Flexible Pavement Design Evaluation Using Mechanistic-Empirical Approaches

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Abstract-This study presents an evaluation of different pavement design sections using a software developed by AASHTO Pavement Design Guide and a mechanistic software known as "Kenlayer". The basic aim was to ascertain the effect of different parameters like pavement thickness, asphalt layer thickness, material properties of each layer on pavement performance indices likerut depth, international roughness index and stress-strain response. Present study further predicts the sensitivity of different parameters involved in a pavement design. Study reveals that the asphalt thickness component contributes significantly towards reducing the pavement rut value, and international roughness index, as compared to aggregate base course thickness. Subgrade material properties overall contributed in affecting the IRI. This study also reveals that the poisson ratio affects the performance pavement performance indices. An increase in the poisson ratio of each layer, increases the pavement rut resistance. The study provides a comprehensive approach to evaluate the materials requirement under a given pavement design conditions. The findings of the study directly applies on similar kind of pavements. It provides a guideline to the pavement designer how to evaluate the role of different layers and their properties to reduce the premature failures.

Keywords-Pavement, Mechanistic-Empirical Pavement Design, Poisson Ratio, Rutting, IRI

I. INTRODUCTION

Sargodha city is famous about crushed aggregate supplies in central Punjab, Pakistan. Sargodha quarry is one of the major Quarries in Pakistan. The city has hot weather in summer and moderate cold in the winters. The maximum temperature reaches up to50 °C in the summer. Sargodha is connected to the M-2 by different interchanges at different locations. A large number of loaded and unloaded trucks move through Sargodha interchanges daily carrying Sargodha crush, causing damage to the pavement. Premature pavement failure as a result of abnormal loading was the consequences. Pavement agencies are using different pavement analysis methodologies like Road note 31 and AASHTO design guide to improve the pavement design. Present study focused on Makhdoom interchange (M-2) to Sargodha provincial highway with a length of 39.2 kilometers. The study suggests the design improvement technique to reduce the rutting failure and riding quality issues.

Pavement evaluation mainly involved ride quality, surface distresses like rutting, cracking etc., surface friction and surface deflection. Asphalt pavement undergoes different type of distresses under heavy load and varying traffic spectrum. One of the major distresses that affect the pavement structural performance is rutting. Ruttingcan be controlled by changing thicknesses and material properties of different pavement layers. High temperature stability of intermediate course of asphalt pavement was one of the major element developing rutting [i].Rutting is prominent in higher summer temperatures and under heavy loads. The pavement rut value increases linearly with the gradual passage of vehicularload up to certain limit then it grows. Therate of rut development depends on the ambient temperature [ii]. Middle layer of asphalt pavement generate 60% of total rutting and remaining 40% came from other surface layers. Laboratory testing showed that shear stress in the middle layer of asphalt pavement was the highest in magnitude [iii].

In addition to rutting, ride quality and other surface distresses contribute effectively in a pavement performance. Those distresses also increase the rate of deterioration of pavement structures. Overall serviceability of a pavement section can also be representative by a distress called as roughness, which defines the rid quality of a pavement. Pavement performance has become the focus point of pavement designs. Pavement ride quality has also an impact on traffic safety. International Roughness Index (IRI) has been a well-known tool for evaluating pavement riding quality. Road agencies have been using IRI for evaluation of newly constructed asphalt pavements [iv]. Crash rates for a pavement have been linked with the pavement roughness. Elghriany et al.(2015) concluded that with the increasing IRI value, pavement looks more susceptible to higher crash rates and pavement having less IRI was safer for travelling [v].

A stream of traffic may include both light and heavy vehicles, which may have different loading impact. Heavy vehicles; typically the trucks damage the pavement depending upon the axle type, axle load and their speed. This also accompanied variation of traffic volume. Given the complex nature of variations, pavement material response is also a complicated phenomenon. Advances in computational mechanics and with the applications of statistics the ability to predict pavement response to load and climate effects can now be possible to certain extent. For a pavement design, mechanistic or empirical design methodologies can be adopted. Pavement designed either by a mechanistic or empirical approach alone may lead to a poor performance.

