COMPARATIVE STUDY OF FLEXIBLE AND RIGID PAVEMENTS BY FINITE ELEMENT METHOD

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Abstract - Axisymmetric finite element analyses have been done for flexible and rigid pavements. Both the pavements have been analysed with base course and without base course. In first analysis the flexible pavement as well as rigid pavements have been analysed without base course with pavement thickness equal to 100 mm and subgrade modulus equal to 5000 kN/m². In the second analysis pavement thickness equal to 75 mm and base course thickness equal to 250 mm with subgrade modulus equal to 5000 kN/m² has been analysed. In the third analysis pavement of thickness equal to 100 mm with base course thickness equal to 450 mm and subgrade modulus equal to 5000 kN/m² has been analysed. In the fourth analysis pavement of thickness 100 mm with no base course with subgrade modulus equal to 15000 kN/m² has been analysed. Based on these analyses conclusions have been made. The nodal deflection as well as element stress for flexible pavement is more than the rigid pavement. For both pavements the nodal deflection as well as element stress decreases with decreasing height. At larger height the nodal deflection as well as element stress of flexible pavement is greater than the rigid pavement. For both the pavements with base course the deflection as well as element stress of flexible pavement is greater than rigid pavement. For pavement of thickness 100 mm and no base course and subgrade modulus equal to 15000 kN/m², also the variation of nodal deflection and element stress with pressure is more in flexible pavement than the rigid pavement.

Keywords: Pavement thickness, base course, finite element analysis, nodal deflection, element stress.

I. INTRODUCTION

The flexible pavements consist of asphalt concrete wearing surface built over a base course and they rest on compacted subgrade. The flexible pavements are able to resist only very small tensile stresses. The design of a flexible pavement is based on the principle that the surface load is dissipated by carrying it deep into the ground through successive layer of granular materials. Some of the design methods for flexible pavements are Group Index Method, California Bearing Ratio Method, North Dakota Method, Burmister’s Design Method and U.S. Navy Plate Bearing Test Method. Rigid pavements are made up of Portland cement concrete, and may or may not have a base course between the pavement and the subgrade. Because of its rigidity and high tensile strength, a rigid pavement tends to distribute the load over a relatively wide area of subgrade, and a major portion of the structural capacity is supplied by the slab itself. The rigid pavements are used for heavier loads and can be constructed over relatively poor subgrade. Flexible pavements with asphalt concrete surface courses are used all around the world. Also rigid pavement with and without base course are used in many countries all around the world. The various layers of the flexible pavement and rigid pavement structure have different strength and deformation characteristics which make the layered system difficult to analyze in pavement engineering. The fine-grained soils in the subgrade, exhibit nonlinear behavior. Finite element programs that analyze pavement structures need to employ this kind of nonlinear characterization to more realistically predict pavement responses.

II. LITERATURE REVIEW

Wang et.al (1972) studied the response of rigid pavements subjected to wheel loadings using linear finite element model. The slab was modeled with medium thick plate elements assuming Kirchoff plate theory. The foundation was considered to be as an elastic half space. Slab stresses and deflections were computed using finite element model with both a continuous foundation and Winkler foundation, and were compared to stresses computed using Westergaard’s equation. In general Westergaard’s solution agreed closely with the finite element method results assuming Winkler foundation.

Tabatabaie and Barenberg (1980) developed a more general finite element program called ILLI-SLAB which is still in use today. ILLI-SLAB utilizes the same medium as thick plate elements employed in earlier models. The effect of a bonded or unbonded base can be incorporated using a second layer of plate elements below the slab. The subgrade is modeled as Winkler’s foundation. Verification of models developed with ILLI-SLAB was achieved by comparison with theoretical solutions for stresses and displacements. The results compared well.

Huang (1983) extended his earlier models to allow the consideration of multiple slabs and various load transfer devices in a manner similar to ILLI-SLAB.
It should be noted that dowels were modeled as having shear stiffness only across the joint i.e bending deformations of the dowels were not considered. The subgrade was modeled as an elastic half space and loss of contact between the subgrade and the slab was considered.

Tayabji et al (1986) developed the program JSLAB for analyzing pavements resting on a Winkler foundation. The model incorporates features similar to ILLI-SLAB, utilizing plate elements to model the slab and a bonded or unbonded base. Dowels were modeled with modified beam elements that incorporated the effect of shear deformations and elastic support provided by the concrete. As in ILLI-SLAB, aggregate interlock and keyways were modeled with springs.

