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Implementation and Proof-Checking of Mechanistic-Empirical Pavement Design for Indian Highways Using AASHTOWARE Pavement ME Design Software

Arpan Ghosh[a] A. Padmarekha[b] J. Murali Krishnan[c1]

[a] *Pavement Engineer, V R TECHNICHE Consultants Pvt Ltd, Uttar Pradesh, India, Email - arpan.ghosh@vrtechniche.in*
[b] *Associate Professor, School of Mechanical and Building Sciences, Vellore Institute of Technology, Vellore, India, Email - apadmarekha@vit.ac.in*
[c] *Associate Professor, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India, Email - jmk@iitm.ac.in*

Abstract

In the current practice of flexible pavement design as per Indian Roads Congress (IRC), the influence of cyclic change in pavement temperature, traffic speed and aging on the material behaviour has not been considered. However, these factors influences the behavior of bituminous mixture and hence the pavement thickness. In this investigation, the influence of temperature, vehicle speed and aging on the dynamic modulus of the bituminous mixture was considered and an IRC pavement cross section was analyzed using AASHTOWARE pavement ME design software. The traffic data required for the design was collected from an existing National Highway and weather data used corresponds to Chennai city. For material characterization, two types of bituminous mixture sample were fabricated in the laboratory satisfying the Bituminous Concrete grade-2 (BC-2) and Dense Bituminous Macadam grade (DBM) specification of the Ministry of Road Transport and Highways, India. The dynamic modulus of these samples were measured at frequencies ranging from 0.01 to 25 Hz at temperatures ranging from 5 to 55 ºC and the mater curve was constructed and used in the pavement design. It was found that most of the cross-sections failed to satisfy the design requirements when subjected to rigorous analysis, design and proof-checking. For a target life of 8 years, the required thickness of the bituminous layer was worked out and the thickness was found to be considerably high when compared to the existing thickness as proposed in the IRC guidelines.

Keywords: Mechanistic-Empirical design; dynamic modulus; master curve; truck speed; pavement temperature; rutting; fatigue cracking;

1 Corresponding author. Tel.: +91 44 2257 4284; fax. : + 91 44 2257 0545.
E-mail address: jmk@iitm.ac.in

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Introduction

In the current practice of flexible pavement design as per Indian Roads Congress (IRC) the thickness of the pavement layers are decided based on two main distresses and they are rutting and fatigue cracking (IRC 37, 2012). The vertical compressive strain on top of subgrade is considered as a design factor for rutting and the horizontal tensile strain at the bottom of bituminous layers is considered as a design factor to limit fatigue cracking. Depending on the expected traffic loading and bearing capacity of the subgrade soil, IRC 37, 2012 provides different templates for thickness based on the limiting design factors for rutting and fatigue cracking. Most of these design charts are derived by considering the critical temperature of the pavement as 35 °C. However, the pavement temperature changes in a cyclic manner and at various geographical locations across India, the minimum pavement temperature can be as low as -10 °C and the maximum pavement temperature as high as 70 °C (Krishnan and Veeraragavan, 2012). The temperature greatly influences the properties of the asphalt mix and the material characterization at an average temperature will not always captures the critical rutting and fatigue response of the pavement.

Another factor that influences the asphalt layer response is the speed of the vehicle. The rutting on the asphalt layer due to slow moving truck is considerably high when compared to the rutting induced due to fast moving vehicle. To characterize the behavior of the asphalt mix due to various truck speeds, AASHTO recommends the use of frequency dependent dynamic modulus function (NCHRP, 2004). For the mechanistic empirical pavement design approach as per AASHTO, the dynamic modulus of asphalt mixtures are measured at different temperatures and frequencies and the master curve is constructed appealing to time temperature superposition principle. Using the master curve and the shift factors at different temperatures, the dynamic modulus at any temperature and frequency (speed) can be interpolated.

