RATIONAL AND ECONOMIC DESIGN OF REINFORCED CONCRETE PAVEMENTS
BASED ON FINITE ELEMENT ANALYSIS

A THESIS

BY

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In this research the behavior of a conventional concrete pavement of uniform thickness and a thickened edge box type pavement with holes for utility services have been investigated under traffic wheel loads using finite element technique. The effects of thickness, width and length of a conventional pavement, thickness of subbase (of CBR 20) and the subgrade CBR on the pavement deflection, tensile stress and subgrade pressure were studied. For the box type pavement the variables included are the end and mid-slab thickness, the width and length of slab, the thickness of the subbase and the CBR of subbase and subgrade. Eight noded isoparametric brick element has been used for the analysis.

The study shows that for a conventional pavement, the maximum values of pavement deflection, tensile stress and subgrade pressure are reduced with an increase in slab thickness. The presence of a subbase further reduces the above values among which the most significant reduction takes place in the subgrade contact pressure value. An increase in pavement width and length of slab also reduces the tensile stress and deflection. When a better quality subbase is used, the deflection and tensile stress are reduced. Similar effects are noticed for a better quality (higher CBR) subgrade. But the most significant benefit is observed for change in CBR from 1 to 4.

The pavement deflections of a box-type pavement, particularly with an equivalent subbase are much lower than the corresponding values for a conventional pavement. The subbase also substantially reduces the tensile stress in the pavement. The type of pavement, whether conventional or box-type, is much more important in reducing pavement deflection and stresses than the quality of the subbase expressed in terms of CBR value.

Based on the findings of the present study, a new design rationale has been suggested for both box and conventional type of pavements, which will help to make the design of concrete pavements more economic and rational.
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CHAPTER ONE
INTRODUCTION

1.1 General

Determination of stress and deflection in reinforced concrete pavements has been a subject of major concern for many years. As highway pavement system involves many design parameters and a complex slab-soil interaction it was not possible until recently to analyze the pavement problem in a rational way. Various classical solutions in equation form resulted from field testing of highway pavements and very simplified analysis of pavement problems were widely accepted as design basis of concrete pavements for quite a long time.

In absence of detailed and realistic studies of load-deflection behavior of pavement system the design methods evolved by various agencies often result in either uneconomic or unsafe designs of highway concrete pavements. As a result the field performance of concrete pavement was often not upto the level to justify its huge initial cost.
Recent research on concrete pavements, as reported by Saxena (1982) is indicative of the possibility of rationalizing the design characteristics of concrete pavements and even obtaining improved pavement performance by changing pavement shape. Later investigations concerning the actual behavior of the concrete pavements by Chou (1983) and Hansen et al (1991) upheld the fact that the concrete pavement system do not respond in the same manner as it was thought conventionally. Their findings and suggestions have opened a new door into the detailed research of concrete pavements.

Therefore, with the availability of larger computer and suitable finite element technique a comprehensive study into the behavior of both conventional and improved shaped concrete pavements is necessary.

1.2 Background of the Research

All the concrete pavement design methods suggested by leading highway authorities are based on various classical solutions which are approximated by a number of simplifying assumptions. There is no scope of incorporating the various physical parameters like
pavement size, shape and layer parameters into those design methods. Again these conventional design methods do not take much care of subgrade behavior i.e. the actual stress and deflection occurring in the subgrade. But all the concrete pavement distresses are initiated primarily from subgrade. Therefore, a detailed study in the behavior of highway subgrade and incorporating this into highway design method is essential.

In the metropolitan area highways there are virtually no slack periods during which highway maintenance can readily be done. The quality of work suffers due to poor working conditions and it is quite expensive to maintain traffic flow. Therefore, it is required to make concrete pavement maintenance requirement as low as possible.

Again, as a highway concrete pavement is expensive, it is necessary to economize the design procedure while at the same time ensuring the durability of the pavement by having a rational design basis.

With this objective in mind various researchers began to use sophisticated finite element technique in analyzing pavement problem from as early as seventies. But most of their works were
involved up to the study of pavement load-deflection behavior. Few had tried to integrate their study into a definite shape with a view to utilizing them for obtaining appropriate pavement design basis. Saxena (1982) have come up with some innovative proposals regarding the change of pavement shape in order to get better performance and economy. Chou (1983) suggested the incorporation of subgrade load-deflection behavior in the design process of concrete pavements. Hansen et al (1991) tried to figure out the pavement pumping distress phenomenon with field investigation.

