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RUT PREDICTION MODEL FOR LONG LIFE ASPHALT CONCRETE PAVEMENT

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Abstract: The objective of this research was to model rutting of long life asphalt concrete (AC) pavement subjected to non-uniform traffic loading and ever-changing temperature cycles during its service life. Estimation of critical stress states within the pavement structural layers had been evaluated using finite element (FE) program based on long life asphalt concrete concept. A Burger-based rut prediction model, which evaluated the accumulation of rutting within the asphaltic layers, had been developed and programmed by taking into account the prevailing traffic loading spectrum, material properties, structural geometries and the fluctuations of the temperature likely to happen across the depth of pavement during the presumable design period. 2D and 3D pavement models had been analyzed with different layer modulus. The FE analyses showed that critical vertical and shear stresses were developed within the surface and binder layer, respectively. The rut prediction model indicated that the rate of rutting had been predominantly influenced by the viscous parameter and temperature of the asphaltic layers. In addition, structural geometry, traffic characteristics, wander effects and speed played major role on rutting. It had been concluded that selecting an optimum structural thickness and material parameter were vital to reduce the rate of rutting. The analyses indicated that thicker asphaltic layers reduced the distresses developed within the substructures (Subbase and subgrade) and confined the rutting within the superstructures (asphaltic layers)..

1 BACKGROUND

The repetitive traffic loading that the road experiences during its service life combined with environmental factors causes permanent deformation, fatigue cracking, instability and other forms of damages. Estimation and prediction of the maximum distresses within the pavement layer is vital for proper design of the pavement. Modeling of the deformation behavior of AC enables better understanding of the deterioration mechanism and assists to design most economical and long lasting road. At the same time, better understanding of materials behaviors and structural responses of asphalt concrete allows for optimization of asphalt pavement thickness and material choice.

Many models developed so far estimate the number of repetitions to failure in the rut and/or fatigue mode. But basic fundamental traffic characteristics such as speed, loading spectrum, wander effect and temperature fluctuation rather have not been included in damage prediction model. Because of such reasons a pavement deformation model has been developed which aimed mainly at rut accumulation over a period of time due to time dependent mixed traffic flow as well as daily and seasonal temperature variations. An attempt has been made to evaluate the permanent deformation with different material parameters, temperature fluctuation, structural geometry as well as traffic characteristics.

1.1 Traffic Characteristics

Excessive deformation resulting from frequent repetitions of vehicle loads in heavy duty asphalt-concrete pavements has been the main concern. The simplest pavement structural model asserts that each individual load inflicts a certain amount of unrecoverable damage, however, trucks have a greater share and wheel loads of heavy vehicles are considered as primary contributors.

Most design standards require quantification of various loading levels that a pavement encounters over its design life. A possible solution is to use the number of equivalent single axle loads (ESAL) which converts wheel loads of various magnitudes of the mixed traffic to a single load. The other solution is the load spectra approach that uses the actual traffic data without converting into ESAL and correspond time variations of the traffic flow, which is adopted in this research as shown schematically in Figure 1 below.

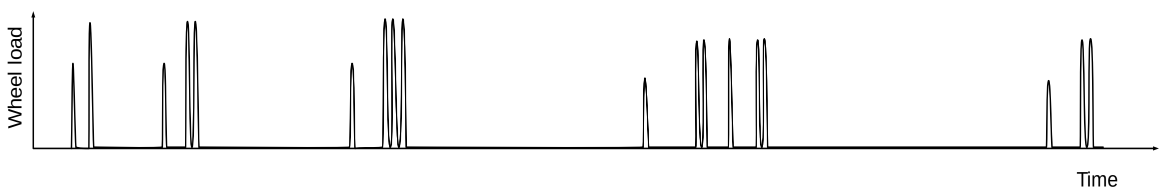


Figure 1: Schematic representation of wheel load applications with time

Many of the existing mechanistic pavement response models did not include vehicle speed and wander effect as an important factor. But evidences showed that the magnitude of the calculated pavement strain response had decreased with increased vehicle speed (Siddharthan et al. 2002). In addition, the distribution of vehicles path in the transverse direction played a significant role in pavement performance (White et al. 2002). At the beginning of the service life the evenness of the pavement may give the drivers psychological freedom to manoeuvre their vehicles within the available lane space. The wander effect plays here a constructive role in minimizing the rut formation. After a period of time the gradual appearance of rutting along the wheel track would rather influence drivers to adhere to the center of lane which ultimately accelerate the rut formation along the wheel track.