The bituminous mixture also ages due to repeated traffic loading and climatic changes (Petersen, 2009). As the material ages, the mixture becomes stiffer and this greatly influences the fatigue response of the layer. One can capture the appropriate fatigue response of the layer only if the material characterization input is age dependent function. The accuracy of the pavement design depends on how accurate one simulates the material response similar to the real life behavior. In this investigation, rutting and fatigue response of the pavement with cross section recommended by IRC 37, 2012 is analyzed using AASHTO design approach. For this purpose, extensive laboratory investigation was carried out to capture the dynamic modulus values of the asphalt mixtures at various temperatures, frequencies and aging condition and used in the pavement design. For a mechanistic-empirical pavement design as per AASHTO design approach, one also needs an extensive weather data to determine pavement temperature at various depths. Also, the traffic data required for the design include vehicle volume, its hourly/monthly distribution, and axle load distribution. The details of the data used for the design and distress response prediction are explained in the following section.

Weather Data

Environmental factors significantly influence the performance of the pavement, especially the performance of asphalt layers. To predict the cyclic change in pavement temperature, AASHTO uses Enhanced Integrated Climatic Model (EICM) to simulate the temperature profile at various depth of the pavement. For this purpose, hourly data for air temperature, precipitation, wind speed, percentage sunshine, ambient relative humidity values and water table depth of Chennai city were used. Consecutive three years hourly data was used to predict the pavement temperature over entire design period. A total of 26280 data set were used to generate pavement temperature at various depths.

The dynamic modulus of the bituminous mixture varies with the temperature. In the AASHTO pavement design, temperatures at various depth of bituminous layer were used and the dynamic modulus of the bituminous mix at corresponding temperature was determined from the master curve. If one uses average monthly temperature for this purpose, the effect of extreme temperature that induces intense damage will be ignored. To account for the extreme changes in temperature, the temperature over a design interval (month) were normally distributed and were divided into five different subsection. Each subsection corresponds to 20 % of frequency distribution and the design temperature (T) for these section were obtained from

$$T = \mu + z(\sigma), \quad (1)$$

where, μ represents the average temperature, σ represents standard deviation and z represents normal deviate of the subsection (NCHRP, 2004). During design, the asphalt layer thickness is divided into sub-layers and the temperature distribution was determined for each sub-layer.

To implement the effect of temperature to the pavement design, one needs an extensive weather data. Recently, Nivitha and Krishnan, 2013, used an extensive weather data of most of the cities in India and determined the temperature of the pavement. They proposed the regression equation to determine the temperature of the pavement at the depth of 20 mm below the surface. They also generated the pavement temperature contours for India. For rigor design, one also requires the model that predicts the temperature variation across the depth of the pavement.

Traffic Characterization

In the design of flexible pavements, most of the design approaches uses equivalent axle load concept and converts different axle load into number of standard axle load. The standard axle load is used to determine the strain response of the pavement. Two issues have to be sorted out in this approach of traffic input. The strain induced due to axle load greater than the standard axle load may not be same as that of the strain due to standard axle load. This is especially true for bituminous like material in which the strain do not recover completely during rest period. Another issue is that the number of standard axle is determined from the annual average daily truck traffic (AADTT). If one considers the real life scenario, the traffic various seasonally. To account for this seasonal variation, AASHTO method of pavement design considers the monthly and hourly adjustment factor and number of axle load for a specific design life increment is obtained from normal distribution of monthly traffic variation. The monthly adjustment factor for traffic is obtained from the ratio of average daily truck traffic of each month to AADTT. This monthly adjustment factor was separately obtained for each class of vehicle. For this purpose, during traffic counts one has to collect data based on the class of vehicle.

