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A Study on Calculation of Rutting Depth of Pavement Asphalt Concrete Layer In Under Vietnam Conditions

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Abstract

In this paper, we present the basis of the theoretical calculation of rutting depth of asphalt concrete pavement and its application in calculating the rutting depth of different kinds of asphalt concrete under conditions in of Vietnam.

Keywords: Soil-cement deep mixing method, cement-soil piles,cement content, soft soil improvement.

INTRODUCTION

There are many factors that affect the formation and development of plastic deformation of asphalt pavement such as composition of material aggregate, content and shape of skeleton, bitumen and additives, the quality of construction, the magnitude and density of axle as well as the environmental conditions of the construction area. Therefore, the need to study the method of predicting asphalt concrete plastic deformation, and thereby to calculate and select the materials to meet exploitation requirements is very necessary, especially for tropical climate countries as Vietnam. In this paper, the author present theoretically the basis for calculation of rutting depth of asphalt pavement deformation and apply them in Vietnam climate condition.

PHYSICAL AND MECHANICAL PROPERTIES OF STUDIED WEAK SOFT SOILS AND EXPERIMENTAL MATERIALS

Calculate plastic deformation asphalt concrete

Under the effect of wheel dynamic load, the mechanical model describing the behavior of the asphalt concrete material can be selected from three successive groups of elements (Figure 1). Group I characterizes the elastic properties of the material which is modeled by a spring element with the stiffness G0. Group II represents its viscoelastic properties and the linear deformation which is denoted by a spring element with the stiffness G1 welded parallel to the plunger element with the viscosity coefficient η1. The third element group characterizes the viscosity and plasticity of the asphalt concrete that consists of a Sanvenant - Coulomb element with a static flow limitation σ.tgφ which is parallel to the plunger with the Newton viscocity nonlinear coefficient , also known as the visco-plastic coefficient, and its value varies and depends on velocity distortion [3].

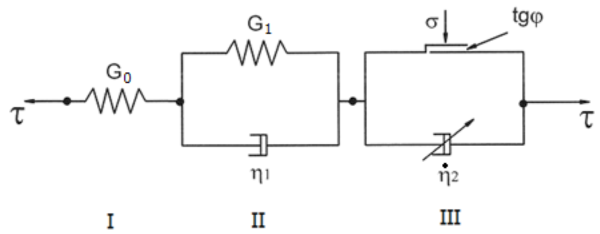

Figure 1. Mechanical model of asphalt concrete material is subjected to dynamic load

The nonlinear viscosity coefficient η2 is determined by the formula:

$$\dot{\eta}_2 = \frac{\tau - \sigma tg\,\varphi}{\dot{\gamma}} \qquad (1)$$

where τ and σ are the shear and normal stresses respectively at the calculated section, MPa; tgφ- coefficient of internal friction of asphalt concrete; $\dot{\gamma}$ - deformation velocity, 1/s.

With respect to small affected load, the shear stress is smaller than the static flow of the material (τ≤σtgφ), and thus in the material there exists only the elastic deformation of the element group I and the viscoelastic deformation of the element group II. When the shear stress exceeds the limit value σtgφ, the visco-plastic strain occurs which is the plastic flow deformation of the asphalt concrete layer.

In order to calculate and evaluate plastic asphalt concrete deformation, it is now common practice to use MEPDG [1] and theoretical methods. With the aim of applying the experimental mechanical method to the calculation plastic deformation under Vietnamese conditions, it is necessary to conduct a field study to determine the experimental coefficients in the formula to accord to the Vietnamese conditions. Using the theoretical calculation method, only the physical properties of the sample of the material should be tested to include in the calculation formula. We present below the theoretical method that can be used in present conditions of Vietnam.