A. Mechanistic-Empirical Pavement Design Guide (MEPDG)

In 1996, the National Cooperative Highway Research Program (NCHRP) launched Project 1-37A to develop a new design guide for pavement structures. The design guide was based on mechanistic-empirical (M-E) principles. The MEPDG is a mechanistic-empirical (M-E) method for designing and evaluating pavement structures. In MEPDG structural responses (stresses, strains and deflections) are mechanistically calculated based on material properties, environmental conditions and loading characteristics [vi]. MEPDG involved application of the dynamic modulus technique for asphalt concrete and the resilient modulus for unbound materials. Improved material characterization and constitutive models made it possible to incorporate nonlinearities, rate effects, and other realistic features of material behavior [vii]. Following models for rutting prediction in asphalt pavement has been incorporated by MEPDG:

$$RD_{AC} = \sum_{i=1}^{N} (\varepsilon_p)_i \, . \, \Delta h_i \quad (1)$$

Where; RD_{AC} = asphalt concrete layerrut depth, N = shows number of sublayers in a pavement, $(\varepsilon_p)_i$ = vertical plastic strain at mid-thickness of ith asphalt layer, Δh_i = = ith sublayer thickness. Any increment in surface distress increased the rate of surface roughness that directly affect the pavement ride quality (NCHRP, 2004).MEPDG incorporated roughness prediction model for the international roughness index (IRI). Aguiar et al. (2011) evaluated the pavement performance by incorporating the long-term pavement performance data (LTPP) into M-E-IRI model and concluded that M-E-IRI model was one of the best model for evaluating the pavement performance [viii]. Following relationship shows the roughness model for a certain age of conventional flexible pavements with granular base;

$$IRI = IRI_0 + 0.0463FC\left(e^{\frac{age}{20}} - 1\right) + 0.00119TC_L + 0.1834COV_{RD} + 0.00736BC + 0.00115LC \quad (3)$$

Where; TC_L = total length of transverse cracks in m/km, FC_T = total area of pavement fatigue cracking and equals to the percent of total lane area in a pavement, BC_T = total area of block cracking and equal to percent of total lane area, LC = length of sealed longitudinal cracks measured in m/km outside the wheel path. Several improvements have been proposed in the current MEPDG, which incubates several problematic and sensitive pavement regarding issues. However, MEPDG considers the similar input parameters that have been used previously in different design aids [ix]. Different research studies reported the importance of MEPDG in a pavement design and evaluation. Chehab and Daniel, (2006) implemented the MEPDG for design of flexible pavement and AC overlays for New England and New York states. A comprehensive sensitivity analysis were carried out. Different levels were utilized to assess distresses and the computed values were related with the field-measured values [x].Pavement structural performance is the function of pavement subgrade performance. Wang et al. (2010) used the heavy vehicle simulators on AASHTO class A-2-4, A-4 soils and concluded that pavement subgrade performance was fully dependent on soil type. Actual measurements under the HVS (heavy vehicle simulator) loading was further analyzed by developing mechanistic-empirical pavement design guide (MEPDG) subgrade rutting model [xi]. Chen et al. (2004) developed mechanistic-empirical model to assess rutting resistance of a pavement. According to this study the accumulated value of rut mainly depends on material property and traffic loading. The study revealed that MEPDG effectively assess pavement performance [xii].MEPDG not only used for evaluation of pavements but also has its applicability as basic pavement design tool. Goh and You, (2009) implemented MEPDG for rutting prediction of asphalt mixtures with varying design traffic levels and concluded that asphalt mixtures with lower design traffic levels showed less rutting as compare to other mixtures [xiii].

B. Kenlayer

The Kenlayer is a part of the KENPAVE package. This software can be used to assess both the rigid and flexible pavement. Kenlayer software was used to evaluate the structural condition of a pavement by measuring the critical strains [xiv]. Kenlayer software is based on an elastic multilayer pavement system analyzed under a circular loaded area. Asphalt layer was assumed to be linearly elastic. For non-linear analysis, unbound layers; base and subgrade has been treated as stress dependent layers [xv]. Following relationship has been used for the design repetitions model in Kenlayer.