The current AASHTO design approach is uses the actual axle load and not the standard axle load. Each axle type (single, tandem and tridem axles) are grouped based on the axle loads and the cumulative number of each axle loads group for different axle types were used for the design. For this investigation, the truck counts for different truck classes and the axle load data were collected on one of the existing national highway near Chennai and used for the design purposes. From the traffic data collected, it was observed that the type 2, type 3 and type 2-S2 class of vehicle as per IRC 3, 1983 contributes to most of the truck volume. Vehicles with tridem axle which cannot be accounted to any class of vehicle as per IRC 3, 1983 were also observed during traffic survey. AASHTO method of pavement design uses the vehicle class classification as per FHWA, 2001. Some class of vehicle as per IRC does not match with any class of vehicle class classification as per FHWA. For instance, FHWA has no vehicle class classification of type 2-S2 class (truck with two single axle and one tandem axle) as per IRC. In such cases, these trucks were counted with class 6 as per FHWA after considering suitable factor of number of axles per truck. The number of axles per truck for different class of vehicle used is tabulated in Table 1. Also, for the design purpose, axle loads from each truck class were separated based on axle type and then grouped based on axle load. Figure 1 shows the axle load distribution for single axle type for class 6 and class 7 vehicles (as per FHWA, 2001).

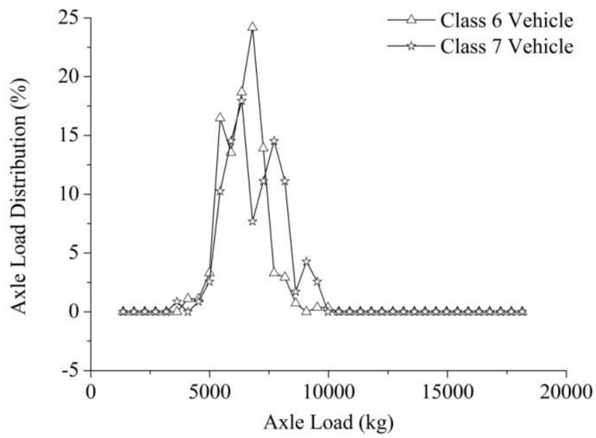


Figure 1. Distribution of Axle Wheel Load

Table 1. Traffic Data used for the Design

Design Parameters	Traffic Data
Annual Average Daily Truck Traffic (Both Direction)	4000
Design Lane width	3.5 m
Axle spacing	
Tandem	1.31 m
Tridem and quad	1.25 m
Number of axles per truck	
Class 4 - Single and Tandem axle	1.62 and 0.39
Class 5 - Single axle	2
Class 6 - Single axle and Tandem axle	1.02 and 0.99
Class 7 - Single, Tandem and Tridem axle	1, 0.26 and 0.83

To study the influence of traffic speed on the rutting and fatigue response of the pavement layer, the design was carried out for two different vehicle speeds of 60 and 100 kmph. The other traffic related factors used for the design are listed in table 1.

Material Characterization

4.1 Binder Characterization

In this investigation, bituminous mix is produced using VG30 grade binder. The performance grade testing of the unaged binder was carried out in accordance with ASTM D7175, 2008 using Anton Paar dynamic shear rheometer (MCR 301). The dynamic modulus and phase lag obtained from the performance grade testing results were used to determine the viscosity of the unaged binder. The equation (2) and (3) were use for this purpose.

$$\eta = \frac{|G^*|}{10}\left[\frac{1}{sin\delta}\right],^{4.8628} \quad (2)$$

$$\log log\, \eta = A + VTS\ logT_R\ , \quad (3)$$

where η represents viscosity, $|G^*|$ represents dynamic modulus, δ represents phase angle, T_R represents reference temperature and A and VTS are regression parameters. The aging viscosity is calculated from this viscosity and the shift factor for dynamic modulus master curve of bituminous mix is obtained from the aging viscosity.

