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Mechanical Responses and Modeling of Rutting in Flexible Pavements

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Abstract: Dramatic increases in the number and weight of vehicles have resulted in severe rutting on flexible pavements. A mechanical-based rutting model was developed to account for material properties changes in the progression of rutting over time and cumulated compressive strains of all layers due to traffic overloading. Nonlinear, viscoelastic, and viscoplastic deformation components of the pavement structures were characterized by theoretical modeling. Laboratory tests were conducted to obtain the essential parameters. A test field road was constructed to validate the prediction model. Results indicated that structural arrangement of pavement layers had a significant influence on rutting performance of the asphalt layer. Permanent deformation trafficked at 20 kph was two times higher than that at 90 kph. Both measured and predicted rut depths were in good agreement. Incorporation of the mechanistic approach in the prediction of rutting was shown to be viable and provided valueable information on the contribution of each layer to permanent deformation in flexible pavements.

Key Words: rutting, mechanical response, test road, flexible pavement

1. INTRODUCTION

Increased traffic factors such as heavier loads, higher traffic volume and higher tire pressure demand a better-designed pavement structure. Data collected from toll stations in Taiwan indicated that the average tandem axle weight of heavy vehicles reaches 22.5 tons, which is much higher than the allowable weight, i.e., 14.5 tons. Rutting becomes the major failure modes for flexible pavements around Asian countries. Approximately one third of flexible pavements need to be rehabilitated annually, which costs about 70 percent of the maintenance budget in Taiwan. Pavement engineers have been trying for years to control and predict the rutting trend. There exists an urgent need to improve the design of the pavement structure to provide a high quality and long lasting pavement. The Taiwan Area National Freeway Bureau (TANFB) constructed an in-service test road to investigate the effect of the pavement response on pavement performance under traffic loading.

Two basic approaches have been used in the pavement design to analyze the rutting behavior. The first approach is to statistically relate rutting to pavement conditions such as material properties, loading and environmental features. Several methods use indices such as the soil classification and the California bearing ratio (CBR) and the soil to estimate pavement performance (Peattie 1962; Lai and Anderson 1973). These empirical approaches are only applied to a given set of environmental, material, and loading conditions. The second approach is to formulate the rutting mechanism and associate the hypothesis with pavement responses. The Asphalt Institute model (1982) and the Shell model (1978) are the typical example, which assumes that most of the rutting is due to permanent deformation within the subgrade layer. These mechanistic approaches more realistically characterize in-service pavements and improve the reliability of designs. Data from various reports, however, indicate that the subgrade contribute only parts of the total rutting, and the surface, base and subbase layers contribute the major portion of the total rutting (Kennedy et al. 1977; Monismith 1994; Gibson et al. 2003; Tashman et al. 2005).

The subgrade-strain-based rutting models developed by the Asphalt Institute and the Shell Company neglect the combined contributions of the asphalt concrete (AC) layer, the base, and the subbase layers to rutting. This method does not account for materials' hardening effect in the progression of rutting over time. The mechanical response parameters of pavements, required for pavement performance models, can be analytically evaluated. Although several techniques have been proposed for the second approach, it has not been widely used because of the difficulty in obtaining comprehensive characterizations for the various paving materials and mechanical responses under traffic loading. With a rapid increase in computing capability, the dynamic finite element program has been used to calculate the pavement response (Zaghloul and White 1993; Scarpas et al. 1997; Uzan 2005).

Asphalt paving materials exhibit creep under sustained loading and partial time-dependent recovery upon complete unloading. Modeling such a response is commonly performed by decomposing the strain tensor (additively) into recoverable and irrecoverable parts (Sousa et al.

1993; Chehab et al. 2003; Tashman et al. 2005). A viscoelastic (VE) constitutive model, including an instantaneous elastic term, can be used to represent the recoverable component. Such a model simulates creep under load that can fully recover upon unloading (i.e., VE solid behavior). The irrecoverable component is represented by a viscoplastic (VP) constitutive model that is only active under load. Subjected to moving wheel loads, pavement materials experience complex multiaxial stress-paths that include rotation of principal stresses accompanied by shear stress reversals.

