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Study and Analysis of Flexible Pavement by Nonlinear Finite Element Method

[1]K.RAJESH, [2]G.VISWANADH

[1](M.Tech) Structural Engineering, Dept. of Civil Engineering
[2]Assistant Professor, Dept. of Civil Engineering
Priyadharshini Institute of Tech & Science

Abstract:- Need for better road transportation facility is increasing day-by-day and in order to fulfill the need researches are carried out from a long period. Construction of a road becomes simple only after the design of a pavement is complete, today engineers are facing challenges in designing pavements that can serve a long duration without premature failures. Pavement design is one of the most important aspects of any transportation project. Poor and inadequate design may result to reduce the life of flexible pavement and increase the annual maintenance cost. It becomes the prime importance to design a durable and economic pavement structure. A durable structure can be designed only after proper analysis. Multilayered analysis is widely used but it assumes the pavement material to behave linearly which in practice is not true hence analysis of materials with nonlinear behavior is required. To obtain accurate response it is essential to analyse the pavement structure considering responses from each and every particle which is a tedious process with multilayered program, to make obtain accurate responses a powerful method like finite element method is used. In the present work an attempt has been made to study and analyse a pavement structure using a finite element based software tool and compare the results with that of a multilayer based program. Overall response helps in identifying the pavement parameters which has major impact on the performance of the pavement structure, by this it will be possible to design a pavement with long durability and high performance.

Keywords – Flexible Pavement;Finite element method, Pavement responses; tensile strain, compressive strain, Kenlayer;Michigan flexible pavement design software (MFPDS) Linear; non-linear analysis; Multi-layer theory.

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1. INTRODUCTION

Road transportation forms the arteries and veins which plays vital role in economic growth of a nation. This makes the construction of good roads a priority. Flexible pavement are the major type of pavements constructed in India extensively, it has been observed that these pavements suffer premature failure due to variation in traffic volume, load, material properties and environmental factors. To overcome such failures in pavement it is essential to have an efficient analysis method. There are several available methods for pavement analysis, the Burmister's layered elastic theory is the commonly adopted method to analyse the pavement but the drawback is that we cannot analyse pavement with unbound base course or materials with nonlinear characteristics. Hence an advanced method evolved after an extensive research and it was referred as finite element analysis. In FEA the pavement structure will be discretized into uniform sized elements where the pavement responses are obtained by applying load on a mesh configuration. The pavement structure can be assigned with material properties which delivers a realistic mode to achieve pavement responses. It will be essential to predict the performance of pavements before construction since the estimate and cost before and after construction of pavements may vary, hence design can be finalized only after analyzing the pavement for its responses on load application. In order to view the responses and its impact on pavement with linear and nonlinear materials a finite element software tool Michigan Flexible Pavement Design Software (MFPDS) is used. The pavement parameters having remarkable influence on pavement performance are observed from results and by performing sensitivity analysis.

2. BACKGROUND AND OBJECTIVES OF STUDY

Critical points of a pavement structure the flexible pavement is of layered structure which comprises of many layers with varied thickness and material properties. The surface is composed of bitumen, base/subbase with granular material and the subgrade with natural or compacted fine grained soil. Fig – 1 represents the cross sectional view of flexible pavement with the critical locations for analyzing a pavement. Most of the pavements fail due to premature rutting and fatigue type of failures which originate from the critical locations as indicated in the Fig-1. By identifying these critical responses a pavement can be designed to overcome premature failures.

Software tool used Today the road construction has spun into a new dimension where the construction is carried out extensively, which intern requires tool for analysis and design of durable pavement structure to satisfy the increasing demand. It is well known fact that finite element method of analysis provides effective results than other methods of analysis with high accuracy and less time, hence software based on finite element method serves the purpose and makes it handy for an engineer to analyse and design pavements. In the present study Michigan Flexible Pavement Design Software (MFPDS) is used to determine the pavement responses. MFPDS is a finite element analysis based software developed by Harichandran, R. S (2000). The software combines both multilayer based tool and finite element based tool. Using the software Mechanistic analysis may be performed with MichPave nonlinear finite element program or the Chevronx (enhanced Chevron) linear elastic layer analysis program. Both programs have been enhanced from previous versions. MichPave has been enhanced to use a distant lateral boundary and many more finite elements than previous versions. As a result the computed responses are significantly more accurate than in previous versions. New performance models to predict rut depth and fatigue life have been implemented. Each layer in a pavement cross section is assumed to extend infinitely in the horizontal direction. Displacements, stresses and strains due to a single circular wheel load are computed. Due to the assumptions used, the problem is reduced to an axisymmetric one. The pavement structure on MFPDS is converted into a finite mesh as in Fig –

The elements used are four nodes ax symmetric elements with aspect ratio of these elements less than 1:4