4.2 Bituminous Mixture Characterization

Two types of bituminous mixture sample were fabricating using VG30 binder. The aggregate gradation for the mixture pertains to the Bituminous Concrete grade-2 (BC-2) and Dense Bituminous Macadam grade-2 (DBM) specification of the Ministry of Road Transport and Highways, India. The BC-2 mix for all the samples were prepared for a 4±0.5% target air voids with 5% bitumen content. The DBM mix for all the samples were prepared for a 3.5±0.5% target air voids with 4.5% bitumen content. The binder content and the aggregate gradations were decided after conducting detailed mix design for BC and DBM mix as per Asphalt Institute mix design procedure (Asphalt Institute, 2003). The mixing of binder and aggregate were carried out at 160 ºC and the mixture was aged for 4 hour ± 5 min. This was carried out by maintaining the temperature of the mixture at 135 ºC in oven for 3 hr 30 min and at 155 ºC for 30 min. The aged mixture was compacted using the Superpave Gyratory compactor. The number of gyration was selected for the traffic intensity above 30 million ESAL. The cylindrical specimens of 165 mm height and 150 mm diameter were produced and cored to the size of 150 mm height and 100 mm diameter for testing.

The bituminous mix sample was subjected to haversine compressive loading using Asphalt Mixture Performance Tester. The haversine load amplitude corresponding to axial strain between 75 and 125 microstrains were used for testing and the experiments were conducted at different frequency of 0.01, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20 and 25 Hz and at 5, 15, 25, 35, 45 and 55 ºC. The test was conducted as per AASHTO TP: 79-10. The axial deformation was recorded using three displacement transducers and dynamic modulus and phase lag were calculated. Figure 2 and 3 shows the dynamic modulus of BC and DMB mixture. The dynamic modulus mater curve for BC and DBM were constructed appealing to time temperature superstition principle and the master curve along with the shift factor is used in the pavement design. Figure 4 and 5 shows the master curve and corresponding shift factor for BC and DBM mixture at the reference temperature of 21°C.

In real-life conditions, the dynamic modulus values vary spatially for any given day. For the realistic calculation of stresses and strains, it is necessary that the appropriate dynamic modulus at any given critical calculation is calculated. It is also understood that the dynamic modulus values increase as the material ages and such aging is intertwined with the spatial point in the asphalt layers. Using the AASHTOWARE software, the dynamic modulus at different depths of BC and DBM layer at mid quintile temperature variation for a truck speed of 100 kmph obtained is shown in figure 6.