The objective of this study are to develop a mechanistic-based rutting model for predicting the long term performance of flexible pavements that can account for material properties and mechanical responses under realistic cycle traffic loading, and then to verify these models through an in-situ test road. The objectives are stated as follows:

- Establish a mechanistic-based rutting model including contributions of all layers in pavement,
- Evaluate engineering properties of hot-mix asphalt mixtures,
- Analyze pavement responses under traffic loading, and
- Verify observed and predicted rutting by model calculation.

2. MODEL DEVELOPMENT

Assume that there are n loading groups (trucks) and that each loading group i is associated with a vertical compressive strain $\varepsilon e_{i,j}$ in pavement layer j, as listed in Eq. (1). It is related to the number of load applications by a negative power model. The negative power relationship reflects the pavement hardening effect due to repetitive loading. The following model relates: (a) the vertical compressive plastic strain εpi,j in a given layer resulting from one load increment of loading group i, to (b) the elastic compressive strain $\varepsilon e_{i,j}$ in layer j resulting from the load passage and the number of load applications N.

$$\varepsilon p_{i,j} = \mu_j * \varepsilon e_{i,j} * N^{-\alpha_j} \tag{1}$$

where μ_j=slope of the elastic-strain/plastic-strain line for layer j; $-\alpha_j$ =negative exponent reflecting hardening of layer j with repetitive loading. The total plastic strain in layer j due to the accumulated loading group n is calculated by the equation as follows:

$$\varepsilon p_{i=n,j} = \int_0^n \mu_j * \varepsilon e_{i,j} * N^{-\alpha_j} dN = \frac{\mu_j \varepsilon e_{n,j}}{1-\alpha_j} n^{1-\alpha_j} \tag{2}$$

Similarly, the cumulative plastic strain in layer j resulting from loading group k is calculated from Eq. (9):

$$\varepsilon p_{k,j} = \frac{\mu_j \varepsilon e_{n,j}}{1-\alpha_j} \left\{ k \left[\frac{\varepsilon e_{k,j}}{\varepsilon e_{n,j}} \right]^{\frac{1}{1-\alpha_j}} \right\}^{1-\alpha_j}$$

$$= \frac{\mu_j}{1-\alpha_j} \left\{ k \left(\varepsilon e_{k,j} \right)^{\frac{1}{1-\alpha_j}} \right\}^{1-\alpha_j} \tag{3}$$

The cumulative plastic strain for all loading groups in layer j is summarized as follows:

$$\varepsilon p_{k,j} = \sum_{i=1}^{k} \frac{\mu_j}{1-\alpha_j} \left\{ i \left(\varepsilon e_{i,j} \right)^{\frac{1}{1-\alpha_j}} \right\}^{1-\alpha_j} \tag{4}$$

The parameter μ_j and α_j are constant of each layer by the layer thickness. If there are L layers, each having h_j thickness, then the total plastic deformation ρ_p is obtained by:

$$\rho_p = \sum_{j=1}^{L} h_i \frac{\mu_j}{1-\alpha_j} \left\{ \sum_{i=1}^{k} \left[i \left(\varepsilon e_{i,j} \right)^{\frac{1}{1-\alpha_j}} \right] \right\}^{1-\alpha_j} \tag{5}$$

where ρ_p=cumulative permanent deformation in all layers from all loading groups (ie., rut depth); $\varepsilon e_{i,j}$ =vertical compressive strain in layer j due to the passage of a loading group i; and h_j=thickness of layer j. The pavement responses that induce at the critical locations are illustrated in Figure 1.