Krauthammer and Western (1988) focus on the relationship between shear transfer capabilities across pavement joints and the effects on the behavior of the pavement. The approach of the present study is to develop a numerical model that could accurately represent the mechanism for shear transfer across reinforced concrete pavement joints and implement it in an existing finite element code. The tool is then used for the analysis of various pavements for which experimental data are available; the model is further refined until the numerical results are in good agreement with the experimental information.

Helwany et al (1998) in their study illustrate the usefulness of finite element method in the analysis of three-layer pavement systems subjected to different types of loading. The method is capable of simulating the observed responses of pavements subjected to axle loads with different tyre pressures. The pavement materials are considered as linear elastic, nonlinear elastic, and viscoelastic. Finite element modeling of pavements has been found extremely useful.

Hadi and Arfiadi (2001) state that the design of rigid pavements involves assuming a pavement structure then using a number of tables and figures to calculate the two governing design criteria, the flexural fatigue of the concrete base and the erosion of the subgrade. Each of these two criteria needs to be less than 100%. The designer needs to ensure that both criteria are near 100% so that safe and economical designs are achieved. This paper presents a formulation for the problem of optimum rigid road pavement design by defining the objective function, which is the total cost of pavement materials, and all the constraints that influence the design. A genetic algorithm is used to find the optimum design. The results obtained from the genetic algorithm are compared with results obtained from a Newton-Raphson based optimization solver.

Subagio et al (2005) discuss a case study for multi layer pavement structural analysis using methods of equivalent thickness. An approximate method has been developed to calculate stresses and strains in multilayer pavement systems by transforming this structure into an equivalent one-layer system with equivalent thicknesses of one elastic modulus. This concept is known as the method of equivalent thickness which assumes that the stresses and strains below a layer depend on the stiffness of that layer.

Das (2008) discusses the reliability issues in bituminous pavement design, based on mechanistic-empirical-approach. Variabilities of pavement design input parameters are considered and reliability, for various proposed failure definitions, of a given pavement is estimated by simulation as well as by analytical method. A methodology has been suggested for designing a bituminous pavements for a given level of overall reliability by mechanistic empirical pavement design approach.

Beiabih and Chandra (2009) have compared the cost of flexible and rigid pavements. It is necessary to ensure that they are designed for the same traffic loading. A total of 90 flexible pavements and 63 rigid pavements are designed, and their costs compared. The costs include construction cost and fixed maintenance cost. Mathematical expressions are developed to relate the cost of pavements with subgrade CBR and traffic in million standard axles. Flexible pavements show wider range of variation in cost with respect to design parameters of traffic and subgrade CBR. The overall variation in cost of rigid pavements is comparatively small. It is observed that flexible pavements are more economical for lesser volume of traffic.

Tarefder et al (2010) present that reliability is an important factor in flexible pavement design to consider the variability associated with the design inputs. In this paper, subgrade strength variability and flexible pavement designs are evaluated for reliability. Parameters such as mean, maximum likelihood, median, coefficient of variation, and density distribution, function of subgrade strength are determined. Design outputs are compared in terms of reliability and thickness using these design procedures. It is shown that the AASHTO provides higher reliability values compared to the probabilistic procedure. Finally, the reliability of the flexible pavement design is evaluated by varying hot mix asphalt properties. Alternative designs are recommended for the existing pavement thickness by modifying material and subgrade properties to mitigate different distresses.

Long and Shatnawi (2011) address the structural performance of experimental rigid pavements constructed in California. The experimental project consists of seven Portland Cement concrete pavement sections with various layer structures. Falling weight deflectometer was utilized to conduct deflection testing for back calculation of layer moduli and subgrade reaction moduli, evaluation of joint transfer capacity, and detection of voids under the slabs. In addition, pavement distress condition was also evaluated as it relates to the integrity of pavement structure. The major findings in this study indicate that thick slab and lean concrete base lower the pavement deflection response and prevent the formation of voids under the slab corners, but lean concrete base has no significant effect on subgrade reaction moduli values.

Ameri et al (2012) have used finite element method to analyse and design pavements. Finite element method is able to analyse stability, time dependent problems and problems with material nonlinearity. In this paper, a great number of the prevalent pavements have been analyzed by means of two techniques: Finite element method and theory of multilayer system. Eventually, from statistical viewpoint, the results of
analysis on these two techniques have been compared by significance parameter and correlation coefficient. The results of this study indicate that results of analysis on finite elements are most appropriately compiled with results came from theory of multilayer system and there is no significant difference among the mean values in both techniques.