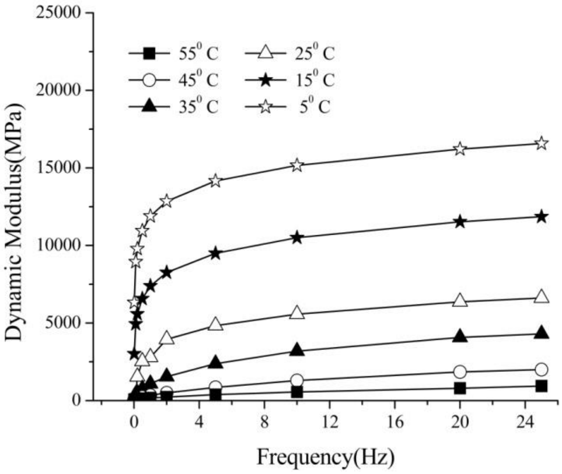


Figure 2. Dynamic Modulus of DBM Mix

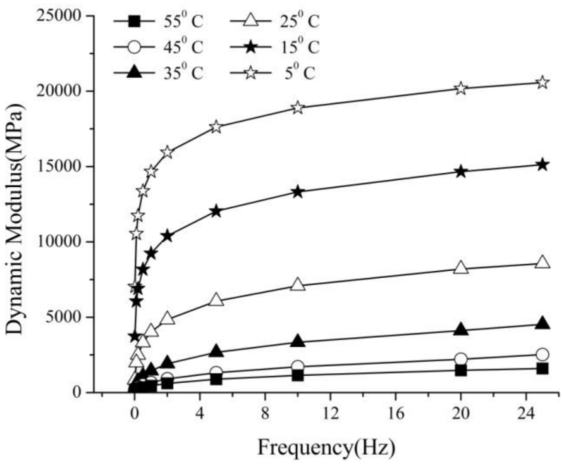


Figure 3. Dymanic Modulus of BC Mix

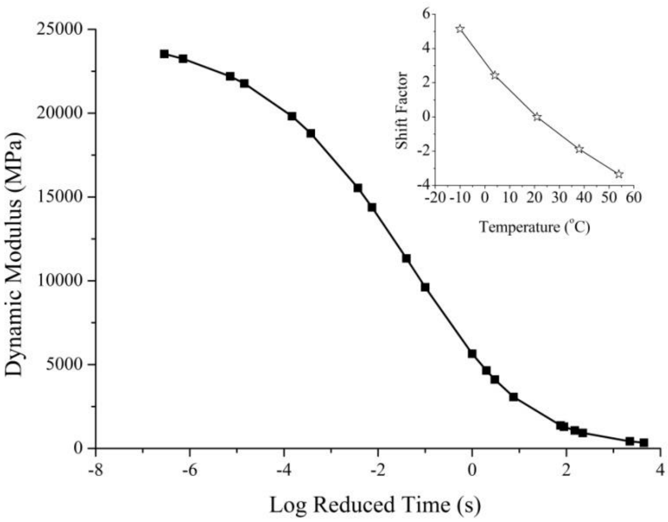


Figure 4. Master and Shift Factor for DBM Mix

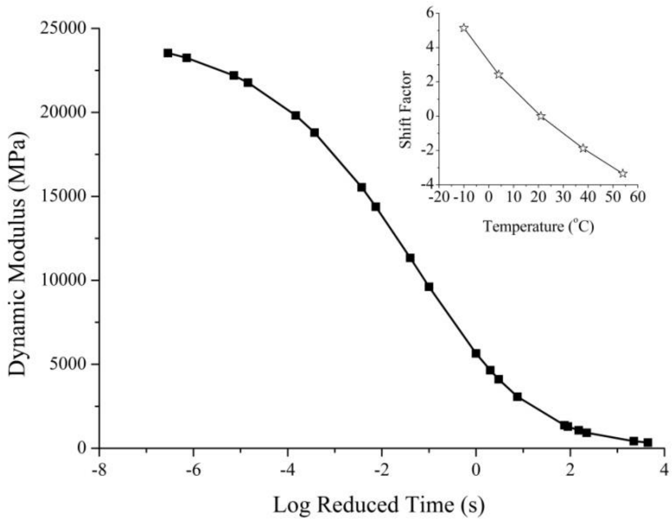
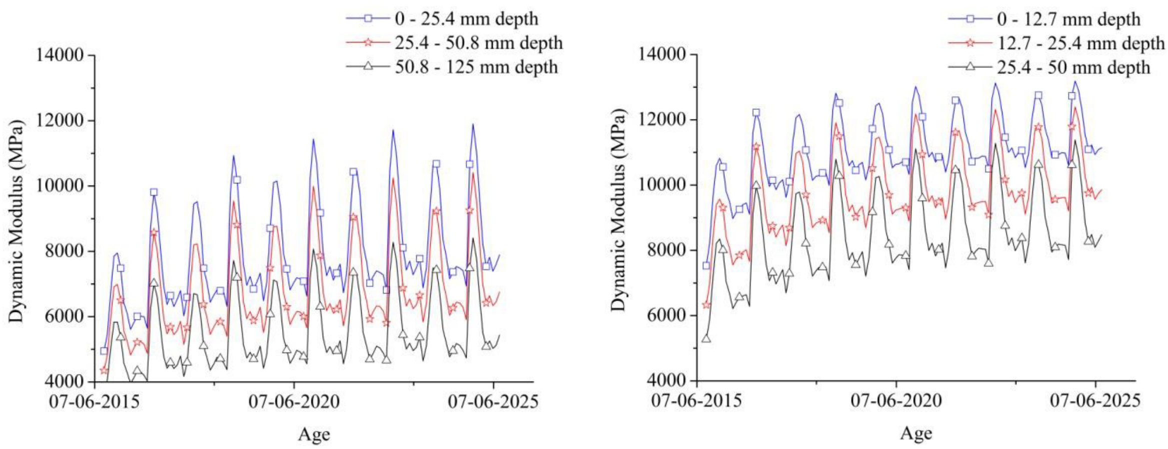