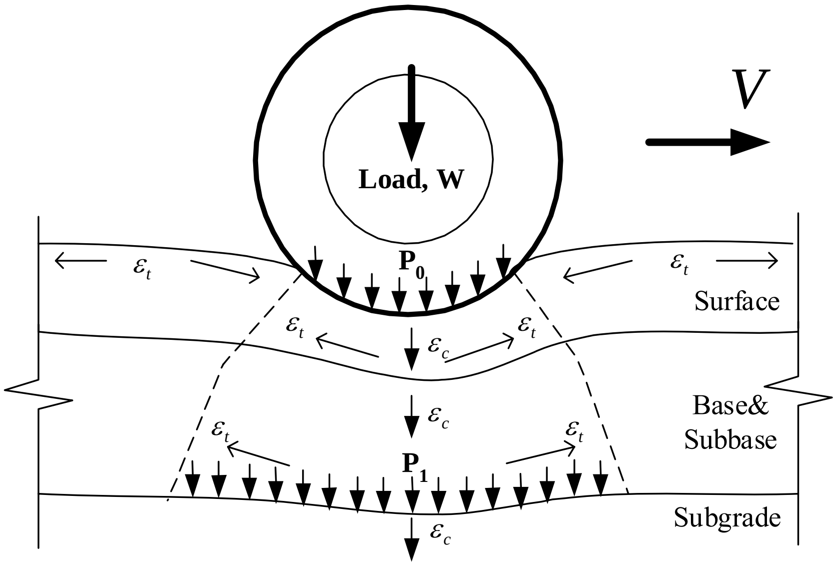

Figure 1 Responses at critical locations in a pavement

3. MATERIAL CHARACTERIZATION

To investigate the effects of the full characteristic property of the AC layer, a simple static creep test was performed in this study. The main objective to perform the static creep test in this study is that it could be used to evaluate the potential possibility of permanent deformation effectively (Sousa et al. 1993; Chaboche 1997; Schapery 1999; Huang et al. 2002; Uzan and Motola 2006; Uzan and Levenberg 2007). To prepare AC specimens before testing, these samples were made into cylindrical shapes of 100 mm in diameter (D) and 190 mm in height (H) by Superpave Gyratory Compactor (SGC) through a constant vertical pressure 600 kPa, also as a factor to evaluate the size-effect of AC specimen in experimental design. The SGC compacts mixture in a mold through a combination of constant vertical pressure and a constant angle of gyration. The angle of gyration, in conjunction with the vertical pressure 600 kPa, produces a kneading action that compacts the asphalt mixture specimen. After AC specimens were made, it will allow characterization of the temperature-stress dependence at several selected temperatures, 40 ℃ and 60℃, and stresses, 240 kPa, during 60min(±15sec) loading and 60min(±15sec) unloading period of the static creep testing that characterizes its dependence of these same specimens. Under a constant stress-rate performing, resulting deformation, time-dependent strain $\varepsilon(t)$ is calculated and recorded. From recording results, the deformation component can direct be calculated easily, which could explain the full mechanical behavior.

In a typical static creep loading test, a load is applied as constant value to an AC specimen, which then deforms. From the dimensions of the specimen and the magnitude of the applied load, the constant stress σ_0, resulting deformation, strain ε (t) is calculated. The creep compliance, D(t), is then given by the following relationship:

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} \tag{6}$$

The total creep compliance of an AC specimen under loading and unloading periods of the static creep testing consists of elastic, plastic, viscoelastic, and viscoplastic components. Figure 2 shows the complete deformation behavior.