Jain et. al (2013) discuss about the design methods that traditionally being followed and examine the “Design of rigid and flexible pavements by various methods and their cost analysis by each method”. Flexible pavements are preferred over cement concrete roads as they have a great advantage that these can be strengthened and improved in stages with the growth of traffic and also their surfaces can be milled and recycled for rehabilitation. The flexible pavement is less expansive also with regard to initial investment and maintenance. Although rigid pavement is expansive but less maintenance and have good design period. It is observed that flexible pavements are more economical for lesser volume of traffic. The life of flexible pavement is near about 15 years whose initial cost is less needs a periodic maintenance after a certain period and maintenance costs very high. The life of rigid pavement is much more than the flexible pavement of about 40 years, approximately 2.5 times life of flexible pavement whose initial cost is much more than flexible pavement but maintenance cost is very less.

Dilip et.al (2013) discuss the uncertainty in material properties and traffic characterization in the design of flexible pavements. This has led to significant efforts in recent years to incorporate reliability methods and probabilistic design procedures for the design, rehabilitation, and maintenance of pavements. This study carries out the reliability analysis for a flexible pavement section based on the first-order reliability method and second-order reliability method techniques and the crude Monte Carlo Simulation. The study also advocates the use of narrow bounds to the probability of failure, which provides a better estimate of the probability of failure, as validated from the results obtained from Monte Carlo Simulation. Based on literature review it is found that not much work has been done by finite element method considering material nonlinearity of subgrade. Very few literature has been reported for comparative study of flexible and rigid pavement. Hence there is lot of scope of comparative study of flexible and rigid pavements by nonlinear finite element method.

FINITE ELEMENT ANALYSIS

In this paper axisymmetric finite element analyses have been done by considering the concrete pavement, asphalt concrete pavement and base course as elastic material and subgrade soil as a nonlinear material. The material nonlinearity has been considered by idealizing the soil by Drucker-Prager yield criterion. Fig.1a and Fig.1b show the finite element discretization considered in this analysis. The nonlinear finite element equation has been solved by Full Newton Raphson Iterative Procedure. The concrete pavement, asphalt concrete pavement, base course and the subgrade have been discretized by four nodded isoparametric finite elements. There are 308 elements and 345 nodes considered in this analysis. 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 pavement considered are 75 mm and 100 mm while the thickness of base course considered are 250 mm and 450 mm. Pressure acts at radius 150 mm.
Material Properties

Elastic Modulus of Concrete Pavement = 20000000 kN/m², Poisson’s Ratio=0.30

Elastic Modulus of Asphalt Concrete Pavement=2759000 kN/m², Poisson’s ratio=0.35

Properties of Subgrade

<table>
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<th>Elastic Modulus</th>
<th>Poisson’s Ratio</th>
<th>Cohesion</th>
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<td>25 kN/m²</td>
</tr>
<tr>
<td>15000 kN/m²</td>
<td>0.45</td>
<td>30 kN/m²</td>
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RESULTS AND DISCUSSIONS

Fig.2 shows the pressure vs nodal deflection curve for flexible and rigid pavements for subgrade modulus equal to 5000 kN/m². At pressure 50 kN/m² both pavements have same deflection. For pressure greater than 50 kN/m², at any pressure the deflection of flexible pavement is greater than rigid pavement. This increase of settlement (deflection) increases with increase in pressure and is maximum at highest pressure.

Fig.3 shows the pressure vs element stress curve for flexible and rigid pavements for subgrade modulus equal to 5000 kN/m². At pressure 50 kN/m² both pavements have almost same element stress. For pressure greater than 50 kN/m², at any pressure the element stress of flexible pavement is greater than rigid pavement. This increase of element stress increases with increase in pressure and is maximum at highest pressure.

Fig.4 shows the height vs nodal deflection curve for flexible and rigid pavement for decreasing height. For both pavements the nodal deflection decreases with decreasing height. From height greater than 16 m the nodal deflection of flexible pavement is greater than the rigid pavement and this increase of nodal deflection is maximum at maximum height.

Fig.5 shows the height vs element stress curve for decreasing height. Upto height equal to 19 m both the pavement show the same element stress. Above 19 m height the element stress of flexible pavement is greater than the rigid pavement and is maximum at the maximum height. With decreasing height the element stress for both the pavements decreases and below 19 m height both pavements have same element stress.