Therefore, taking the finite element technique as an analysis tool exploring the possibility of having an improved pavement shape and inclusion of various realistic suggestions into the pavement design process is warranted.

In the present study, attempts have been made to analyze the pavement system involving more related pavement parameters as possible using finite element technique. The possibility of having innovative pavement shape for improved performance has also been examined. It is expected that this study would be able to suggest changes in pavement shape and design basis in order to have a low maintenance concrete pavement.
1.3 Objective of the Research

The objectives of the research were as follows:

1. To investigate the actual behavior of both the conventional and box-type of concrete pavements by finite element method.

2. To investigate the effects of various parameters like pavement length, width, subbase strength and thickness on the behavior of the pavements.

3. To develop a new design method for a more rational and economic design of concrete pavements.

1.4 Scope and Methodology of the Research

In an attempt to investigate the behavior of concrete pavements under the action of wheel loading and to come out with a recommendation for a rational and economic design procedure a survey of related literatures, available concrete pavement design methods have been made. Salient features of the conventional design
approaches are presented in order to figure out the limitations and underlying assumptions of those design approaches; thus enabling the distinction of superiority of the design method suggested by present study.

A finite element model of pavement system has been developed. Comprehensive analyses of a conventional shape and an improved shape pavement called Box-type suggested by Sexena (1982) have been made using isoparametric 8 noded brick element. Rigorous analysis has been made to find out stress pattern and load-deflection behavior of pavement slab and underlying subgrade layer.

The sensitivity analyses of the various parameters of pavement system have been carried out and the results of this parametric study are helpful to envisage the structural response of pavement system and to provide indication for preparing a rational and economic design basis for concrete pavements.

On the basis of the findings of the present study a new design proposal and related design charts have been prepared regarding rational and economic design of concrete pavements.

The thesis is organized in the following order:
1. A review of available concrete pavement design methods and recent developments in concrete pavement analysis is presented in Chapter 2.

2. Chapter 3 summarizes the analysis and interpretation of results along with the methodology followed for analysis.

3. Proposals for a rational design of concrete pavements and suggestions regarding economization of pavement design are formulated on the basis of conclusions of the present study in Chapter 4.
CHAPTER 2
LITERATURE REVIEW

2.1 General

Pavements are extremely complex physical systems involving a complex soil-structure interaction problem with associated numerous variables. Extensive research in pavement engineering is being carried out beginning as early as from first quarter of this century. Various classical solutions of pavement problems had come into being from that time till late sixties which were based on various simplifying assumptions. During seventies with the beginning of high speed computer age more realistic solutions of pavement problems were possible. At the same time powerful finite element technique has also come forward to solve the complicated pavement problems.

2.2 Stresses in Rigid Pavement

Stress inducing factors in rigid concrete pavements may be categorized as follows: stresses due to wheel loads, cyclic changes in temperature, changes in moisture content, volumetric changes in subgrade or base courses and discontinuity of subgrade support caused by permanent deformations of the subgrade or loss of support through pumping. Stress due to wheel load largely depend on the
magnitude of the axle load, wheel distribution and tire contact pressure. Cyclic changes in pavement temperature which occurs due to shifting between day and night cause warping, expansion and contraction in the pavement. Due to warping pavement surface experiences tensile stresses. And due to expansion and contraction pavement is stressed indirectly from friction with the subbase layer. Change in the moisture content of subbase and subgrade layer causes volumetric changes in those layers. This volumetric change causes warping and related stress in pavement. However, stress resulting from this volumetric change is little in magnitude. When support below pavement slab is lost or discontinued the slab portion acts as beam and this causes stress in the pavement slab.

It is widely accepted among engineers that the reinforcement is assumed to add very little to the structural capacity of the pavements. Reinforcement used in pavement rather helps to hold the cracked pavement in position and therefore not allowing the cracks formed by temperature warping and contraction stress to widen further. In this way temperature warping and contraction stresses in pavements are taken care of indirectly. Therefore, the problem of pavement design lies in selecting a pavement thickness and a subgrade or subbase/subgrade combination to take care of wheel load stress and harmful pumping mechanism.
2.2.1 Stresses Due to Wheel Loads

In his original work, Westergaard (1927) considered three cases of wheel loading:— (a) Corner load, (b) Edge load and (c) Interior load.