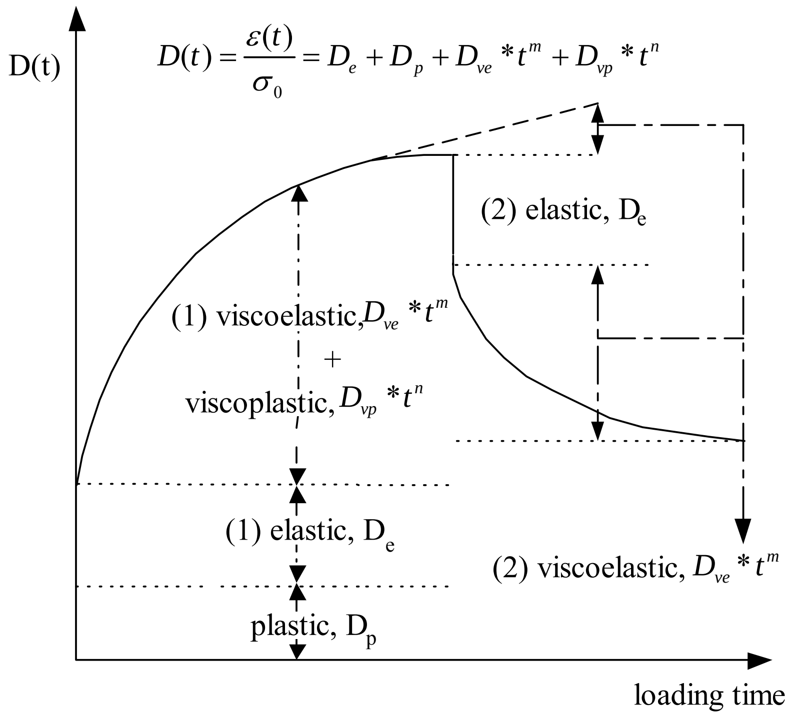

Figure 2 Creep Components of asphalt concrete

Based on all creep compliance from the static creep test, the total creep compliance is calculated through the assumption that the different deformation components can be calculated separately and then be added to account for the permanent deformation. The creep compliance can be expressed as follows:

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} = D_e + D_p + D_{ve} * t^m + D_{vp} * t^n \tag{7}$$

where D_e = elastic compliance; D_p = plastic compliance; $D_{ve,\ m}$ = viscoelastic compliance and time-dependent parameter; $D_{vp,\ n}$ = viscoplastic compliance and time-dependent parameter; t = loading and unloading time(0~7200 sec).

A creep-law model is used to characterize the viscoplastic properties of the asphalt mixtures. This viscoplastic compliance is calculated by time hardening power law, as listed in Eq. (8). The loading time, t, is for deterioration simulations where the impact time of each loading cycle from traffic is accumulated into a total loading time. A finite-element program, ABAQUS, is used to apply Eqs. (7) and (8) to characterize material properties..

$$\dot{\bar{\varepsilon}}^{cr} = A \cdot (\bar{\sigma}^{cr})^n \cdot t^m = q \cdot \frac{D_{vp}}{m+1} \cdot t^{m=1} \tag{8}$$

where $\dot{\bar{\varepsilon}}^{cr}$ = equivalent creep rate; $\bar{\sigma}^{cr}$ = the equivalent creep stress; t is the total creep/duration loading time; A, m and n are material parameters; and q=equivalent deviatoric stress.

4. FINITE-ELEMENT METHOD

The ABAQUS program is a three-dimensional, dynamic finite-element (3D-DFEM) program that has the capacity to simulate actual vehicle loading conditions and estimate the structural response for flexible pavements. This program has been successfully used by other researchers (Zaghloul and White 1993; Cho et al., 1996); thus, ABAQUS was employed in this study to analyze the response of flexible pavements under traffic loading. ABAQUS solves the dynamic analysis of traffic loading by using the eigenmodes of the system as a basis for calculating the response. The traffic flow is separated into four levels of service (LOS) dependent on the travel speed, i.e., LOS A at 90 kph, LOS B at 60kph, LOS C at 45kph and LOS D at 20kph (MOTC 2007). The D level of service indicates high density, but stable traffic flow.

A time-dependent loading is presented in Figure 3. The time segment is a function of speed and the length of the contact area. This process is repeated for the different elements in the wheel path at different times depending on the traffic speed. In 3D-DFEM, the load-time history on the loaded areas varies as a function of the velocity of the moving vehicle. The time segment is assumed to be 10^{-5}sec as micro-time (Δt) when a wheel just gets on the starting node or away from the terminal node. The typical traffic loading of a semitrailer is shown in Figure 4