The asphalt concrete layer in the pavement can be subjected to the vertical forces of the wheel track or with additional horizontal force due to braking or horizontal inertia force when the vehicle is running on the horizontal curve. These loads result in normal and shear stresses in the asphalt concrete layer. When the stresses are sufficiently large, plastic deformation can occur in the asphalt concrete layer on the lanes that creats ruttings along the wheel track (see Figure 1). In the case of the plastic deformation of the asphalt concrete layer only, considering an element just under the load center, the normal stress causes volumetric strain and the shear stress causes deviatory strain. In fact, when the asphalt concrete layer has been compacted to ensure the required tightness, the amount of volumetric strain is very small, so it could be ignored in calculation. The deviatory strain is distributed equally to both sides. The general appearance of the rutting pattern is shown in Figure 2.

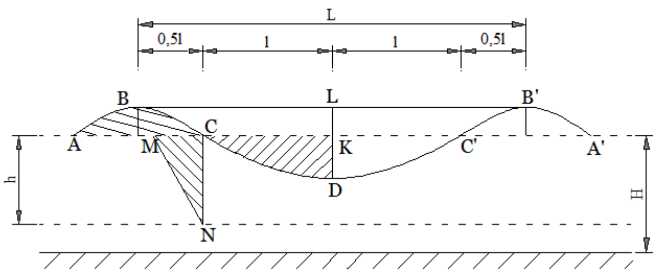

Figure 2: Typical rutting on the asphalt pavement

In Figure 1, LD distance is the depth of the rutting and the straight line IJ '= L is the distance between the two peaks of the rutting so-called the rutting width while h is the depth of the plastic deformation of the asphalt layer.

In this article, the method of calculating the plastic deformation of asphalt pavement due to both vertical loading and horizontal force and braking will be theoretically present. Based on the material model shown in Figure 1, asphalt concrete is a material that has visco-elastic properties, the shear deformation of the asphalt concrete is calculated from elastic, viscoelastic and viscoplastic deformations of the three element groups as follows:

$$\gamma_p = \frac{\tau}{G_o} + \tau.\psi(t) + \frac{t(\tau - \sigma tg\varphi)}{\eta_2} \tag{2}$$

whichwhere : γ_p – plastic deformation of the asphalt concrete layer; τ – shear stress in the asphalt concrete layer, MPa; ψ(t) – the rheology function that characterizes the visco-elastic propertises of the material, MPa-1:

$$\psi(t) = \frac{1 - \exp(-\frac{t}{\theta})}{E}$$

where t - the duration of the load, s, t = D/V, where D,V are the equivalent diameter of the wheel track and the speed of the vehicle respectively; σ – vertical stress in the asphalt concrete layer, MPa; θ – delay duration of the deformation of the asphalt concrete, s; E- Young modulus of the material, MPa; tgφ – coefficient of internal friction of the material; η2 - viscoplastic coefficient of the asphalt concrete, MPa.s.

In the right hand side of equation (2), the two first terms represent the values of the elastic and viscoelastic deformations of the asphalt concrete which will disappear when unloaded, so they will be egnored in considering the plastic deformation. At the plastic deformation stage, there exists only the third term with the visco-plastic coefficient η2 determined by equation (1). Substituting the visco-plastic coefficient into (2) and neglecting the elastic and viscoelastic deformations, we have the plastic deformation after one time of load action:

$$\gamma_p = t.\dot{\gamma} \tag{3}$$

where $\dot{\gamma}$ is deformation velocity of the asphalt concrete at calculated temperature of the pavement,1/s.

As the asphalt material exhibits the rheology property, the deformation velocity depends on the speed of the loading process and the environment temperature. According to studies conducted by the Russian Road Research Institute [3], the value of the plastic deformation velocity at the calculated temperature can be determined by the one at the temperature of sample testing and it is usually taken at 50oC. Under static load and at low temperature, the asphalt concrete exhibits elastic properties and its shear strength depends only on the adhesion C and the internal friction angle φ of the material. However, when the asphalt concrete subjected to dynamic load and at high temperature, it exhibits rheological and visco-plastic properties, so the shear resistance of the asphalt concrete depends not only on the adhesion C and the internal friction angle φ but also some other rheological parameters of the material. In order to consider the rheological characteristics of the asphalt concrete, the Russian Road Research Institute has proposed the plasticity coefficient (m) and the visco-plastic deformation energy (U) that characterizes the behavior of the rheological material under the dynamic load and the behavior of the asphalt concrete at high temperatures respectively.