a) Stresses due to Corner load

\[ M = -P/2(1-(a_1/l)^{0.6}) \]  \hspace{1cm} (2.1)

For the corner load the bending moment is computed as

\[ M = -P/2(1-(a_1/l)^{0.6}) \]  \hspace{1cm} (2.1)

where, \( P \) is the applied load, \( a_1 \) is the distance between corner
point of slab and loading point, and \( l \) is the radius of relative stiffness. Radius of relative stiffness is defined as, 

\[
dl = \frac{Eh^3}{12(1-\mu^2)k}^{1/4} \quad \ldots \ldots (2.2)\]

where, 

- \( E \) = Modulus of elasticity of the pavement
- \( h \) = Thickness of pavement (inch)
- \( \mu \) = Poisson's ratio of the pavement
- \( k \) = Modulus of subgrade reaction (pci)

From equation 2.1 using section modulus per unit width \( (h^2/6) \) Westergaard was able to give equation for corner tensile stresses which is as follows:

\[
\sigma_c = \frac{3P}{h^2(1-(a_i/l)^{0.6})} \quad \ldots \ldots (2.3)
\]

where, \( P \) is applied load, \( h \) is slab thickness and \( l \) is the radius of relative stiffness.

Since, the original work done by Westergaard, many investigators have improved on the methods of stress computations. Bradbury (1938) in order to account for the partial subgrade support of the slab at the edges rather than full support as assumed by Westergaard, introduced an empirical formula based on the lines of Westergaard's theory (Sharma 1985). To account for the slab partial
contact with the underlying layer Bradbury has taken modulus of subgrade reaction (k) of soil as one fourth of its actual value. Due to this reduction of k value 1 value is increased to \( \sqrt{21} \) and with this reduction in k value Bradbury computed higher corner tensile stress. Kelly (1939) introduced an empirical formula of the Westergaard type. This formula was based on Arlington test carried by Teller and Sutherland (1935). The empirical formula was developed by modifying the exponent in Westergaard equation for corner loading. Modification was done in such a manner as to cause the computed values to coincide more nearly with the observed data for the case of incompletely supported slab corners.

b) Stresses for interior loading

The equations for interior and edge loading are based upon two theories (Yoder and Witczak 1975). For the first, designated ordinary theory, it is assumed that straight lines through the slab remains straight and perpendicular to the neutral axis under load. For the second, designated special theory, this assumption is abandoned in the immediate vicinity of the load. The Westergaard equation for the interior loads for \( \mu = 0.15 \) is,

\[
\sigma_1 = 0.316p/h^2(4\log_{10}(1/b) + 1.069) \quad \text{......(2.4)}
\]
where, \( b = \sqrt{1.6a^2 + h^2} - 0.675h \) and \( a = \) radius of wheel contact area

For values of \( a \) less than 1.724\( h \), the special theory applies. For larger values of \( a \), the ordinary theory is used, that is, \( b = a \).

c) Stresses for edge loading

The equation of stress for the edge load is,

\[
\sigma_e = \frac{0.572p}{h^2}(4\log_{10}(1/b) + 0.359) \quad \text{(2.4)}
\]

Pickett and Ray (1951) developed influence charts for the solution of the general stress equations. The charts were developed for two cases of loading: (i) assuming that the subgrade acts as a dense liquid (conventional) (ii) based upon the elastic solid case.

But the above stress computation techniques suffer from various limitations. Only a single subgrade property \( k \) can be considered. Effect of Pavement length and width on pavement stress was not considered in these techniques. Influence of subbase layer on pavement stress was not also taken into account in these computation methods.
2.3 Review of Available Design Methods of Conventional Rigid Pavements

2.3.1 General

For suggesting a more economic and rational design method than the available ones it is required to review the scope and limitations of the available design methods. Three of the established design methods are taken for review. These are - i) Portland Cement Association (PCA) method, ii) AASHTO method, iii) Indian Road Congress (IRC) method. The following few paragraphs will deal with the review of these design methods of highway rigid pavements.

2.3.2 Portland Cement Association (PCA) Method

The design methods developed by PCA Engineers (Yoder and Witczak 1975) is based upon stress analysis given by Westergaard which derived on the basis of many simplifying assumptions. The salient features of this method are summarized as follows:

Flexural tensile stress in concrete is the main deciding factor for determination of pavement thickness. Other parameters used in thickness design are modulus of rupture of concrete, modulus of
subgrade reaction of soil, and magnitude and number of repeated wheel loads.