Figure 2: Rut formation along the wheel track

In this research, a load spectrum approach has been adopted to characterize the traffic input. About 15 types of vehicles with corresponding wheel loads, vehicle proportions, hourly flows, operating speeds and wander effects have been taken into account.

1.2 Thermal Properties of Asphalt Concrete Pavement

The temperature distribution in a pavement has directly been affected by the thermal properties and environmental conditions to which the pavement has been exposed (Yavuzturk et al. 2005). The ability to accurately predict asphalt pavement temperature is helpful to perform back-calculations of materials' parameters. Due to heat exchange, the change of the pavement temperature has been delayed compared with air temperature (Huang et al. 2008); the deeper the location has been the later each portion of pavement has reached its highest temperature. The temperature distribution within a pavement (Wellner and Kayser 2008) indicated that the thermal propagation depended on the conductivity of the material, the amplitude of periodical temperature change at the surface of the asphalt pavement, cycle time and other thermal behaviour of the system. Typical temperature gradient across the depth of the asphaltic layer is illustrated as shown in Figure 3 below.

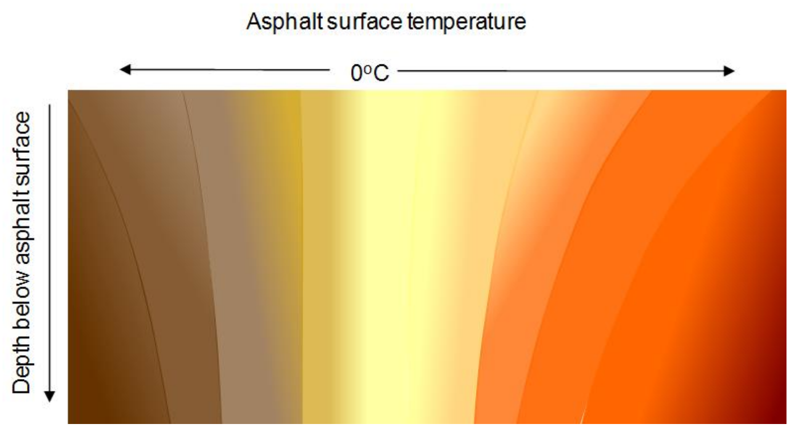


Figure 3: Temperature gradient within the asphalt layer

It has been indicated (Werkmeister et al. 2003) that the maximum temperature occurs at the superstructure relative to substructure. This highly affects the viscoelastic characteristics and performance of the asphalt concrete layers. The stresses applied on asphalt pavements at high temperature caused relatively higher damage (Wellner and Kayser 2008).

Temperature plays dominant role in the variation of modulus of AC layers. The variation has typically been related to the average temperature of a layer, which in turn depended on the temperature gradient within the layer (Nazarian and Alvarado 2006).

2 PAVEMENT RUTTING

Most failure criteria have been attributed mostly to the weak pavement structure (subgrade) in terms of the vertical compressive strain to the number of cycles to failure. However, rutting has been observed in Germany in some thicker asphaltic layers due to the fact that pavements had been constructed over a strong and non-yielding substructures that led rutting to be developed and confined within the AC layers. Pavement constructions with thick asphalt layers contributed lesser or no risk of rutting in the granular layer even at higher number of load application (Werkmeister et al. 2003), implying that only asphalt layers are liable to rutting for thicker AC pavements.

Rutting is a major distress form when the ambient temperature is high such as in hot tropical climate regions or during the summer months of temperate zones. At elevated temperatures, AC mixes has become softer and exhibited markedly different volume-change and shape-distortion deformation modes in terms of their sensitivity to temperature and rate of loading (Harvey et al. 2009). At high temperature or under slow moving loads, hot mix asphalt exhibited purely viscous flow, which resulted in severe rutting (Elseifi et al. 2009).

3 LONG LIFE PAVEMENT DESIGN CONCEPT

Modelling and analysis of long life asphalt concrete pavement have been advocated for the past several years. Until recently, asphalt concrete roads have been designed to serve 20–25 years. In fact, some roads which had been constructed with the same design life have been serving for more than 30–40 years. The long-life pavement structures have consisted of but not limited to impermeable, durable, and wear resistant top layers; a stiff and thick rut-resistant intermediate layer; and a flexible fatigue-resistant bottom layer resting on a stable and high-strength foundation (Walubita et al. 2008). Of course, pavements that are built above certain threshold strength would have sustainable structural life.