We can calculate the deformation rate $\dot{\gamma}_{T^{0C}}$ at the calculated temperature through the deformation speed at 50oC ($\dot{\gamma}_{50^{0C}}$) by the following relationship:

$$\dot{\gamma} = \dot{\gamma}_{50^0 C}(\frac{\tau_{\max} - \sigma tg\phi}{C})^{1/m}.k(T) \tag{4}$$

where m is the plastic coefficient of the asphalt concrete which can be determined by laboratory tests on the samples; τmax is the maximum shear stress due to the vertical and braking loads, MPa; k(T) is the adjustment coefficient that converts the deformation velocity from the experimental temperature to the calculated temperature and it can be determined by following formula:

$$k(T) = \exp\left[-\frac{U}{R}\left(\frac{1}{273{,}15 + T_{tt}^{oC}} - \frac{1}{273{,}15 + T_{tn}^{oC}}\right)\right]$$

where R is gas constant and is taken 0,008304kJ/ particle gram; U- visco-plasticity deformation energy that characterizes the behavior of asphalt concrete at high temperatures which is determined on the asphalt concrete samples in the laboratory, kJ/particle gram; T_{tt}^{oC} - calculated temperature of the asphalt concrete layer, °C; T_{tn}^{oC} - experimental temperature of the samples (it is normally taken 50 °C); C- the cohesion of the concrete determined at the experimental temperature, T_{tn}^{0C}.

Substituting Eq. (4) into Eq. (3) one obtains the plastic deformation of one time of the loading as the relationship below:

$$\gamma_p = t.\dot{\gamma}_{50^0 C}\left(\frac{\tau_{\max} - \sigma tg\phi}{C}\right)^{1/m}.k(T) \quad (5)$$

Eq. (5) only considers plastic deformation due to the effect of the load for one time. In order to calculate the total plastic deformation during the pavement exploitation period, one has to take into account the effect of the total axle flow and the variation frequency of the calculated temperature in the asphalt concrete layer during the exploitation period from minimum to maximum temperatures as well as considering the probability of overlap of the wheel through a calculated section along the width of the lane.

In order to determine the total axial flow resulting in plastic deformation, one uses the following formula:

$$Ntt = Nqđ.\, k \quad (6)$$

where Nqđ – the total equivalent axial flow during the exploitation term; k – probably of the wheel moving pass one point on the considered lane that is determined by the practice servey.

The temperature in the asphalt concrete layer is variable throughout the exploitation period from Tmin ÷ Tmax (oC). At each temperature level, one obtains one value of the deformation of the asphalt concrete. For the purpose of considering this change, the frequency of occurrence of each temperature level during the exploitation period should be taken into account that is determined through the observed data during the calculated period of the highway. This frequency of calculated temperature is determined by the relationship below:

$$P(T) = \frac{t(T^0 C)}{t_{kt}} \quad (7)$$

where: t(T0C)- the working time of pavement at T^0C, h; tkt- total pavement exploitation time, h.

Substituting Eqs. (6) and (7) into Eq. (5) one has total plastic deformation following horizontal direction of the asphalt concrete layer of the exploitation duration as follows:

$$\gamma_p = N_{tt} t.\dot{\gamma}_{50^0 C}\left(\frac{\tau_{\max} - \sigma tg\phi}{C}\right)^{1/m}.\int_{T_{\min}}^{T_{\max}} P(T).k(T).dT \quad (8)$$

where T is the variation of calculated temperature from T_{min} to T_{max}.

