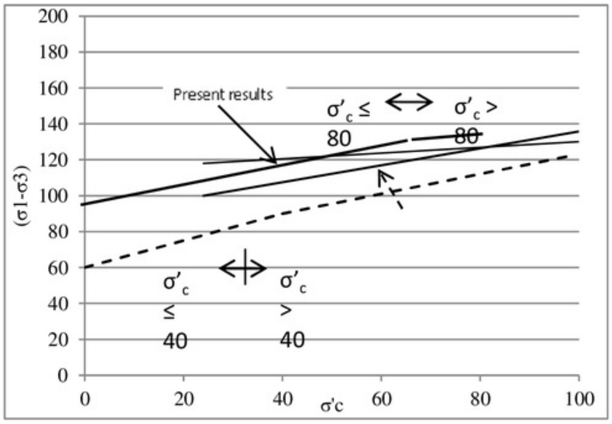

Figure 6 Threshold stress value versus effective stress

5. DESIGN CHART

A design chart for determining highway formation thickness has been developed based on the threshold stress laboratory tests on clay with sand soil. Threshold stress can be related to the formation depth based on the condition where the effective stress is increased as the formation depths increases.

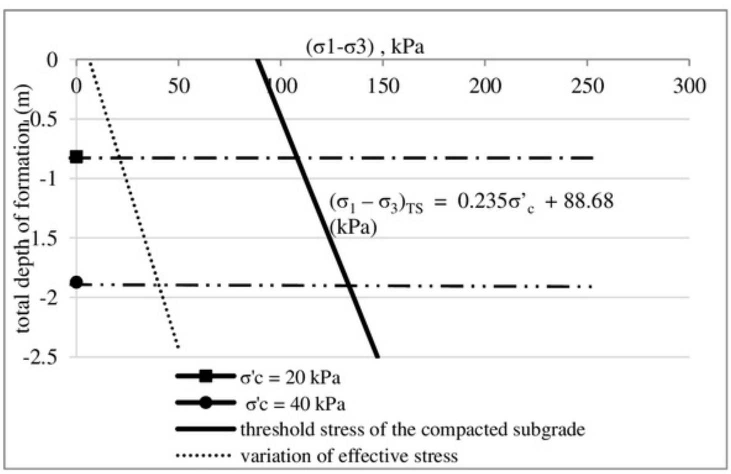

Figure 7 Design Chart

Figure 7 presents the design chart for determining thickness formation. It shows the variations of threshold stress with depth where the threshold stress line is determined by cyclic triaxial test, where the threshold stress of the subgrade soil is the maximum stress level caused rapid permanent deformation [10][12].

It is the relationship between threshold stress in terms of $(\sigma_1 - \sigma_3)$ induced at specified thickness formations. The deeper the pavement thickness is, the bigger will be the threshold stress values of the subgrade soil. The variations of effective stress along with formation depth have almost the same trend as the threshold stress variations.

From this design chart, the threshold stress values of the compacted subgrade can be determined for the various total thicknesses of the highway formations. Different total formation depths resulted in different values of the threshold stress whereas the depth of formation increases, the threshold stress of the soil also increases.

6. CONCLUSION

Conventionally, a highway formation design refers to the fixation of each layer's thickness overlying the subgrade soil. However, it must be recognized that the design of these layers encompasses a broader scope.

There are three steps involved in the proposed design of highway formation: (a) estimation of the induced stress, (b) evaluation of the threshold stress, and (c) designing the formation thickness. The threshold stress approach is based on the limitation of the stress induced on top of the highway structure. This stress should be less than the threshold stress of the subgrade. The stress ($\sigma_1 - \sigma_3$) calculated based on Huang's definition assume that the load acting on top of the highway structure is uniform thus the properties of the surface and base layers may be taken into account [4]. The subbase thickness varies according to the stress obtained so that it is slightly below the threshold stress of the soil. The minimum thickness obtained where the induced stress is less than the threshold stress is adopted as the formation depth.

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