The allowable concrete flexural tensile strength is measured by modulus of rupture tests on beams subjected to third point loading.

The modulus of subgrade reaction (k) of soil is determined by plate bearing test.

Repetitions of traffic loading during design life is covered by considering the fatigue characteristics of concrete. The wheel load to be used for design purpose is obtained by multiplying the actual wheel load by a factor of 1.1-1.2 depending on the wheel and axle type. In this method the traffic is categorized into axle load groups and the stress for an assumed thickness of pavement is determined from the charts shown in Fig.2.2 & 2.3. Stress ratio which is defined as the ratio of flexural tensile stress from wheel load to modulus of rupture of concrete is then determined. The allowable repetitions for the stress ratio due to a wheel load is then determined by using Table 2.1. The number of allowable repetitions in compared to the estimated number of load applications during the design period of the pavement. The percent of the allowable repetitions used by each load is determined and summed up. Theoretically, the design is considered to be appropriate if the sum of fatigue resistance used is less than 100
Figure 2.2 Design chart for single-axle-truck loads. (From Portland Cement Association.)
Figure 2.3 Design chart for tandem-axle truck loads. (From Portland Cement Association.)
### TABLE 2.1. Stress Ratios Allowable Load Repetitions\(^a\) (201)

<table>
<thead>
<tr>
<th>Stress Ratio</th>
<th>Allowable Load Stress</th>
<th>Stress Ratio</th>
<th>Allowable Load Repetition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.51(^c)</td>
<td>400,000</td>
<td>0.69</td>
<td>2,500</td>
</tr>
<tr>
<td>0.52</td>
<td>300,000</td>
<td>0.70</td>
<td>2,000</td>
</tr>
<tr>
<td>0.53</td>
<td>240,000</td>
<td>0.71</td>
<td>1,500</td>
</tr>
<tr>
<td>0.54</td>
<td>180,000</td>
<td>0.72</td>
<td>1,100</td>
</tr>
<tr>
<td>0.55</td>
<td>130,000</td>
<td>0.73</td>
<td>850</td>
</tr>
<tr>
<td>0.56</td>
<td>100,000</td>
<td>0.74</td>
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<tr>
<td>0.57</td>
<td>75,000</td>
<td>0.75</td>
<td>490</td>
</tr>
<tr>
<td>0.58</td>
<td>57,000</td>
<td>0.76</td>
<td>360</td>
</tr>
<tr>
<td>0.59</td>
<td>42,000</td>
<td>0.77</td>
<td>270</td>
</tr>
<tr>
<td>0.60</td>
<td>32,000</td>
<td>0.78</td>
<td>210</td>
</tr>
<tr>
<td>0.61</td>
<td>24,000</td>
<td>0.79</td>
<td>160</td>
</tr>
<tr>
<td>0.62</td>
<td>18,000</td>
<td>0.80</td>
<td>120</td>
</tr>
<tr>
<td>0.63</td>
<td>14,000</td>
<td>0.81</td>
<td>90</td>
</tr>
<tr>
<td>0.64</td>
<td>11,000</td>
<td>0.82</td>
<td>70</td>
</tr>
<tr>
<td>0.65</td>
<td>8,000</td>
<td>0.83</td>
<td>50</td>
</tr>
<tr>
<td>0.66</td>
<td>6,000</td>
<td>0.84</td>
<td>40</td>
</tr>
<tr>
<td>0.67</td>
<td>4,500</td>
<td>0.85</td>
<td>30</td>
</tr>
<tr>
<td>0.68</td>
<td>3,500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) From Portland Cement Association.

\(^b\) Load stress divided by modulus of rupture.

\(^c\) Unlimited repetitions for stress ratios of 0.50 or less.
percent. If this value is too low an overdesign is indicated whereas values too higher than 100 indicates an underdesign. The process will be repeated until a value close to 100 is obtained.

Thus, there is no scope in this method to consider pavement size, shape, subgrade and subbase layer parameters which can have much influence on pavement performance.