The formula of plastic deformation (8) devotes calculating and selecting the asphalt concrete in accordance with the exploitation requirements. The calculated distortion value γp needs to be less than the one of permissible deformation that depends on the grade of road. The plastic deformation parameters in formula (8) are completely determined by the sample test in laboratory and they depend on the type of asphalt concrete used.

Using the distortion value obtained by the formula (8), one can computes the rutting depth of the asphalt concrete layer. In Figure 1, if it is assumed that only the distortion deformation results in the rutting of the asphalt pavement, the volume of the deformation area per unit length with the bottom of the cross section CKD, will be equal to the one of the conventional horizontal shear deformation with the bottom of the cross section CMN. It can be see that the area of CKD is equal to the one of CMN and they are assumed triangles, and thereby one has:

$$\frac{CK.KD}{2} = \frac{CN.CM}{2} \quad (9)$$

where CN- the depth of the plastic deformation of the asphalt concrete (in Figure 1, it is denoted h); CM- the conventional horizontal displacement of the asphalt concrete layer

The relationship below is deduced from Eq (9):

$$\gamma_p = \frac{CM}{CN} = \frac{CK.KD}{CN^2} = \frac{l.KD}{h^2} \quad (10)$$

It can be shown from Figure 1 that, the values of l, L, KD, LD are geometrical dimensions of the rutting obtained from the field measurements. From these actual measurements, it is possible to accept following approximate values: l =L/3; KD=2.LD/3, and then from Eq (10) on has:

$$\gamma_p = \frac{2.LD.L}{9h^2} = \frac{2.\delta.L}{9h^2} \quad (11)$$

where δ- rutting depth (δ =LD in Figure 1); L- the width of the rutting, cm; h- the depth of the plastic deformation region of the asphalt concrete, cm.

Eq. (9) gives us the relationship for computing the rutting (Rutting Depth RD = δ) as follows:

$$RD = \frac{9.\gamma_p.h^2}{2.L} \quad (12)$$

where γp is calculated by Eq. (8).

The exploitation condition is only ensured when the calculated deformation arccoding to Eq. (8) or the rutting computed from Eq. (12) must not exceed the permissive value. The permissive value in the exploitation is regulated corresponding to each grade of the pavement. In the formulas (11) and (12), to determine the deformation values γ or the rutting depth RD, it is necessary to know the depth of the plastic deformation h in the asphalt concrete layer. The value of h can be obtained by calculating or surveing the actual samples that depends on the discharge of the traffic, vehicle axle load (magnitude, tire pressure) and type of the pavement. For the highway pavement, eg. grade I and II, the depth of rutting takes the value from 5 to 7cm, and in calculation one can choses h = 6cm.

INVESTIGATE THE DEGRE OF TEMPERATURE-DEPENDENCE PLASTIC DEFORMATIONS OF THE ASPHALT CONCRETE UNDER CONDITIONS IN VIETNAM

Input data

- Temperature calculation: As specified in [2,3], the maximum temperature Tmax, which serves asphalt concrete deformation calculation, is determined at depth of 2 cm from the pavemnet surface. In order to calculate the temperature at this position that is caused by air temperature and solar radiation, in the calculation we recommend the experimental formula of the Asphalt Concrete Institute as follows:

$$\begin{aligned} T_{2cm} &= 0,9545(T_{kk,\max} - 0,00618Lat^2 \\ &+ 0,2289Lat + 42,2) - 17,78 \end{aligned} \quad (13)$$

where $T_{kk,max}$ – the highest temperature of average 7 days per year, ^{0}C; Lat – the latitude of calculated region.

For example, for the region of Hanoi at the northern latitude of 21, the air temperature Tkk, max = 40.00C. From Eq. (13) we can determine the temperature at depth of 2cm from the pavement surface that is equal to 62.66^{0}C.