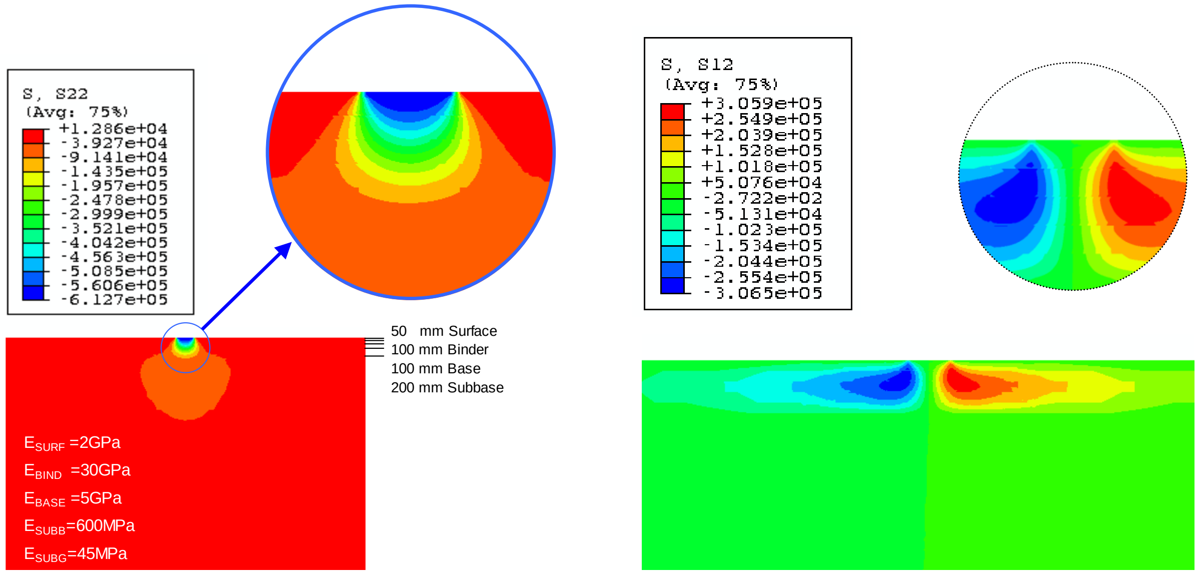
Researches indicated that major distress forms are associated with the thickness of the pavement structure. It has been found (Nunn and Ferne 2001) that high rates of rutting were associated with thin asphalt pavements, whereas, thicker sections showed a slow rate of rutting which was confined to the top layer of the pavement. It was suggested (Park et al. 2005) that the ability of AC pavements to carry heavy axle loads was achieved by improving the stiffness of the asphalt structure and adjusting the thickness.

An effort has been made to stretch the life of the pavement through mitigation (Epps 2000) of the source of distress and use of more resistant materials. It has been reported (Lee et al. 2007(1), Lee et al. 2007(2)) that high modulus asphalt binders and mixes showed higher dynamic modulus and lower rutting depths than those of the conventional mix at high temperatures. The low voids content and high stiffness of hot mix asphalt concrete (HMAC) also provided protection to the base course and great resistance to rutting (Corté 2001).

4 FINITE ELEMENT ANALYSIS

In this research, the primary responses of AC pavements are evaluated by ABAQUS finite element program. The stress states responsible for rutting were vertical compressive and shear stresses, which were proportional to the applied tire pressure on the surface of the pavement. For thicker pavements, the maximum vertical compressive stress has been developed in the wearing layer and confined within the wheel foot print of the AC layers. There has been a significant drop in magnitude of this stress at lower depths (at subbase and subgrade layers), however, the influence area got wider. On the other hand, the maximum vertical strain has been observed at the top of the subgrade (as evidenced in many literatures) due to its lower stiffness characteristics. Relatively, the vertical strains within the intermediate layers (binder, base and sub base) have been lower than strains in both the wearing and subgrade layers because of higher vertical stress within the wearing course and higher elasticity modulus in both binder and base layers.