Figure 5. Master and Shift Factor for BC Mix



a) DBM Layer b) BC Layer

Figure 6. Dynamic Modulus at Different of BC and DBM Layer at Mid Quintile Temperature

Mechanistic Empirical Pavement Design/Distress Functions

The rutting and fatigue response of the pavement with 200 mm granular sub-base, 250 mm granular base, 125 mm DBM and 50 mm BC layer is studied using AASHTOWARE pavement design software. This pavement section is an IRC section corresponding to 10 % subgrade CBR and 150 msa traffic (IRC 37, 2012). Figure 7 and 8 shows the rutting and fatigue response of different layers. Within the design period of 10 years, the rutting of bituminous layer exceeds the target design value (10 mm) and the other factors such as rutting of base, sub base layer, fatigue cracking are well within the target value. For further analysis, the rutting of bituminous layer alone is considered. In AASHTO design approach, the rutting in the pavement was determined for individual layer. The ratio of plastic to resilient strain represents the rutting response of the bituminous layer. The transfer function given in equation (3) is used to obtain the rutting response of the bituminous layer.

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_{r1} a_1 T^{a_2 \beta_{r2}} N^{a_3 \beta_{r3}}, \quad (4)$$

where, ε_p represents plastic strain, ε_r represents resilient strain, T represents layer temperature N represents number of load repetition, β_{ri} represents field validation factor and a_i represents non-linear regression factor. Figure 9 shows the rutting response of the total bituminous layer for a traffic speed of 100 and 60 kmph. As expected, rutting corresponding to the traffic speed of 60 kmph is higher when compared to that of rutting at 100 kmph. Figure 10 shows the time period at which rutting reaches the target value of 10 mm. As clearly seen, the rutting of bituminous layer exceeded the target value (10 mm) in less the 2 years. In order to improve the rutting performance of the bituminous layer, the thickness of layer has to be increased. The thickness of the bituminous layer required for the target rutting of 10 mm were determined using thickness optimization tool. The optimization was carried out by changing the DBM layer thickness and the BC layer thickness was kept constant (50 mm). It was observed that for the target rutting of 10 mm, reliability of 90 % and for design life of 8 years, DBM layer thickness required to cater 4000 truck traffic per day is 313 mm. Table 2 compares the various distress predicted at the end of the design period with the target value.

Table 2. Distress in the pavement with bituminous layer thickness of 363 mm (50 mm BC + 313 mm DBM)

Distress Type	Target Value	Predicted
Terminal IRI (m/km)	2.70	1.97
Permanent deformation - total pavement (mm)	20.00	17.41
AC bottom-up fatigue cracking (percent)	25.00	1.49
AC thermal cracking (m/km)	189.40	5.15
AC top-down fatigue cracking (m/km)	378.80	157.69
Permanent deformation - AC only (mm)	10.00	9.90