C. Sensitivity Analysis Sensitivity analyses demonstrate the effect of various parameters on flexible pavement. The analysis is being carried out using the finite element based software tool. In general sensitivity analysis helps in predicting how much sensitive is the pavement response with respect to variation in pavement parameters. Through the sensitivity analysis of pavement responses, the input variables mostly affecting the fatigue cracking and rutting are determined. In the sensitivity analysis, each of layer thickness and modulus of surface layer are varied one at a time from its assumed minimum value, while the other parameters will be kept constant. D. Nonlinear material in base/subase and subgrade course of flexible pavement It is well known that granular materials and subgrade soils have non-linear resilient behavior varying with the level of stresses. The resilient modulus of granular materials increases with the increase in stress intensity. A major disadvantage of the layered elastic theory is the assumption that each layer is homogeneous with the same properties throughout the layer. This assumption makes it difficult to analyze layered systems composed of non-linear materials like untreated granular bases and sub-base. The resilient modulus of these materials is stress dependent and varies throughout the layer. Linear analysis is a simple approximation for design and analysis purpose. Several material models have been developed to analyse nonlinear material with multilayered method, but the output is not precise which hinders the prediction capability. By adopting nonlinear material behavior analysis becomes more difficult as the material behavior varies at particle level. This can be solved by combining the material model with finite element method which produces realistic and precise results. In the present study software tool with K-θ and bilinear material model is used to analyse base/subbase course with linear as well as nonlinear material characteristics.

Nonlinear material in base/subase and subgrade course of flexible pavement

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3. METHODOLOGY

3.1. Indian Road Congress Method:

1) Wheel Loads*:*

One of the main design parameter for pavement design is the wheel load. Though the legal axle load limits in India are fixed as 10.2, 19 and 24 tons for single, tandem and tridem axles respectively the actual axle loads operating on highways in Indian are much higher due to lack of enforcement. It is necessary to collect the data of axle load spectrum of commercial vehicles[3] both during the day as well as during the night hours for the analysis of fatigue damage in the slab. The percentage of heavy vehicles during the night hours may be much higher for many high ways.

2) Fatigue Considerations:

According to IRC guidelines, IRC 58 has adopted the Westerguards equation to estimate the load stress and Bradbury equation to estimate temperature stress. The load stress is the highest at the corner of the slab lesser at the edge and least in the interior. The new version of IRC58 (2011) has also introduced –

1) Design of pavements considering the combined flexural stress under the simultaneous action of loads and temperature gradient for different categories of axles.
2) Design for bottom-up fatigue cracking caused by single and tandem axles load repetitions.
3) Design for top down fatigue cracking caused by single, tandem and tridem axles load applications.
4) Consideration of in-built permanent curl in the analysis of flexural stresses

3.2. American Association State Highway State Highway and Transportation Officials

The 1993 AASHTO guide of design of pavement structures considers the following factors in the design:

1) Estimated Future Traffic (W18) over the design life. The design guide is based on the total number of equivalent standard axle loads (ESAL)[4].
2) Reliability.(R%)- The reliability of a pavement design is the probability of roads under survival of roads under prevailing conditions. It varies from 80% to 95%.
3) overall standard deviation (So)- An overall standard deviation of 0.25 to 0.35 for traffic is recommended for rigid pavements
4) Effective Modulus of Sub grade Reaction (K in psi)- Effective Modulus of sub grade reaction is used to estimate the support of cement concrete slab by layer below.
5) Concrete elastic modulus (E).it can be estimated from the cube strength of concrete and its value is represented in psi[5].
6) Concrete modulus of rupture (Sc)-The modulus of rupture to be incorporated in the mean value after 28 days of curing, using three points loading.

4. DESIGN APPROACH AND DETAILS

The pavement designs are given for subgrade CBR values ranging from 2% to 10% and design traffic ranging from 1 msa to 150 msa for an average annual pavement temperature of 35 degree Celsius. Using the following input parameters, appropriate designs were chosen for the given traffic and soil strength:

1.) Design traffic in terms of cumulative number of standard axles

2.) California Bearing Ratio value of subgrade.

4.1. Design Traffic

In case of a new road, an approximate estimate should be made of traffic that would pay on the road considering the number of villages and their population along the road alignment and other socio-economic parameters. Traffic counts can be carried out on an existing road in the vicinity with similar conditions and knowing the population served as well as agricultural/ industrial produce to be transported, the expected traffic on the new proposed road can be estimated. The method considers traffic in terms of the cumulative number of standard axles (8160 kg) to be carried by the pavement during the design life. This requires the following information:

1. Initial traffic in terms of CVPD:

Initial traffic is determined in terms of commercial vehicles per day (CVPD). For the structural design of the pavement only commercial vehicles are considered assuming laden weight of three tons or more and their axle loading will be considered. Estimate of the initial daily average traffic flow for any road should normally be based on 7-day 24-hour classified traffic counts.

2. Traffic growth rate during the design life:

Traffic growth rates can be estimated (i) by studying the past trends of traffic growth, and (ii) by establishing econometric models. If adequate data is not available, it is recommended that an average annual growth rate of 7.5 percent may be adopted.