The structural properties have significant role on pavement responses. A 2D pavement model has been analyzed with different layer modulus with varying thicknesses. A typical FE model of wearing, binder base and subbase courses with thicknesses of 50mm, 10mm,10mm and 20mm, respectively, and corresponding elastic modulus of 2GPa, 30GPa, 5GPa and 600MPa is illustrated as shown in Figure 4 below. For comparison purpose, the layers' thickness and elastic modulus had been made to vary for different analyses except the subgrade layer which has sufficient thickness and constant modulus of elasticity.



a. Vertical stress distribution

b. Shear stress distribution

Figure 4: FE analysis output of 2D AC pavement model

As shown in Figure 4, the maximum vertical and shear stresses developed at the surface and intermediate layer, respectively. The analysis indicated that increasing the binder E- modulus decreased the magnitude of the vertical stress developed within each layers. An increased the E-moduli of the binder twice yields 4.9% and 14.3% reduction in vertical stresses developed at the mid-depth of the binder and base layers, respectively, just directly below the point of load application. While increasing the same by forth fold yielded as well 11.1% and 27.6% reduction in these layers. There was a reduction in vertical and shear strains and an increased in lateral stress within the wearing course with higher E-values wearing layer. It was clearly indicated from the analysis that the strength of the asphaltic layers was in favour of the subbase and subgrade layers in decreasing the stress-strain states. Higher elasticity modulus in the binder course rather increased the shear stress developed with in the binder itself and decreased the same in the base course and vice versa. The shear strain, in both cases reduced with increasing the E-moduli of the layers.

The structural thicknesses greatly affected the responses of the pavement. The analysis indicated that the stress-strain states in general decreased with increasing the asphaltic layer thicknesses. There have been significant reductions in the shear stress and strain states as well as reduction in vertical strains below the asphaltic layers with increasing AC thickness.

5 RUT PREDICTION MODEL AND ANALYSIS

Accurate performance predictions are possible only if the nature of the material is properly modeled. The temperature, strain rate as well as the state of stress dependency and the material responses can not be neglected. An attempt made to evaluate the damage accumulation with FE demanded huge memory space and high computation-time to simulate prevailing traffic and climatic/temperature/ change simultaneously. A rut prediction has been developed and programmed (with C programming language) based on Burger material model. The model evaluated the accumulation of rutting during the presumable design period of the pavement under the prevailing traffic and temperature ranges for every hour of a day throughout the year. The pavement responses under various loading, material properties and pavement structural geometries have been extracted from FE analyses.

5.1 Burgers Model

The rheological parameters were obtained by approximating the creep curve with theoretical curves determined for the viscoelastic Burgers model. Equations 1 through 4 describe the relation between time and the Burgers model's rheological parameters.

For loading time $t<t_0$

[1] $$\varepsilon(t)=\sigma_0\left[\frac{1}{E_1}+\frac{t}{\eta_1}+\frac{1}{E_2}(1-e^{-tE_2/\eta_2})\right]$$

For time $t>t_0$

[2] $$\varepsilon(t)=\sigma_0\left[\frac{t_0}{\eta_1}-\frac{1}{E_2}e^{-tE_2/\eta_2}(1-e^{-t_0E_2/\eta_2})\right]$$

Where $\varepsilon(t)$ - strain (mm/mm) at time t

σ_0 - applied stress (pa)

E_1, E_2 - immediate and delayed elastic modulus (pa), respectively,

η_1, η_2 - immediate and delayed Burger's viscous component (pa.s), respectively

t_0 - maximum loading time (s)

t - any time (s)

In case of a relaxation test where constant strain is applied, the time dependent modulus of elasticity is expressed as:

[3] $$E(t)=E_1e^{\frac{-t}{\tau_1}}+E_2e^{\frac{-t}{\tau_2}}, \text{ or}$$

[4] $$E(t)=E_1e^{\left(\frac{-E_1t}{\eta_1}\right)}+E_2e^{\left(\frac{-E_2t}{\eta_2}\right)}$$

Where E(t)-time dependent relaxation modulus (pa)

τ_1, τ_2 - immediate and delayed relaxation parameters (s), respectively.