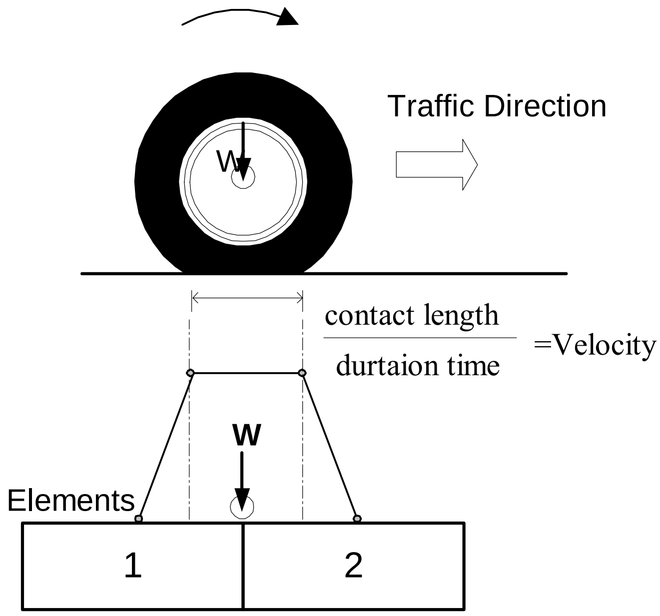

Figure 3 Relationship of load amplitude and wheel-load passing on one-point

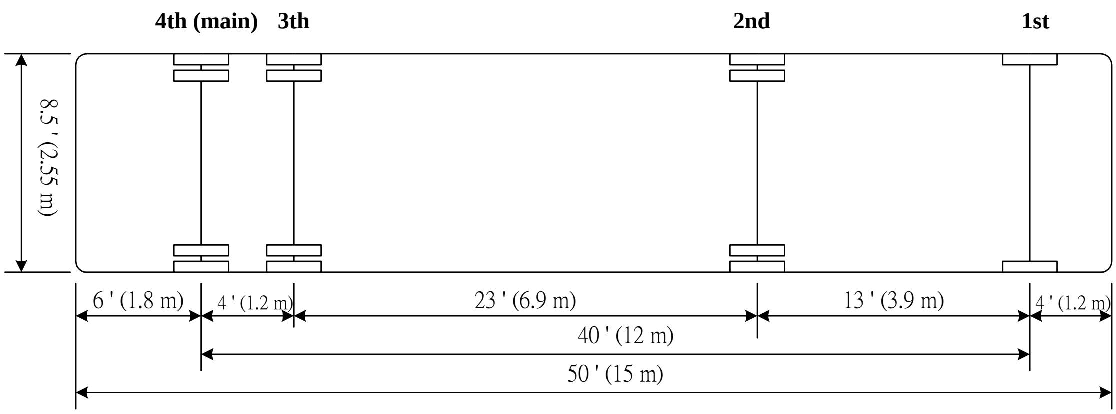

Figure 4 Typical configuration of a semitrailer

In the 3D-DFEM analysis, paving materials were divided into two groups: asphalt mixtures and granular material. Resilient modulus experiments were conducted for each group, and the actual material behavior was taken into account. Asphalt mixtures were modeled as a viscoelastic/viscoplastic material that is time- and temperature-dependent. The time-dependent properties were represented by instantaneous and long-term shear moduli. The temperature effect was considered through the changes in shear modulus values at different temperatures. Granular materials, which consist of base, subbase and subgrade, were modeled using the Drucker-Prager model. This is an elastic-plastic model in which granular materials are assumed to behave as elastic materials for low stress levels. When the stress level reaches a certain yield stress, the materials will start to behave as an elastic-plastic material.

The 3D-DFEM model was developed to represent the pavement structure using brick elements. Because of symmetry, one-half of the wheelpath, together with one side of the surrounding region, was used. The finite-element mesh consists of a fine mesh close to the load and a coarse mesh far from the load. Mesh dimensions in the vertical direction was selected to match the pavement thickness. A 5.28-m long wheelpath with half-infinite elements on both sides was used to reduce the end effect. Both the asphalt concrete surface and base courses were model as a double-element layer. The subbase course was modeled as a single-element layer, where as the subgrade was modeled using half-infinite elements. The appropriate boundary conditions were used. The mesh dimensions were constrained to satisfy the appropriate aspect ratio to have the loaded area required and to achieve the desired degree of detail.