2.3.3 AASHTO Design Method

The AASHTO design procedure is based on the AASHO Road Test pavement performance algorithm (AASHTO 1986). It uses an equation similar to that developed by Westergaard (1927) which was used to determine stresses for a corner load. Poisson’s ratio was taken as 0.2 and the distance from the corner to the center of the load was assumed to be 25 cm. This design method uses the concept of pavement terminal serviceability index. Other parameters used in this method, are effective modulus of subgrade reaction \( (k') \), subbase type and subbase thickness. The effective modulus of subgrade reaction \( (k') \) is obtained by modifying the field modulus of subgrade reaction \( (k) \) in the following manner:

i) Modification to k-value is done to account for seasonal variation of road bed soil condition.
ii) Modification to k-value is done to incorporate the effect of rigid foundation near the surface. This effect considers road bed soil resilient modulus and composite modulus of subgrade reaction. Road bed soil is assigned an elastic modulus value for each season depending on sensitivity of road bed material. And composite modulus of subgrade reaction value is estimated depending on subgrade layer composition.

iii) Modification to k-value is also done to account for average relative damage. Average relative damage is the average of relative damages in various seasons which are estimated using tentative pavement slab thickness.

iv) Finally, the k-value is adjusted for potential loss of support arising from subbase erosion.

Then, total 18 kips equivalent single axle load applications is estimated for the design period. A percent of reliability and an overall standard deviation are set for a particular pavement design problem. Using these parameters along with the previously determined k'-value a slab thickness is determined from the AASHTO design chart (shown in Fig.2.4)

Thus, this method is purely an empirical approach of design rather than a rational one. The effect of pavement slab size is not encountered in this method. Also, equivalency of various axle
NOTE: Application of reliability in this chart requires the use of mean values for all the input variables.

Figure 2.4 Design chart for rigid pavements (2)
loads to 18 kips single axle load is based on empirical charts.

2.3.4 Indian Road Congress (IRC) Method

As reported by Sharma (1985) this method was based on analytical technique of Teller and Sutherland (1935) which is a little modification of Westergaard analysis. In this method pavement size is taken into account by considering joint spacing and lane width. A tentative pavement thickness is determined using selected pavement length and width. Then, value of parameters like - concrete flexural strength, modulus of subgrade reaction, modulus of concrete are used to check the tensile stress in pavement. Two design charts (shown in Fig.2.5 & 2.6) are used to determine the tensile stress in the pavement edge and corner region respectively. But these design charts are for a particular wheel load of 4100 kg. Therefore, simplification of converting various axle loads to 4100 kg equivalent axle load is necessary. Also, number of axle load repetitions is not directly used in the design process. Rather, an adjustment to pavement thickness is suggested which is also a limitation of this method.
Fig. 2.5 Design chart for calculation of corner load stress.

Design Parameters

- $P = 4100\,\text{Kg}$
- $\mu = 15\,\text{Cm}$
- $E = 3 \times 10^5\,\text{Kg/\text{Cm}^2}$
- $\mu = 0.15$

Conversion Factor

- $1\,\text{kg} = 2.204\,\text{lbs}$
- $1\,\text{cm} = 0.394\,\text{inch}$
Fig. 2.6 Design chart for calculation of edge load stress.\textsuperscript{(12)}
2.4 Recent Trend in Pavement Analysis

With the advent of high speed computers and powerful finite element technique more realistic analysis of pavement systems were attempted from as early as seventies. Tabatabaie and Barenberg (1980) used finite element model based on classical theory for medium-thick plates on Winkler foundation. The computer program developed by these researchers can handle only two-layered pavement systems with subgrade behavior taken as Winkler foundation.

Huang and Deng (1983) developed a finite element computer program for determining stresses and deflections in multiple slabs on elastic solids. Using this computer program pavement system was analyzed and it was found that assumption of an elastic solid foundation is an improvement over the Winkler or liquid foundation. But this Winkler foundation has been used most frequently for the analysis of concrete pavements. This finding warranted the change in the design basis of available concrete pavement design methods. However, Deng's study did not cover detailed effect of various parameters related to pavement size, shape, subbase and subgrade properties.

Chou (1983) found that Westergaard solution on liquid foundation computes bending stresses in concrete slab with reasonable accuracy. But it computes subgrade pressures under concrete
pavement that are much smaller than those computed by finite element method for slabs on an elastic foundation. Chou (1983) from his finite element study of subgrade contact pressure under rigid pavement concludes that excessive subgrade pressure that occurs at slab edges and at corners can cause large permanent deformations in the subgrade soil. This large deformation can cause the stresses in the concrete slab to increase. And eventually this will lead to the early failure of the concrete pavement. This large permanent deformation leaves behind large void spaces under rigid pavement. This void spaces when filled with water develops pavement faulting mechanism called pumping. Pumping is characterized as the ejection of free water and subgrade (or subbase) material through joints and cracks or at the pavement edge caused by deflection of the slab. However, according to Chou subgrade pressure below the range of 12-15 psi can save most of the subgrade soil from this sort of permanent deformation and resulting pavement distress.