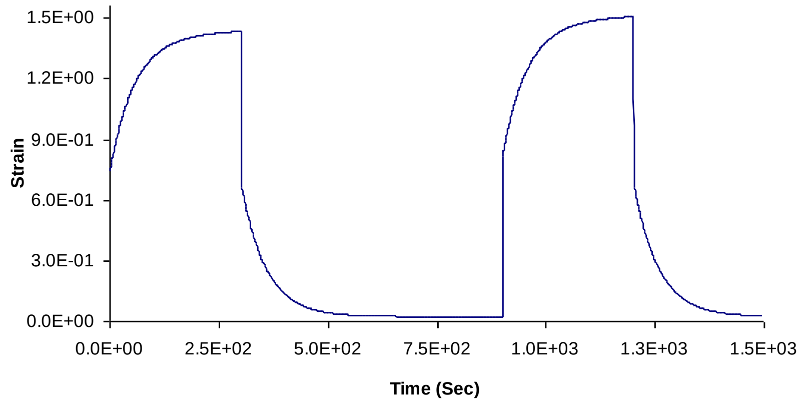


Figure 5: Burger model strain response during loading and unloading cycle

The viscous components of the material governed the rutting behaviour and depended on the rate of loading and unloading. The instantaneous response reflected the time-independent component, whereas the viscous response reflected the time-dependent component. The relative contribution of each component depended on temperature and loading condition.

To predict the accumulation of rutting during the service life, the stress state was evaluated at the mid depth of each asphaltic layer. The total rut depth was obtained by summing the products of the average permanent strain at mid depth and corresponding thickness of each layer (using Equation 5). The permanent strain, ε_i^p, has been evaluated for every single wheel load application at presumable temperature (Equation 1 and 2). The time factors associated in the Burgers model were computed from the hourly volume and traveling speed of the vehicle.

[5] $$\Delta = \sum_{j=1}^{m}\left[\sum_{i=1}^{n}\left[(\varepsilon_i^p)(\Delta Z_i)\right]\right]$$

Where ΔP - total rut depth (mm),

ε_i^p – average permanent strain in the ith asphalt layer (mm/mm),

ΔZ_i – thickness of the ith asphalt layer (mm),

n – total number of sublayers and

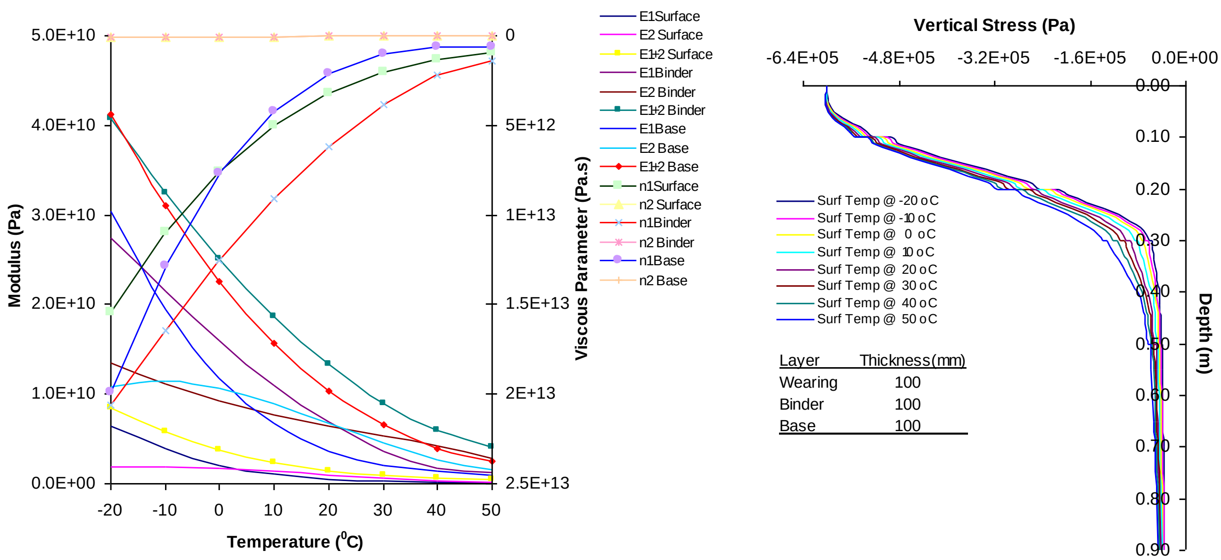
m –total number of wheel load during the service life.

The transient temperature variance of pavement and timing of loading/unloading have been taken into account as this would guarantee a more reasonable simulation, closer to the field situation and more effective to address the rutting behaviour.

5.2 Results

The initial traffic, growth rate, composition, proportion and slow moving heavy vehicles highly affected the results. At later time of the service year, the number of vehicles increases rapidly (depending on the rate of traffic growth) which demands relatively longer loading time (due to traffic congestion and lower operating speed) and/or shorter unloading time which resulted in severe rut formation. Keeping material and structural properties the same, the deformation curve has shown a rapid increment at later years with 7.5 % growth rate which suggests that design standards have to thoroughly select applicable rate to reasonably address associated rutting and avoid over or under estimation of the pavement structure.