5. IN-SERVICE TEST ROAD

The Taiwan Area National Freeway Bureau (TANFB) began a three-year research program to investigate the effect of various asphalt materials on pavement performance. A 4-km in–service test road was constructed to investigate the effects of straight asphalt concretes (AC) and polymer-modified asphalt concretes (MAC) on pavement performance. Pavements sections from 251k+850 to 255k+850 in the south bound were selected for field studies, as shown in Figure 5. The test sections on this 6-lane highway represented typical traffic and environmental conditions that pavements experience in Taiwan. The pavement system was built as a four-layer system, including a 15-cm AC course over a 20-cm bitumen-treated base course, later, a 30-cm granular subbase and a 75-cm subgrade, from top to down, separately. This test road was built with a single aggregate gradation with four binders including two straight asphalts and two polymer-modified asphalts. Two conventional asphalt concretes and two polymer-modified asphalt concretes were used in this study: AC 60/70, AC 40/50, MAC 1 and MAC 2. The former two were commonly binders used for highways in Taiwan. The latter two were mixed in this study to conform to the ASTM specification D-5892. Extensive laboratory tests and field surveys were conducted, and data were analyzed and compared. The data included pavement structure, traffic loading, travel speed, pavement temperature monitoring, materials data and performance surveys in this study. A database administered by the TANFB was employed in this study for the pavement performance.

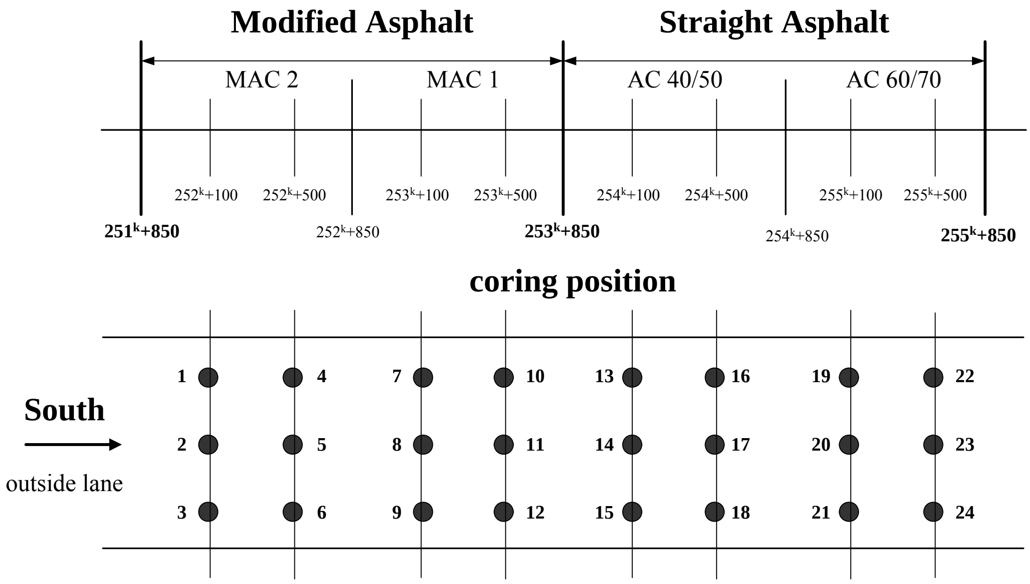

Figure 5 Layout for in-service test road

6. RESPONSES UNDER VARIOUS TRAFFIC SPEEDS

The Highway Manual in Taiwan indicates that the traffic flow can be separated in 4 level of service dependent on the travel speed, i.e., level A in 90 (kph), level B in 80kph, level C in 45kph and level D in 20kph. In order to analyze dynamic mechanical responses under various travel speeds on the surface of flexible pavement in a real traffic phenomenon, the distribution of truck speeds were collected in field, as shown in Figure 6. These speeds are 5 % in 20kph, 15% in 45kph, 30% in 80kph, and 50% in 90kph. The distributed ratios of various speeds were used in this study for dynamic loading analysis. The single-axle traffic loading passing a referenced point of established pavement model was simulated and took into account the variation of travel speed (from 20 to 90 km/h). Of particular interest is the response curve for vertical elastic strain at the top of the AC surface. Figure 7 shows effects of various travel speeds moving over the referenced point; the traffic loading with low speed, 20kph passing, induce the highest compressive strain on the surface; however, with a high speed of 90kph, the strain varies from compression to tension alternately. The swift shift changes in compression and tension may lead to fatigue cracking on pavement surface, particularly under overloading traffic. According to field observations, the load-associated fatigue cracking of flexible pavements that occur in the wheel path could initiate at the bottom of the surface layer and propagate to the surface. It could also be initiated at the surface of the pavement and propagate downward through the surface layer. The penetration of water and other foreign debris into these cracks can further accelerate the propagation of the crack through the surface layer.