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E_1)^{-0.854} \quad (3)$$

Where N_f = number of load repetitions before failure, ε_t = amount of tensile strain as a result of load repetitions measured at the bottom of asphalt layer, E_1 = elastic modulus of asphalt layer. (Mirza et al, 2011) evaluated the design thicknesses of two empirical design methodologies Road Note 31 and AASHTO design guide with ME program Kenlayer and concluded that the differences in approaches results were function of pavement material properties and traffic level [xvi].

For a pavement design, empirical design methodology based on either theoretical or practical approaches were used in the past. Those approaches led most of the pavements toward poor performance. The distresses developed in a pavement is significantly influenced by variation in thicknesses and material properties of different asphalt layers. Present study utilized the MEPDG to analyze the effect of varying thickness and poisson's ratio of AC layer on pavement performance indices (rutting and IRI). Poisson's ratio indicates the strain development in the material as a result of a stress tensor produced with in the material when force is applied. This ratio has a significance till the stress is within the elastic range. Studies in the past prove that poisson's ratio has significant relationship with the dynamic modulus of the asphalt materials. MEPDG recommends dynamic modulus as a good parameter for asphalt material performance. MEPDG provides us a deep insight about the material performance under traffic loading. MEPDG along with the mechanistic approaches such as kenlayers provides better understanding about the material behavior under the traffic loading. This study further used Kenlayer to ascertain the strain behavior and service life of best performing pavement section under MEPDG analysis.

II. Objectives

The main objectives of research study were:-

- Comparing the results of MEPDG analysis with the Kenlayer output and assessing the difference among the performance parameters.
- Assessing the effect of different parameters like pavement thickness and material properties of different layers on pavement performance.
- To study the contribution of chosen variables in the improvement of pavement design.

III. Experimental Program

The representative pavement sections were developed with varying asphalt concrete and base course layer thicknesses. The developed sections were analyzed using MEPDG for pavement rutting performance and riding quality. The varying parameters used in MEPDG were layer thickness and poisson's ratio. The best performing sections under MEPDG analysis were further analyzed using Kenlayer for strain behavior and design repetitions under standard loads. A three phase study was designed to accomplish the study objectives. Fig. 1 summarizes the scope of work.

Phase-I was comprised of, collection of traffic data and development of representative pavement sections with varying pavement layer thicknesses. The collected traffic data was truck traffic data of Sargodha interchange.

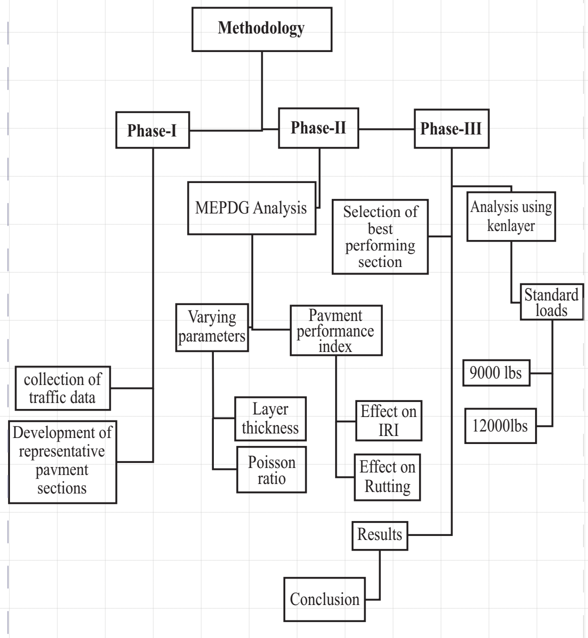

Fig. 1. Scope of work

The developed sections in phase-I were analyzed in Phase-II, using MEPDG. The phase-II comprised into two parts. In part-1, different parameters namely layer thickness and poisson's ratio were selected. In part-2, the effect of selected variables was analyzed on pavement performance indices (rutting and IRI). In phase-III, the selection of best performing pavement sections were analyzed under different standard loads using a Kenlayer software.