On the other hand, the following analysis was made on a maximum temperature ranging of -15 to 50 ^{0}C at 4.5% growth rate with different initial traffic volumes (800 commercial vehicles per day (cv/d) to 1500 cv/d or 27.89 to 52.30 million ESAL 80kN, respectively, at 40 years). The material properties and FE results at different temperature are shown in Figure 6.



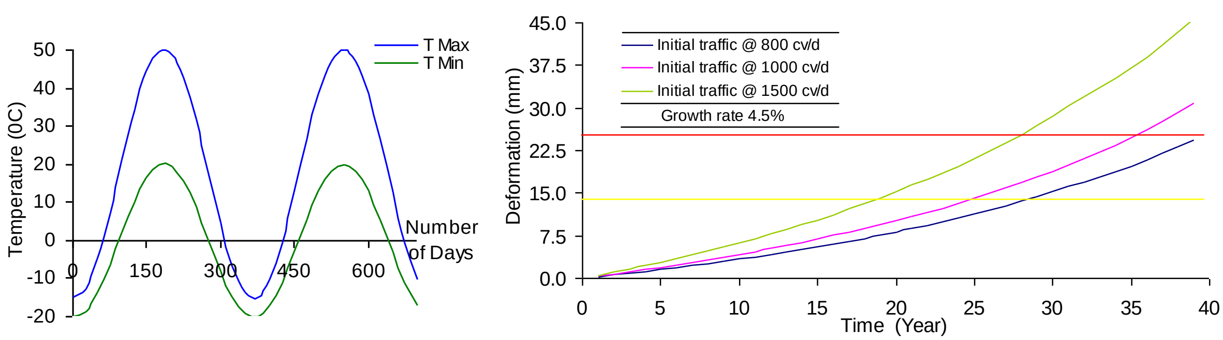
a. Material properties

b. FE vertical stress results

Figure 6: Material properties and FE structural responses at different temperatures

The analyses had taken into account the daily temperature variations expressed in terms of the coordinates of the maximum and minimum daily temperature. As shown in the Figure 7 below, the structural geometry and material characteristics described in Figure 6 can serve for more than 30 years when the forecasted traffic was below 26.55 million ESAL under the temperature range mentioned above.

At the same time, an attempt has also been made to evaluate the effect of material characteristics. The analyses indicated that, enhancing the viscous component brings a change even at relatively higher temperature. The immediate viscosity parameter, particularly at higher temperature, plays a significant role. The same structural geometry could sustain an ESAL of 40–50 million ESAL for about 30-40 years at a maximum temperature range of 0–50 ^{0}C when the immediate Burger's viscous parameter (η_1) in Figure 6 was increased by double.



a. Temperature variation

b. Permanent deformation

Figure 7: Permanent deformation under different traffic volume and temperature

Several results indicated that better performance could be achieved if the viscous parameter at higher temperature was relatively higher. It has been obtained that thicker AC layers with a minimum of range of $x10^3$ GPa.s of immediate viscous parameter (η_1) at higher temperature would give a promising long life to the pavement structure.

6 CONCLUSION AND RECOMMENDATION

It has been concluded that apart from the applied traffic load and the structural geometry; the temperature and the viscoelastic materials properties played leading role on rutting. Higher viscous parameters of the asphaltic layers would guarantee lower rutting rate and better performance. Thicker asphaltic layers reduced the distress developed within the substructure (Subbase and subgrade) and let rutting to be confined within the superstructure. Providing better quality of materials with reference to viscous parameter would insure durable and better performance road. It has been highly regarded and economical to consider the design of pavements on the bases of long service life which could be achieved by thoroughly identifying the various response of a pavement developed due to a combination of different load and environmental factors.

It is recommended that the influence of the shear stress is better modeled and integrated with rut analysis model to refine the work. A comprehensive model is recommended which include fatigue, damages caused by moisture and other modes of failure in order to mitigate the complex nature of possible damage modes and the significance of the particular associated factors. The program contained subroutines which dealt with the traffic characteristics and the daily and annual fluctuation of temperature which could be integrated and implemented in fatigue and low temperature cracking model to evaluate such modes of damages during the service life of the road. In addition, calibrations of the results with field result and/or previous works are most beneficial. Finally, incorporating possible sources of uncertainties and quantifying them statistically would be helpful.

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