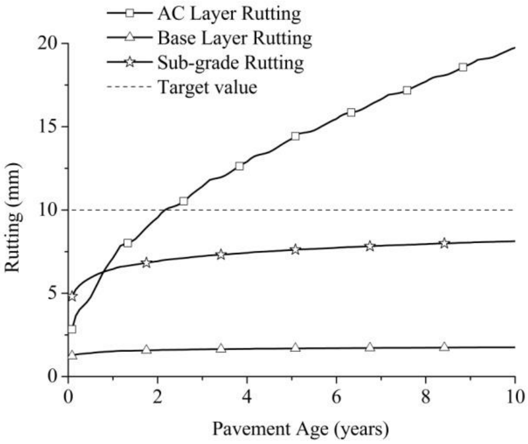


Figure 7. Rutting at different layers of the pavement

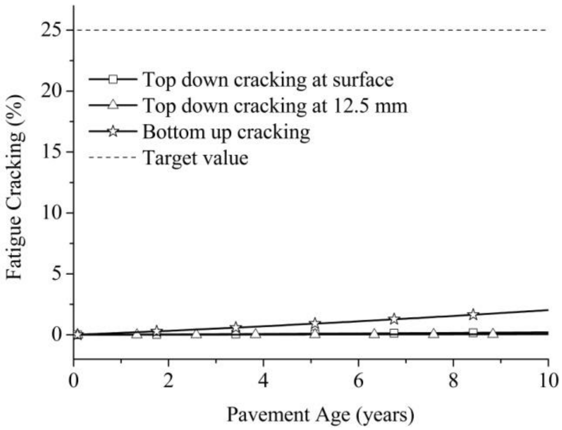


Figure 8. Fatigue cracking on the pavement

Conclusion

For the detailed mechanistic-empirical pavement design of asphalt pavement as per AASHTO, an extensive traffic, weather and material characterization data are required. The traffic data includes number of various classes of truck including hourly and monthly traffic variation, axle load data of various class of vehicle and its distribution. Weather data includes hourly air temperature and other factors that relate pavement temperature to the air temperature. One also needs to conduct an extensive laboratory investigation to acquire the material parameters such dynamic modulus and phase lag of binder and bituminous mix used. Also, the factors such as thermal conductivity and heat capacity of the pavement were required to generate temperature variation across various depth of the pavement. In this investigation, the weather was collected for the Chennai city and the traffic data for an highway near Chennai. The binder and bituminous mix material characterization was carried out in the laboratory and these data were used to proof check IRC section using AASHTO method of pavement design. It was observed that the rutting response of the bituminous layer exceed the target rutting in less than 3 years. In this design process, the pavement temperature prediction using the design software was carried out using the same Enhanced Integrated Climate Model that was recommended by AASHTO. Also distress predictions were carried out using the transfer functions recommended by AASHTO. One needs to validate this climate and distress prediction models for our geographical location.

It is clear that the material characterization greatly influences the design of the flexible pavements. Bituminous pavement design, depending on the rigor required, involves large data. A concerted attempt by all the stakeholders is required to collect rigorous data for a wide range of traffic, climate and bituminous mixtures and binders.

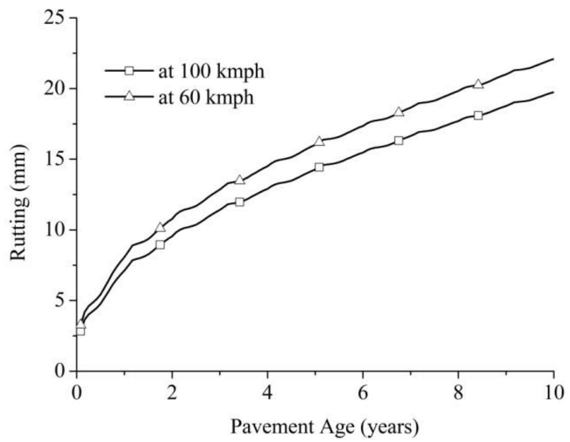


Figure 9. Comparison of Rutting at Various Traffic Speed

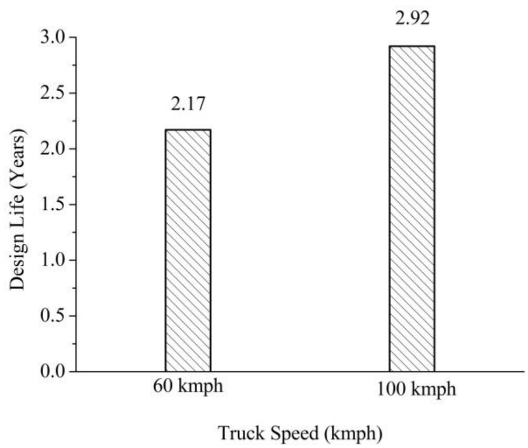


Figure 10. Design Life at Various Traffic Speed

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