IV. Material and Methods

Nine representative pavement sections were developed with varying thicknesses of asphalt concrete and base course layers. The basic purpose was to cover the effect of wheel damage on pavement structure. A large number of loaded and unloaded trucks passed through Sargodha interchange daily carrying Sargodha crush, causing a considerable amount of damage to the pavement. The present study aims to improve pavement design of road section by minimizing distresses and improving the riding quality. MEPDG characterizes the vehicular load ranges with respect to classes and configuration and each axle type has different load regimes. Vehicle class distribution, daily traffic volume and axle load distributions define the number of repetitions of each axle load group at each load level. All types of trucks with respect to their classes and axle can be accommodated in this software. It allows adding axle type and group combinations along with loads. One can use real time field loading conditions through this software and predicts the pavement performance. The Sargodha interchange traffic was used in the analysis. The specific traffic inputs in addition to operational speed also includes annual average daily truck traffic, lanes and trucks (%) in the design direction along with their percent in the design lanes. Nine pavement sections with typical range of thicknesses of asphalt concrete and granular layers are shown in Fig. 2.

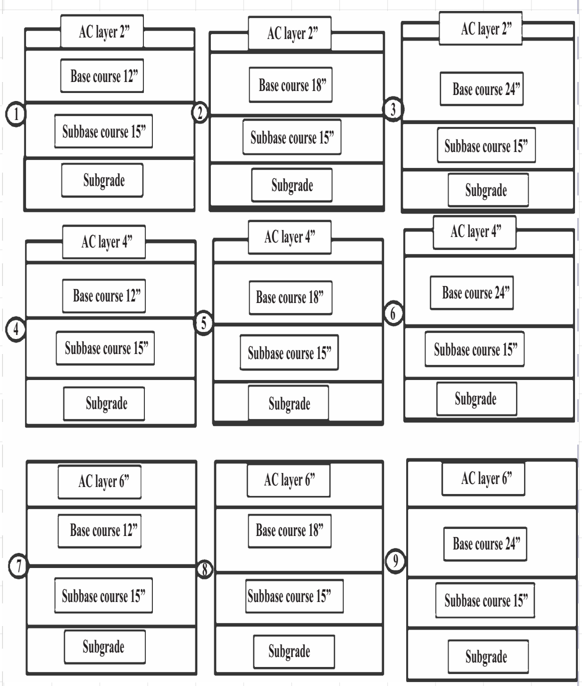

Fig. 2. Initially developed pavement sections

It may be noted from Fig. 2 that each pavement section was varied in asphalt concrete and base course layer thicknesses. Analysis of each developed pavement section was carried out against pavement performance indices (rutting and IRI) using MEPDG. The best performing section (with minimum rutting and required IRI level) out of all 9 sections was further analyzed using MEPDG to ascertain the effect of poisson ratio and subgrade soil type on pavement performance indices as shown in Fig. 3.

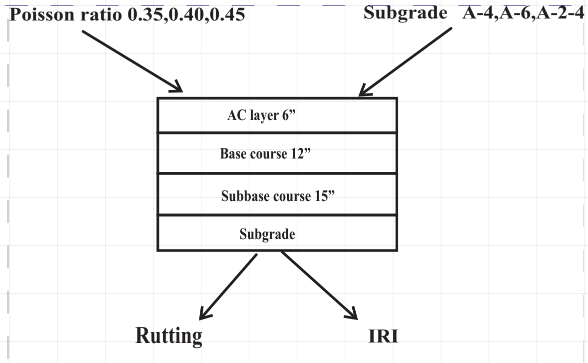

Fig. 3. Parameters for analysis against pavement performance index

It may be noted from Fig. 3 that well performing pavement section selected on the bases of MEPDG analysis results was further analyzed with varying subgrade soils (A_4, A_6, and A_{-2-4}) and Poisson ratio (0.35,0.40,0.45) and its effect on pavement performance indice was studied. The best performing section was further analyzed using Kenlayer software for strain analysis and pavement life prediction. Kenlayer includes the effect of varying subbase thickness on pavement performance. Two pavement sections were developed with varying subbase course thickness. The thickness of asphalt concrete layer was also varied to ascertain the sensitivity of AC layer on strain development as shown in Fig. 4.