Fig.6 shows the pressure vs nodal deflection curve for flexible and rigid pavements for pavement thickness equal to 75 mm and base course equal to 250 mm. At pressure almost equal to 50 kN/m² both the pavement have same nodal deflections. At pressure greater than 50 kN/m² the flexible pavement has greater nodal deflection than the rigid pavement. This increase in nodal deflection is maximum at highest pressure.

Fig.7 shows the pressure vs element stress curve for flexible and rigid pavements for pavement thickness equal to 75 mm and base course equal to 250 mm. At pressure almost equal to 50 kN/m² both the pavement have same element stress. At pressure greater than 50 kN/m² the flexible pavement has greater element stress than the rigid pavement. This increase in element stress is maximum at highest pressure.
Fig. 8 shows the variation of nodal deflection with decreasing height. For both the pavements the nodal deflection decreases with decreasing height. From top height to height almost equal to 19 m the nodal deflection of flexible pavement is greater than the rigid pavement.

Fig. 9 shows the variation of element stress with decreasing height. For both the pavements the element stress decreases with decreasing height. From top height to height almost equal to 21 m the element stress of flexible pavement is greater than the rigid pavement. This increase in element stress is maximum at maximum height.

Fig. 10 shows the pressure vs nodal deflection curve for flexible and rigid pavements for pavement thickness equal to 100 mm and base course equal to 450 mm. Both the pavements have same deflection upto pressure 200 kN/m². Above pressure 200 kN/m² the flexible pavement has more deflection than the rigid pavement and is maximum at maximum pressure. However this increase is comparatively small due to increase in base course thickness.

Fig. 11 shows the pressure vs element stress curve for flexible and rigid pavements for pavement thickness equal to 100 mm and base course equal to 450 mm. Both the pavements have same element stress upto pressure 200 kN/m². Above pressure 200 kN/m² the flexible pavement has more element stress than the rigid pavement and is maximum at maximum pressure. However this increase is comparatively small due to increase in base course thickness.

Fig. 12 shows the variation of nodal deflection with decreasing height. Upto height equal to 19 m both pavements have same deflection. Above height 19 m the flexible pavement has more deflection than rigid pavement. This is maximum at maximum height.

Fig. 13 shows the variation of element stress with decreasing height. Upto height equal to 20 m both pavements have same element stress. Above height 20 m the flexible pavement has more element stress than rigid pavement. This is maximum at maximum height.
Fig. 14 shows the pressure vs nodal deflection curve for flexible and rigid pavements for pavement thickness 100 mm, no base course and subgrade modulus equal to 15000 kN/m$^2$. The nodal deflection increases with increase in pressure. For pressure above 50 kN/m$^2$, the nodal deflection for flexible pavement is more than the rigid pavement. This increase in deflection is maximum at highest pressure.

Fig. 15 shows the pressure vs element stress curve for flexible and rigid pavements. The element stress increases with increase in pressure. For pressure greater than 50 kN/m$^2$, the element stress in flexible pavement is more than the rigid pavement. This is because the rigid pavement takes more pressure and less pressure is transferred to the subgrade. While in case of flexible pavement more pressure is transferred to the subgrade as the asphalt concrete pavement takes less pressure.

Fig. 16 shows the variation of nodal deflection with decreasing height. For flexible as well as rigid pavements, the deflection decreases with decreasing height. Above height 19 m the deflection is more in flexible pavement than the rigid pavement. With decreasing height, the decrease in deflection is more in flexible pavement than the rigid pavement.

CONCLUSIONS
For pressure greater than 50 kN/m$^2$, at any pressure the deflection as well as element stress of flexible pavement is greater than rigid pavement. This increase of settlement (deflection) and element stress increase with increase in pressure and is maximum at highest pressure. For both pavements the nodal deflection as well as element stress decrease with decreasing height. At larger height the nodal deflection as well as element stress of flexible pavement are greater than the rigid pavement and this increase of nodal deflection and element stress are maximum at maximum height. For pavement of thickness 75 mm and base course 250 m, and pavement of thickness 100 mm and base course of thickness 450 mm, the deflection as well as element stress of flexible pavement is greater than rigid pavement. For pavement of thickness 100 mm and no base course and subgrade modulus equal to 15000 kN/m$^2$, also the variation of nodal deflection and element stress with pressure is more in flexible pavement than the rigid pavement. The nodal deflection as well as the element stress decrease with decreasing height for both the pavements. These values for flexible pavements are greater than the rigid pavements.
REFERENCES


