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Design and Analysis of Flexible Pavement by Nonlinear Finite Element Method

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Abstract:- Highway and pavement design plays an important role in the DPR projects. The satisfactory performance of the pavement will result in higher savings in terms of vehicle operating costs and travel time, which has a bearing on the overall economic feasibility of the project. A thorough analysis of the existing pavement is greatly required at this point of time, as an excessive amount of vehicle loads is passing through the project site and it is unknown whether or not the road pavement might sustain its structural integrity. The critical line of equal costs on the plane of CBR versus msa is also identified. This is a swing line which delineates the economic feasibility of two types of pavements. It has been found that the pressure vs settlement curve; pressure vs nodal stress curve ; pressure vs element stress curve are linear for small pressure range and then it become nonlinear. More nonlinearity is seen at higher pressure. Hence material nonlinearity must be considered while analysing and designing flexible pavements. This total work includes collection of data analysis various flexible and rigid pavement designs and their estimation procedure are very much useful to engineer who deals with highways.

Keywords – Flexible pavement, Traffic growth, Kochi port, Design, Overlay thickness.

1. INTRODUCTION

The transportation by road is the only road which could give maximum service to one all. This mode has also the maximum flexibility for travel with reference to route, direction, time and sped of travel. It is possible to provide door to door service only by road transport . Cement concrete pavements generally known as “rigid pavements” are now days replacing bituminous roads due to its economical advantage. A proper well connected rigid road network in a country like India can result in cost savings and economized movement of traffic over longer distances. When properly designed and constructed concrete roads and streets are capable of carrying almost unlimited amount of any type of traffic with ease, comfort and safety. Surfaces of this type are smooth, dust free and skid resistant having a high degree of visibility for both day and night driving and generally having low maintenance cost. They are economical in many locations because of their low cost of maintenance and their low cost of maintenance and their relative performance. They are, of course, classed as high type pavements .The principal use of surfaces of this type has been in the construction of heavily traveled roads and city streets, including those in residential, business, and industrial areas . It is the standard material for urban expressways, even in states where bituminous surfaces are widely used.

All hard road pavements usually fall into two broad categories namely: Flexible and rigid pavements. The government is increasingly shifting its focus from constructing new highways to rehabilitating and reconstructing existing facilities. Since highway rehabilitation projects often cause congestion, safety problems, and limited access for road users, the government faces a challenge in finding economical ways to rehabilitate deteriorating roadways in metropolitan areas while keeping the travelling public as safe as possible and minimizing disruptions for local communities and surrounding businesses. The current practice of constructing concrete pavement on Indian highways is to provide a granular sub-base over the sub-grade to be followed by a Dry lean concrete[1] base with the concrete slab on top which is called "rigid pavement". As a result of nationwide high way construction, more and more length of concrete pavement are constructed. However the deterioration of the concrete pavements has become a growing concern, since the rehabilitation of such pavements is a costly exercise. Hence there is a need of development of more scientific design methodology compared to the existing ones, which will avoid premature failure of pavements.

To design the road stretch as a flexible pavement by using different flexible methods like group index method, C.B.R. method as per IRC : 37-2001, triaxial method, California resistance[2] value method , and as a rigid pavement as per IRC : for the collected design upon a given black cotton soil sub grade and to estimates the construction cost of designed pavement by each method. To propose a suitable or best methods to a given condition or problem. The main objective of this study is to develop a strategy to select the most cost efficient pavement design method to carried out for a sections of a highway network and also to identify the cost analysis of different pavement design methods. Prioritization based on Subjective Judgment, Prioritization based on Economic Analysis.

2. METHODOLOGY

2.1. 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

2.2. 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.

3.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.

3.1. 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.

3.2. 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

3.3. 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.

3.4 . 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.

4. 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.

5. DESIGN AND COST ANALYSIS OF FLEXIBLE AND RIGID PAVEMENTS

The structural capacity of flexible pavements is attained by combined action of the different layers of the Pavement. The load is directly applied on the wearing course and it gets dispersed with depth in the base, sub-base and sub-grade layers and then ultimately to the ground. Since the stress induced by traffic load is highest at the top, the quality of top and upper laye materials is better. The sub-grade layer is responsible for transferring the load from above layers to the ground. Flexible pavements are designed in such a way that the load transmitted to the sub-grade does not exceed its bearing capacity.

The thickness design of a flexible pavement also varies with the amount of traffic. The range of variation in Volume of commercial vehicles at different highways has direct effect on the repetitions of the traffic loads. The damaging effect of different axle loads is also different The Indian Roads Congress method of flexible pavement design uses the concept of ESAL for the purpose of flexible pavement [11]design and the same has been used in this study also.

5.1 Design of Flexible Pavement By Group Index Method

In order to classify the fine grained soils within one group and for judging their suitability as sub grade material, an indexing system has been introduced in HRB[14] classification which is termed as Group

Index. Group Index is function of percentage material passing 200 mesh sieve[12] (0.074mm), liquid limit and plasticity index of soil and is given by equation: (0.074mm) . Liquid limit and plasticity index of soil and is given by equation:
GI=0.2a+0.005ac+0.01bd
Here,
a=that portion of material passing 0.074mm sieve, greater than 35 and not exceeding 75 %
b=that portion of material passing 0.074mm sieve, greater than 15 and not exceeding 35%
c = that value of liquid limit in excess of 40 and less than 60
d = that value of plasticity index exceeding 10 and not more than 30.

5.2 California Resistance Value Method

F.m Hakeem and R.M.Carmany in 1948 provided design method based on stabilometer R- value and cohesiometer Computer- value.Based on performance data it was established by Hveem and Car many that pavements thickness varies directly with R value and logarithm of load repetitions. It varies inversely with fifth root of Computer value.
The expression for pavement thickness is given by the empirical equation.

T=K (TI) (90-R)/C1/5
Here T=total thickness of pavement, cm
K=numerical constant=0.166
TI=traffic index
R=stabilometer resistance value
C =Cohesiometer value.

5.3 Wheel loads

Urban traffic is heterogeneous. There is a wide spectrum of axle loads plying on these roads. For design purpose it is simplified in terms of cumulative number of standard axle (8160 kg) to be carried by the pavement during the design life. This is expressed in terms of million standard axles or msa. Computation of design Traffic In terms of cumulative number of standard axle[13] to be carried by the pavement during design life.

6. Conclusion

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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