It may be noted from Fig 4 that best performing section under MEPDG analysis was further analyzed using Kenlayer software.

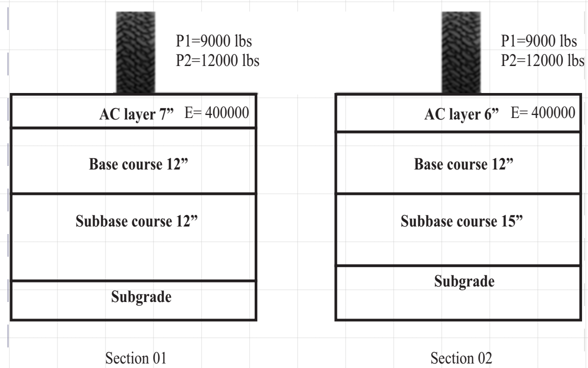

Fig. 4. Pavement sections analyzed under Kenlayer software

To assess the sensitivity of asphalt concrete and subbase layer. Another pavement section was developed by decreasing the subbase layer thickness and increasing the asphalt concrete layer thickness. Two Standard axle loads of magnitude 18 kip (8.16ton) and 24 kip (10.9ton) were selected for analysis of selected pavement sections. The pavement sections were analyzed using same asphalt concrete layer modulus of 400,000 psi (2757.9 MPa). Tire pressure of 100 Psi (0.7 MPa) was maintained during analysis.

Subgrade material consisted of A_4 soil, normally available soil in study region.

V. RESULTS AND DISCUSSION

Nine representative pavement sections were developed with varying thicknesses of asphalt concrete and base course layers. Rutting performance and ride quality of each pavement section was analyzed for a period of 20 years using MEPDG as shown in Table I.

It may be noted from Table I that pavement sections 7, 8 and 9 showed minimum rutting and good ride quality as compared to other sections, but the structural number of the pavement increases effectively.

There was no significant effect of granular base course layer thickness on rutting and IRI. Out of above three mentioned pavement sections, pavement section # 7 has minimum thickness of granular base course layer with respect to remaining two sections as shown in Fig. 5.

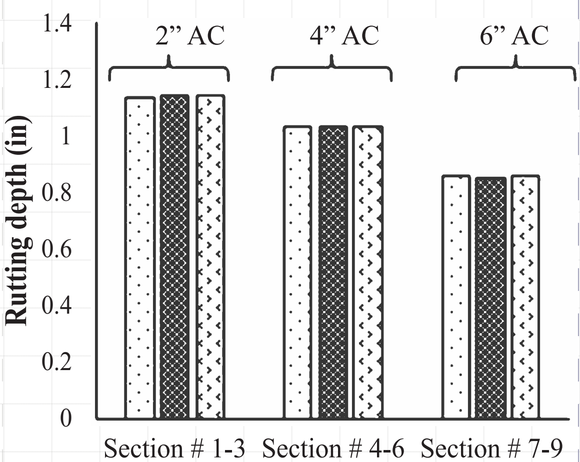

Fig. 5a. Influence of pavement thickness on rutting depth

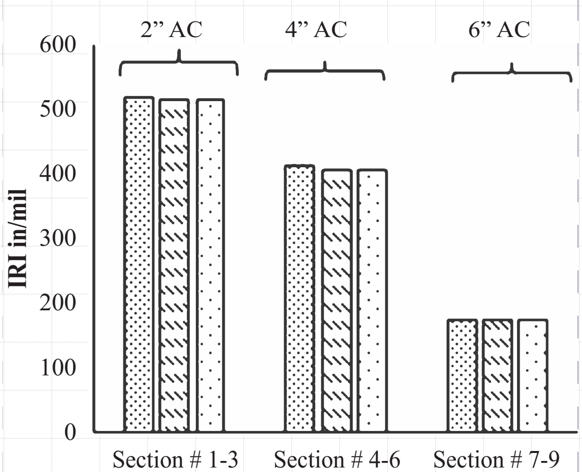

Fig. 5b. Influence of pavement thickness on IRI

It may be noted from Fig. 5 that granular base course layer thickness has insignificant effect on rutting depth and IRI of asphalt concrete pavement. One of the major reasons behind was the basic philosophy of design procedure. MEPDG protect subgrade by thickness of asphalt layer, rather than granular layer. An increase in the thickness of AC layer covers the effect of loading rather an increase in granular layer thickness.