From field investigations of effect of water pumping beneath concrete pavement slabs Elmer et al. (1991) concluded that frictional shear stresses between pavement and the subbase produce loose, fine material. These materials are moved away by water pumping during rainy season leaving voids under pavement slab. According to these researchers pavement faulting and cracking were assumed to be caused by these large voids beneath the pavement.

Therefore to obtain a high performance rigid pavement free from in
<table>
<thead>
<tr>
<th>PICTORIAL REPRESENTATION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MODIFIED CONVENTIONAL WITH INSULATION AND DRAINS</td>
</tr>
<tr>
<td></td>
<td>EDGE-STIFFENER</td>
</tr>
<tr>
<td></td>
<td>ANCHORED</td>
</tr>
<tr>
<td></td>
<td>ANCHORETE GRID SYSTEM</td>
</tr>
<tr>
<td></td>
<td>V-SECTION PAVEMENT</td>
</tr>
<tr>
<td></td>
<td>PILE-SUPPORTED</td>
</tr>
<tr>
<td></td>
<td>BOX-TYPE PAVEMENT</td>
</tr>
<tr>
<td></td>
<td>PAVEMENT ON HYPAR OR CONICAL FOOTINGS</td>
</tr>
</tbody>
</table>

FIG. 2.7 Various Structural form of Pavement Systems (13)
FIG. 2.8 Longitudinal Surface Deflections in Outer Wheel Path for 100-ft (30.5-m) Models

FIG. 2.9 Transverse Surface Deflections at Load in 100-ft (30.5-m) Model
service deterioration has been driving the major research organization and Highway Authorities. The Federal Highway Administration of USA initiated research in the area of premium pavements of low maintenance requirement. With this objective Saxena (1982) presented seven innovative concepts and one modified conventional system of pavement (Fig.2.7). Detailed analytical investigation of conventional and anchored pavement was also covered in his study. Two sample figures (Fig.2.8 & 2.9) taken from his study denotes the improved performance of anchored pavement over the conventional pavement. However, Saxena’s study involves only deflection computation of a single pavement of 100 ft square size. And this study gives no specific suggestions regarding design of a low maintenance pavement. Of the other pavements mentioned in Saxena’s study the Box-type rigid pavements (Fig.2.7) seems to this researchers to serve the purpose of low maintenance pavement due to the added advantage of its shape.

However, the two pavement failure mechanisms one by excessive subgrade pressure and deformation and the other by water pumping are required to be removed from conventional pavement in order to have a better performance pavement. Therefore, this researcher attempted to analyze the detailed aspects of conventional and newly suggested box type pavement by powerful finite element technique. This may pave the way for this researcher to attain a rational and economic design of such high performance concrete pavements.
CHAPTER 3
ANALYSIS AND INTERPRETATION OF RESULTS

3.1 General

Finite element method is one of the most versatile and powerful techniques for analyzing complex pavement system involving a complicated slab-soil interaction. In the present study this method was used to investigate the behavior of pavement system under the action of wheel load. Description of the finite element computer program used for this analysis purpose and the finite element idealization of layered pavement systems are presented in this chapter. Later the pavement analysis scheme for wheel loads and the results of the analysis with simultaneous interpretation and discussions on them are also presented in this chapter.

3.2 Finite Element Computer Program

The present study comprises of investigating the behavior of conventional concrete pavement system as well as the box-type pavement system as mentioned in the earlier chapter (Fig. 2.7) under the action of wheel loads with the help of finite element technique. A generalized finite element computer program, Engineering Analysis System (ANSYS) (Desalvo and Swanson 1985) was used for the purpose of analysis. ANSYS is a generalized finite
element program capable of handling arbitrary load on any shape of physical system. The salient features of this program are summarized in Appendix B.

3.3 Selection of Analysis type and Finite Element

Because of the complex nature of geometry and boundaries of the pavement systems and also due to the arbitrary nature of loading it is appropriate to idealize the pavement system as fully three dimensional. Isoparametric eight noded brick element (Fig. 3.1) with 3 translational degrees of freedom at each node (Desalvo and Swanson 1985) is chosen for the purpose of three dimensional analysis of pavement which is termed as STIF45 in ANSYS Element library. Detailed description of the element is given in Appendix B.