The lowest temperature Tmin, according to [2,3], is determined by the equation below:

$$T_{min} = 0,856\ T_{kk,min} + 1,7 \quad (14)$$

With respect to Hanoi region, the lowest air temperature is 4^{0}C, hence we obtain Tmin=5,12 ^{0}C.

We consider an example with the parameters as follows:

- Pavement structure of grade I consisting of 3 layers of asphalt concrete with the thickness of 20cm that lies on a base layer of 35cm thickness and a subase of 50cm thickness composed from gravel aggregate type I and II respectively. The subgrade has the Young module of 45MPa.

- The highway of grade A has expected exploitation term of 15 years, and the permissive exploitation speed of 120km/h.

- The total equivalent time of the applied load at 1 point for predicting plastic deformation during the exploitation period taking the high level exploitation discharge [3] is 42.8 hours and the magnitude of load is 10T corresponding to tyre pressure q = 0.6MPa.

- In this example, we investiage two kinds of asphalt concrete in which the first one is ordinary asphalt concrete which is used commonly in the Vietnam currently. The material parameters are chosen as follows: the cohesion at 50^{0}C is equal to C= 0.3 MPa [3]; the internal friction coefficient tgφ = 0.9; the visco-plasticity deformation energy U = 315 kJ /molecule gram; plasticity coefficient m = 0.11. The second type is stone matrix asphalt concrete (SMA) with the parameters: the cohesion at 50^{0}C is equal to C=0.25 MPa; the internal friction coefficient tgφ = 0.94; the visco-plasticity deformation energy U = 235 kJ /molecule gram; plasticity coefficient m = 0.135.

RESULTS AND DISCUSSION

The calculation results of deformation and rutting depth based on the formulas (8) and (12) of the two types of asphalt concrete are shown in Table 1. In order to determine the deformation and rutting depth, we use the numerical integration method for the temperature levels corresponding to their different frenquencies during the exploitation term of the road. The integral step in the calculation, ΔT^{0}C, is chosen by 1^{0}C.

In table 1: T^{0}C –Temperature at the point at depth of 2cm from the pavement surface, ^{0}C; P(T) – Frequency of temperature T^{0}C during the exploitation period; $\boldsymbol{\gamma}_p$ – Plastic deformation of asphalt concrete at the temperature T^{0}C during the exploitation period; RD – the rutting depth of asphalt concrete,cm.

The results show that the total deformation after 15 years of operation of asphalt concrete type 1 reaches γ_p = 0.505 and the rutting depth RD = 0.81cm which exceeds the allowable value RD_{limit} = 0.4cm for the velocity of 120km/h according to Russian standard [3]. Therefore, it could be conclude that the asphalt concrete layer does not meet the the requiement of resistance criterion on rutting. With regard to the second type of asphalt concrete, the total deformation γ_p = 0.048, and RD = 0.077cm that is minor to the allowable one (0.4cm). Hence, this asphalt concrete satisfies the resistance requirements the the requiement of resistance criterion on rutting.