TABLE I
RUTTING DEPTH AND IRI OF DEVELOPED PAVEMENT SECTIONS FOR 20 YEARS OF PAVEMENT LIFE

Sect.	1	2	3	4	5	6	7	8	9
Total rut (mm)	29	29	29	26	26	26	23	23	23
IRI (m/km)	33	33	33	26	26	26	11	11	11
SN	2.6	3.4	4.3	3.5	4.3	5.1	4.4	5.2	6

The effect of Poisson's ratio on ride quality was also assessed by using the well performing pavement section as shown in Fig. 6.

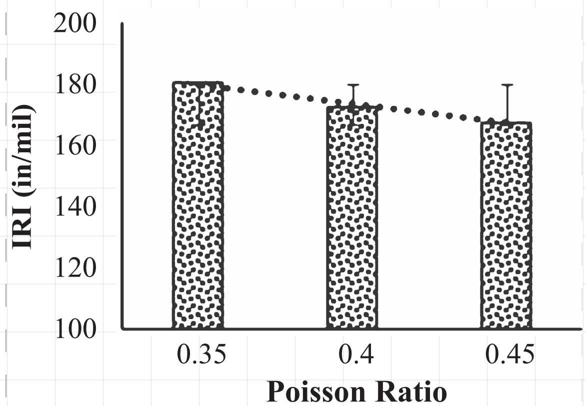

Fig. 6. Influence of poisson's ratio on and IRI

It may be noted from Fig. 6 that IRI of pavement section decreases with an increase in Poisson ratio of AC layer. It is because the material shows more ductile properties which increases its propensity to offer more IRI and relatively higher rate of deterioration.

The selected pavement section was also analyzed for horizontal tensile strain and vertical compressive strain against 18kip (8.16 ton) to 24kip (10.9 ton) load. To assess the effect of variation in subbase layer thickness on strain behavior of pavement, another pavement section was developed as shown in Fig. 4. Horizontal tensile strain at the bottom of the asphalt layer (ε_t) has been presented in Fig. 7.

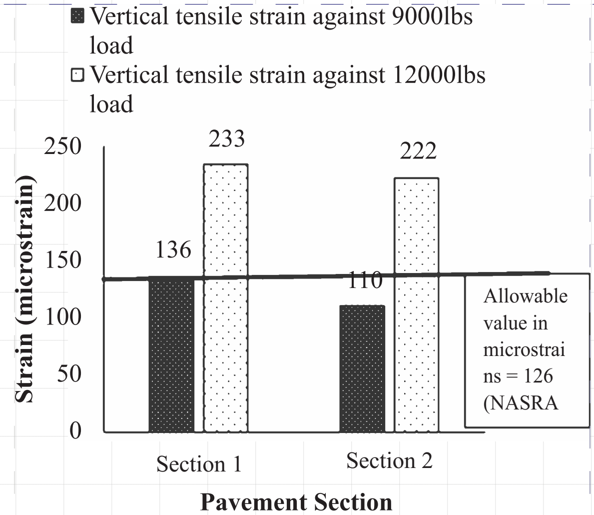

Fig. 7. Axle load versus tensile strain in a pavement

It may be noted from Fig. 7 that by increasing standard load from 18kip (8.16 ton)to 24kip (10.9 ton), tensile strain development in the pavement section increases to prominently high value for both representative pavement sections. But as the thickness of granular layer increases by lowering the asphalt layer thickness, the developed strain decreases for both 18kip (8.16 ton)and 24kip (10.9 ton)loads.Thicker aggregate layer reduces the strain value by spreading the load to a wider area. Vertical compressive strain at the top of subgrade (ε_c) was also analyzed as shown in Fig. 8.