The maximum vertical compressive strain at the top of the AC surface corresponding to travel speed of 20kph is approximately two times greater than that corresponding to a travel speed of 90kph. The lower speed, the more severe distress would be. In other words, pavement distresses would be likely to occur more often during traffic jam than normally operating speed.

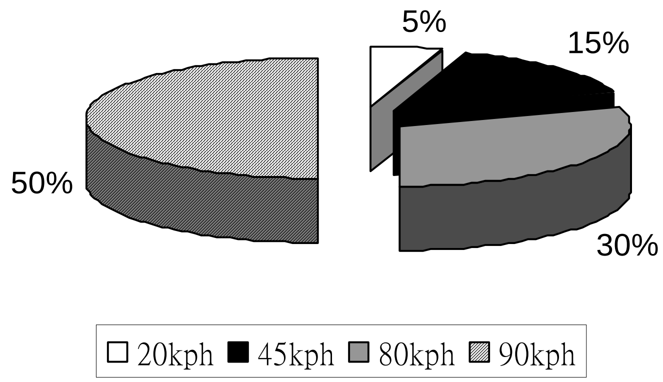

Figure 6 Distribution of truck speed

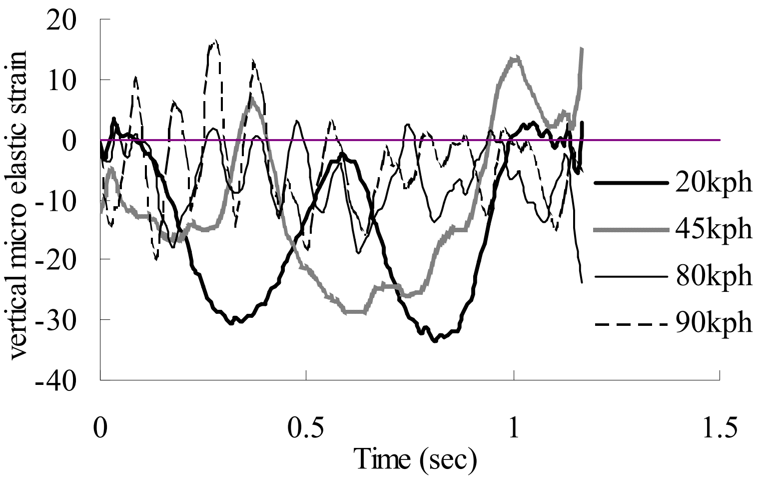

Figure 7 Effects of travel speeds moving on the surface of pavement (AC60/70)

7. VALIDATION

Figure 8 shows the rut depth for the pavements after 9,340,772 repetitions. Traffic loading within the regulated 14.5 tons causes much less rutting than the overloaded 22.5 tons. As the traffic weight is overloading, the surface layer tends to be subjected to more rutting because of stress concentration that leads to rutting at the top of the pavement structure. Note that the bituminous-treated base shows good resistance to rutting, and the granular subbase is susceptible to more rut depths under heavier loads. All layers contribute to the overall rut depth as shown in Figure 8. The contribution of each layer to rutting depends on traffic loading, material property and pavement structure. The AC base has less rut depth than the AC surface in the case of overloading traffic. The increase in permanent deformation in the AC base may result from the large-stone gradation in the AC base. The use of large size stone (maximum size of more than one inch) in the asphalt mixture could minimize the rutting of heavy duty pavements. Other researchers also report similar results (David 1988; Fernado et al. 1997). The difference between AC surface and AC base appears to be insignificant under regular traffic. The highest permanent deformation occurs at the subbase layer when traffic is overloading. It implies that the stress distribution from overloading traffic is more concentrated in the subbase layer, leading to more rut depth.