Table 1. Calculated results of plastic deformation of the asphalt concrete layer

T^{0C}	P(T)	Plastic Deformation of asphalt concrete, γ_p	
		Kind 1	**Kind 2**
5	0.0032	3.96E-12	4.62E-13
6	0.0048	9.90E-12	1.15E-12
7	0.0065	2.17E-11	2.53E-12
8	0.0082	4.41E-11	5.14E-12
9	0.0099	8.56E-11	9.99E-12
10	0.0116	1.61E-10	1.88E-11
11	0.0132	2.95E-10	3.44E-11
12	0.0149	5.31E-10	6.20E-11
13	0.0166	9.41E-10	1.10E-10
14	0.0183	1.64E-09	1.92E-10
15	0.0200	2.84E-09	3.31E-10
16	0.0202	4.51E-09	5.26E-10
17	0.0202	7.09E-09	8.27E-10
...	...	...	....
51	0.0202	6.30E-03	7.34E-04
52	0.0202	9.02E-03	1.05E-03
53	0.0196	1.25E-02	1.46E-03
54	0.0179	1.63E-02	1.91E-03
55	0.0163	2.11E-02	2.46E-03
56	0.0146	2.68E-02	3.13E-03
57	0.0129	3.37E-02	3.92E-03
58	0.0112	4.14E-02	4.83E-03
59	0.0095	4.96E-02	5.79E-03
60	0.0078	5.76E-02	6.71E-03
61	0.0062	6.36E-02	7.41E-03
62	0.0045	6.49E-02	7.56E-03
63	0.0028	5.67E-02	6.62E-03
Sum γ	**1,0000**	**0,5050**	**0,0480**
RD,cm	**-**	**0,810**	**0,077**

Figure 3 shows the results of the relationship between the degree of plastic deformation of asphalt concrete corresponding to the frequency of different temperature levels calculated for 2 cases of normal asphalt (BTNC) and stone matrix asphalt (SMA) concretes during the exploitation period.

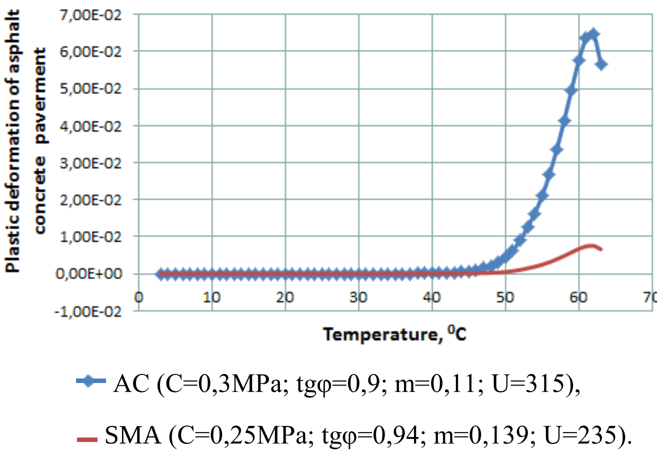

Figure 3. The relationship between the plastic deformation and the different temperure levels during the exploitation period

It is seen in figure 3 that at the temperature from 62 to 63^{0}C, the relative line tends to descend. This is explained that in this temperature range the occurrence frequency of temperature is lower than the other temperature regions (see column P(T) Table 1), so the distortion obtained at these temperatures are lower than at the other. Also from the diagram, when the temperature in the asphalt concrete layer is less than 50^{0}C, the plastic deformation value is very small, i.e. it can be negleable. However, at 50^{0}C or above the plastic deformation begins to increase strongly. The calculated temperature depending on the geographic location, for example in the area of Hanoi (Vietnam) it takes 53-55^{0}C corresponds to the air temperature of about 32^{0}C. At this temperature, as presented above the plastic deformation of the asphalt concrete layer begins to increase rapidly. Therefore, in order to avoid the occurrence of high deformation in asphalt concrete, it is recommended to reduce the exploitation discharge or to limit the vehicle load in hot sunlight hours (usually from 11am to 17pm on sunny days in the summer) when the air temperature exceeds 32^{0}C.

CONCLUSIONS AND RECOMMENDATIONS

By the theoretical calculations, we established the formula of plastic deformation and rutting depth of the asphalt concrete pavement under the effect of vertical wheel load and brake force according to horizontal direction.

By calculating method presented above, we can the choice the suitable asphalt concrete to meet the requirements of each specific route in practice.

In the calculations, the influence of temperature factors on deformation of different asphalt concrete materials was investigated. In the area of Hanoi, when the air temperature reached over 320C the asphalt concrete begins to occur plastic deformation. This is important to managing and exploiting the road to avoid the occurrence of rutting depth of the asphalt pavement.

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