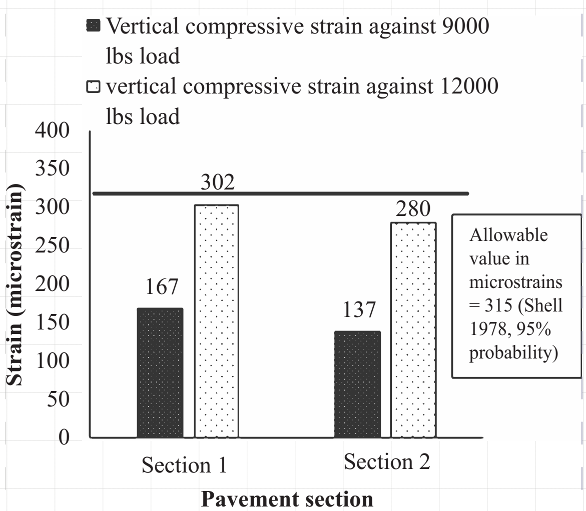

Fig. 8. Axle load versus compressive strain in a pavement

It may be noted from Fig. 8 that by increasing standard load from 18kip (8.16 ton) to 24kip (10.9 ton), compressive strain developed in pavement section increases to significantly in both the representative pavement sections. At the same time as the thickness of granular layer increases by lowering the asphalt layer thickness, the developed strain decreases for both 18kip (8.16 ton) to 24kip (10.9 ton) loads. Fig. 9 shows that as the load increases from 9 kips(4.08 ton) to 12 kips (5.44 ton), the number of repetitions also decreases.

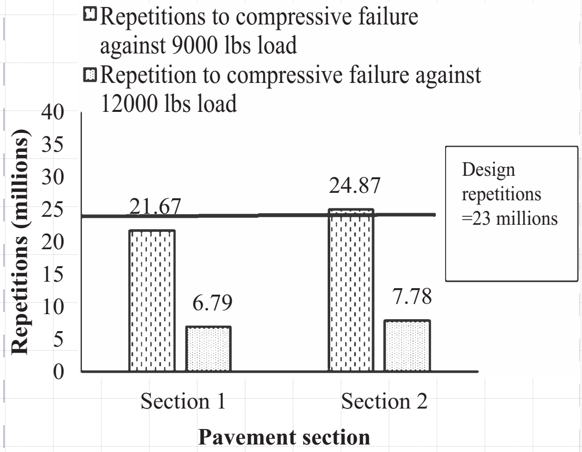

Fig. 9. Axle load versus repetition for pavement life

It may be noted from Fig. 9 that adopting laid methodology, selection of a pavement section for a given condition can be made. The pavement designer can select a section for any given set of load and material conditions. Adopting AASHTO 1993 pavement design for structural design of a pavement can further be analyzed for its adequacy of performance by following analysis with MEPDG and Kenlayer software. This would develop a confidence to designer for probable performance in the field.

VI. Conclusion

Present study investigates the effect of different parameters on a pavement structural capacity and the ability of different software to ascertain stress response in a pavement. Following conclusions have been drawn from this study:

- Rut resistance and riding quality of a pavement section increases with an increase inthe asphalt layer thickness. MEPDG protects the subgrade by increasing the thickness of asphalt layer, whereas Kenlayer software protects the subgrade by increasing the thickness of granular layer and keeping the thickness of asphalt layer constant.
- Rut resistance of asphalt pavement increases with an increase in Poisson's ratio of AC layer. With the increment in poisson ratio of AC layer, the pavement shows good riding quality.
- Tensile strain at the bottom of AC layer and Compressive strain at the top of subgrade increases significantly as standard load on pavement increases from 18kip (8.16 ton) to 24kip (10.9 ton) . At the same time thickness of granular

layer decreases the developed strain for both 18kip (8.16 ton) to 24kip (10.9 ton) loads and design repetitions increases no matter the AC layer thickness decreases.

- Pavement performance parameters like international roughness index can be predicted through MEPDG software, while Kenlayer calculates the stress, strains and repetitions to failure in the pavement. Adopting AASHTO 1993 pavement design for structural design of a pavement can further be analyzed for its adequacy of performance by following analysis with MEPDG and Kenlayer software.
- Based on the findings of present study it is recommended that different design methodologies including mechanistic and mechanistic-empirical pavement design aids may be utilized to review stress response of a designed pavement.

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