3.4 Selection of Finite Element Mesh

Some trial finite element meshes were studied in order to select an appropriate finite element mesh for analysis. The accuracy level of any finite element mesh can be judged from the magnitude of variation in the displacements obtained from trial meshes as the number of degrees of freedom are increased. The following two paragraphs describe the finite element mesh selection procedure for the two different types of pavement systems intended to be analyzed.
Fig. a) 3-D Isoparametric Solid.

Fig. b) 3-D Isoparametric Solid Output.

Fig. 3.1 3-D Isoparametric Solid Element (5)
Fig 3.2 Finite Element Mesh for Wheel Load Analysis of Box-Type Pavement.
3.4.1 Finite Element Mesh of Box-Type Pavement

A finite element mesh for Box type pavement with subbase and subgrade layers is shown in Fig. 3.2. In order to select the appropriate mesh four trial finite element analysis are performed with total nodes of 672, 840, 1008 and 1176 for a certain loading as well as subbase and subgrade condition. Displacement vs. total no. of nodes were plotted in Fig. 3.3. From the Fig. 3.3 it appears that the selection of mesh with 1176 nodes involving 816 brick elements provides reasonable accuracy in results. That is why this mesh is selected for the analysis.

3.4.2 Finite Element Mesh of Conventional Pavement

A finite element mesh for conventional pavement with subbase and subgrade layers is shown in Fig. 3.4. For selecting an appropriate mesh four trial finite element analysis with total nodes of 495, 735, 1029 and 1176 were made keeping the subbase, subgrade and wheel load condition unaltered. Displacement vs. total no. of nodes was plotted in Fig. 3.5. From Fig. 3.5 it is observed that the mesh with 1176 nodes involving 840 brick elements should provide reasonable accuracy in computing displacement. So, the finite element mesh shown in Fig. 3.4 is selected for analyzing conventional pavement system.
Fig. 3.3 Optimization of Finite Element Mesh for analysing Box type Pavement
Fig. 3.4 Finite Element Mesh for Wheel Load Analysis of Conventional Pavement.
Fig. 3.5 Optimization of Finite Element Mesh for Conventional Pavement
3.5 Idealization of the Problem

3.5.1 General

For analyzing the pavement system it is required to idealize the physical system. The following few paragraphs will describe the idealization scheme undertaken for this purpose.

3.5.2 Structural Idealization of the Pavement system

A typical two-lane pavement slab 40 ft in length with subgrade soil depth of 50 ft was selected for the analysis. Fifty feet subgrade soil depth was considered to be adequate for pavement analysis considering the soil depth influenced by wheel load (Sexana 1982). To cover the predicted arch type of deflected shape and associated pavement end stresses an extra 3 ft of subgrade soil was also taken into consideration on both sides of pavement system.

Smooth boundary conditions, which are described in the following paragraph are applied along the bottom and the side faces of the boundary. The objective of using smooth boundary conditions is to make the system as flexible as possible. Here, the bottom surface as well as all other vertical sides were considered to be on rollers so that no rigid body motion takes place. That is,

- at two Transverse end nodes of model, \( UX = 0 \) (Fig. 3.6c & Fig. 3.6d)
- at two longitudinal end nodes of model, \( UY = 0 \) (Fig. 3.6c & Fig. 3.6d)
- at two bottom surface nodes of model, \( UZ = 0 \) (Fig. 3.6a & Fig. 3.6b)

Where, \( UX, UY \) & \( UZ \) are deflection values of the nodes in \( X, Y \) & \( Z \) directions respectively. In this analysis no relative displacements
FIG. 3.6 CONVENTIONAL AND BOX TYPE PAVEMENT SYSTEM.
were allowed at the interface of the two dissimilar material. A single pavement slab was taken for analysis and the interaction with adjacent slabs (i.e. transfer of load and deflection along pavement slab joints) was not considered in this analysis. The box-shape pavement cross-section was idealized using the following guidelines:

i) Selection of End base width

End base (as shown in Fig.3.7) should be such wide that it can avoid local punching of pavement. End base width vs. End vertical stress ($\sigma_v$) plot (Fig.3.8) shows that with zero end width i.e. with a sharpened end high vertical contact pressure is resulted which may be a potential threat for punching of pavement. From the Fig.3.11 it is observed that use of 18 inch of end base width will make the pavement safe from local over stressing due to punching.