3. Design life in number of years:

For the purpose of the pavement design, the design life is designed in terms of the cumulative number of standard axles that can be carried before strengthening of the pavement is necessary. It is recommended that pavements for arterial roads like NH, SH[6] should be designed for a life of 15 years, EH and urban roads for 20 years and other categories of roads for 10 to 15 years.

4. Vehicle damage factor (VDF):

The vehicle damage factor (VDF)[7] is a multiplier for converting the number of commercial vehicles of different axle loads and axle configurations to the number of standard axle-load repetitions. It is defined as equivalent number of standard axles per commercial vehicle. The VDF varies with the axle configuration, axle loading, terrain, type of road, and from region to region. The axle load equivalency factors are used to convert different axle load repetitions into equivalent standard axle load repetitions.

5. Distribution of commercial traffic over the carriage way:

A realistic assessment of distribution of commercial traffic by direction and by lane is necessary as it directly affects the total equivalent standard axle load application used in the design. Until reliable data is available, the following distribution may be assumed.

i. Single lane roads: Traffic tends to be more channelized on single roads than two lane roads and to allow for this concentration of wheel load repetitions, the design should be based on total number of commercial vehicles in both directions.

ii. Two-lane single carriageway roads: The design should be based on 75 % of the commercial vehicles in both directions.

4.2. Subgrade Strength Evaluation

California Bearing Ratio (CBR) is the ratio of force per unit area required to penetrate a soil mass with standard circular piston at the rate of 1.25 mm/min. to that required for the corresponding penetration of a standard material. This test is a penetration test meant for the evaluation of subgrade strength of roads and pavements. The results obtained by these tests are used with the empirical curves to determine the thickness of pavement and its component layers. This is the most widely used method for the design of flexible pavement.

C.B.R. = Test load/Standard load * 100

4.3. Projection of normal traffic based on elasticity of transport demand

In this method the passenger vehicle and goods vehicles were separately treated. For deriving the growth rates of passenger vehicles, population growth[8] and real per capita income growth were used as parameters. In the case of goods vehicles, the growth rate was considered to be dependent upon the growth in agriculture, industrial, mining and trade and commerce sectors. From the point of view of the study, even though Ernakulam district was considered as the immediate influence area, it should be borne in mind that interactions exist among all districts of the state as well as other states.

4.4 . Overlay design

The structural strength of pavement is assessed by measuring surface deflections under a standard axle load. Larger pavement deflections imply weaker pavement and subgrade. The overlay must be thick enough to reduce the deflection to a tolerable amount. Rebound deflections are measured with the help of a Benkelman Beam. Condition survey and deflection data are used to establish sections of uniform performance. At least 10 deflection measurements should be made for each section per lane subject to a minimum of 20 measurements per km. If the highest or the lowest deflection values[15] for the section differ from the mean by more than one-third of the mean, then extra deflection measurement should be made at 25 m on either side of point where high or low values are observed. Measurement of pavement[9] temperature, field moisture content of subgrade soil and other data like annual rain fall and traffic data are to be collected.

5. FINITE ELEMENT ANALYSIS

In this research axisymmetric finite element analyses have been done by considering sub grade soil as a nonlinear material. The material nonlinearity has been considered by idealizing the soil by Drucker-Prager yield criterion. The asphalt concrete and the base course have been idealized as elastic material. The nonlinear finite element equation has been solved by Full Newton Raphson Iterative Procedure[10]. The asphalt concrete, base and the sub grade have been discretized by four noded isoperimetric finite elements. The total number of nodes considered are 345 and total number of element considered are 308. The horizontal domain of discretization considered in the analysis is 20 times the radius of pressure. The vertical domain considered in the analysis is approximately 140 times the radius of pressure. The boundary conditions considered in the analysis are such that the bottom nodes have no degree of freedom, the central nodes have only vertical freedom and the right side nodes also have only vertical degree of freedom. The thickness of asphalt concrete considered is 75 mm and the thickness of base course considered is 250 mm. Pressure acts at radius 150 mm.

6. Conclusion

Finite element based software tool provides a reasonable responses when compared with mutlilayered software tool. MFPDS being a user friendly and being a combination of both finite element method and multilayer analysis method, this tool can be effectively used for analysis and design purpose.The redirection of traffic through the port road has resulted in its own deterioration as not just commercial vehicles but heavily loaded trucks and containers too, commute through this route on an hourly basis. Thorough analysis of the existing pavement is necessary to understand the existing conditions and estimate the futuristic scenario to maintain sustainability of the road pavement and safe travel. Keeping this in view, the study started with the axle load survey on existing pavement and design of pavement for the existing traffic. Further, the design traffic is projected for the horizon year using the available growth rates in the study area and identified the required pavement thickness for the horizon year. From this analysis, it was identified that the existing pavement thickness is insufficient for taking the traffic loads coming on to the pavement in horizon year. Hence in the next step, the existing pavement is designed for the overlay and identified the additional thickness required for the horizon year. Thus, the road pavement in the Kochi port area can be deemed safe and sustainable, once these rehabilitation measures are adopted.

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