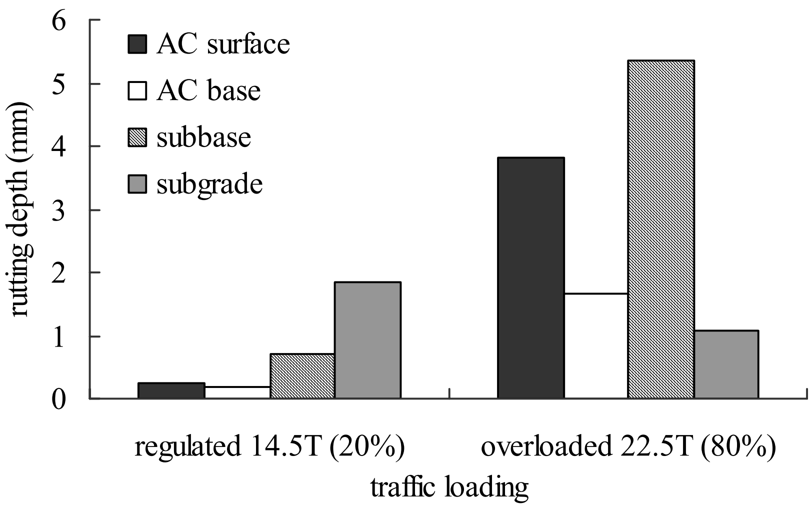

Figure 8 Effects of different traffic repetitions 9,340,772 for a pavement constructed by AC60/70

Table 1 is the list of the predicted versus observed rutting values. The observations are close the predicted values, indicating a good fit between the model and the data. The Wilcoxon Matched Pair test is performed to test the hypothesis that the observed and predicted rutting values are drawn from the same distribution. The significant level of test is at 0.05 (5%). The test shows that the p-value is 0.698, which is much higher than the significance level. Therefore, the observed and predicted rut depths are concluded from the same distribution. The field test results validate the adequacy of the model.

Table 1 Comparisons between analytic predictions and observations in field

Rut depth (mm) observed in field and predicted by the model									
Type of AC		AC40/50		AC60/70		MAC 1		MAC 2	
Observed days	ESALs	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
135	1,732,735	7.0	5.80	8.0	8.11	6.0	5.76	5.0	4.25
196	2,578,549	7.0	7.13	8.0	9.44	6.0	7.09	5.0	5.12
257	3,378,746	10.0	8.26	11.0	10.56	8.0	8.21	6.0	5.72
349	4,577,453	11.5	9.70	14.0	12.01	11.0	9.66	8.5	6.73
472	6,197,109	12.0	11.19	15.0	13.50	12.0	11.15	8.5	8.00
694	9,340,772	12.0	12.60	15.0	14.90	12.0	12.55	10	10.17

9. CONCLUSIONS

This paper is to develop a mechanical model for evaluating pavement responses subject to traffic loading. The proposed rutting model is to take into account various asphalt materials in test sections under actual traffic loading variations. Based on the analyses and test results presented in this paper, the following conclusions can be made:

- A new mechanistic-based model was developed to account for contributions of all layers and to predict rut depth as a function of the pavement responses in all pavement layers. The model allows the characterization of traffic in terms of loading groups instead of traditional equivalent single axle load.
- The strain response of paving materials to applied stresses is decomposed additively into an elastic part, a plastic part, a viscoelastic part and a viscoplastic part. The response and modeling of these components include the development of a constitutive formulation that is capable of generating strain hardening when the loading is applied in one direction.
- The finite element technique gives the user the option of performing calculations with constitutive expressions developed in this study. It also offers the possibility to simulate different traffic loadings on the surface not only from a single wheel but also from a complete truck as loading groups with several axles.
- The vertical elastic strains on the surface of various travel speeds indicated that the maximum vertical compressive strain at the top of the surface layer corresponding to travel

speed of 20kph was approximately two times greater than that corresponding to a travel speed of 90kph. Furthermore, a 20-kph passing speed might cause higher compressive strain on the surface. On the contrary, a 90-kph passing speed could lead to the strain varying from compression strain to tension strain alternately. It implied that low traffic speeds would result in more rut depth while high speeds may be related to fatigue distress.

- Under overloading traffic, the contribution of the surface layer to rutting was less than that of the base and subbase layers combined. The use of polymer-modified asphalt was shown to improve the resistance to permanent deformation from overloading traffic.
- Results obtained from the in-service road indicated a reasonable agreement between predicted and observed rut depths. The field test data validated the mechanistic model proposed in this study.

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