Fig.3.7 Idealization of Box type pavement cross-section
Fig. 3.8 Effect of end base width on edge vertical stress
ii) Slope of the bottom surface of pavement
Starting from centerline of pavement to end base three different slopes (s1, s2 & s3 in Fig.3.7) were given along bottom surface of the box type pavement. The slope near the end base (s3) is the steepest and gets flatter near the centerline of pavement. This shape will help to confine the underlying soil at the same time increasing the structural rigidity of pavement structure due to its shell action.

iii) Dimension of Hollow Space

Hollow spaces are required to be provided at the most thickened edge of the pavement in order to bring in the economy in material use. Element meshes selected for analysis suggests hollow space width of 12 inch in a typical 24 ft wide pavement. This width will be 6 inch in case of 12 ft wide pavement. Now, according to British code of practice as mentioned in Concrete pavement guide (Road Research Laboratory 1970) steel reinforcement in concrete pavement should be placed 2.5 inch below the top surface of the pavement. It is therefore decided not to provide any hollow space within top 4 inch of the pavement. Following this criterion maximum depths for hollow spaces are selected depending on the edge thickness so that no concentration of stress occurs along the bottom corners of the hollow spaces (Fig.3.2).
3.5.3 Properties of Material

Any highway slab-soil system involves a wide variety of subgrade soil. Extreme variability in properties such as soil strength, gradation and permeability always pose a great difficulty in the task of highway design. Considering the wide spectrum of the problem it is therefore decided to choose typical extreme values for soil properties to represent limiting cases rather than to attempt a parametric study of pavement systems under several types of material constituents. The concrete pavement is composed of three different material type:- slab concrete, sub-base aggregate (if used) and sub-grade soil. All the materials are assumed to be linearly elastic, homogeneous and isotropic. The material properties used in this study are described in the following paragraphs.

1) Concrete

The properties of concrete required for analysis of pavement system are Modulus of Elasticity (Ec), density and poisson’s ratio(μc). From experience it is observed that average quality of aggregate and concrete mixing suggests for a concrete strength (fc’) to be taken in the range of (2500-3000 psi). Considering this and using the ACI suggested empirical relationship between Modulus of Elasticity (Ec) and compressive strength (fc’), author used a modulus of elasticity value for concrete as 3x10⁶ psi. According to
the above relationship this value of $E_c$ indicates a concrete flexural strength value of 2770 psi which has been used throughout this study. Poisson's ratio was taken as 0.15.

ii) Sub-base Material

Brick aggregate was selected as sub-base material. The California Bearing ratio (CBR) of brick aggregate varies within the range of 20 to 50. Considering the worst situation of saturated condition a CBR value of 20 is selected for use.

iii) Subgrade Material

Determination and use of California Bearing Ratio (CBR) in subgrade strength evaluation is widely accepted among Highway Engineers (Brown 1979). Most of the naturally occurring and improved subgrade CBR values fall within the range of 1-10 (Road Research Laboratory 1970). Hence, range of CBR value selected for analysis was 1-10. A poisson's ratio value of 0.35 is selected for analysis.

3.5.4 Determination of Modulus of Elasticity of soil

The determination of soil modulus of elasticity ($E$) requires laboratories stress-strain data. But it is not an easy task to suggest a representative $E$ value for subgrade soil from just a few laboratory testing. Again, current practice of assessing subgrade among highway engineers is the determination of appropriate CBR
Therefore, a method is required to evaluate the modulus of subgrade and subbase layer using their CBR values. Heukelom and Klomp (1962) summarized the results of investigations made by the Shell laboratories and Transport and Road Research Laboratory (TRRL) and suggested a simple formula for computing $E$ in the following form:

$$E = 10 \times \text{CBR (MPa)} \quad \cdots \cdots (3.1)$$

Equation 3.1 was used to compute $E$ value of soil in the present study.

3.5.4 Loading

Highway vehicles are of different types. Wide variations in vehicle sizes, weights and wheel arrangements make it difficult to select a unique vehicle load for design purpose. However, gross weight of vehicle, number of repetitions, axle and wheel arrangements are the main factors required to be considered in selecting representative vehicle load. The following idealization of vehicle load was used in this study.
A typical dual-wheel single axle (Fig. 3.9) loading was taken for pavement analysis purpose. The axle load was varied in the range of 10 to 32 kips for the purpose of preparing a design chart. An axle load of 32 kips representing a typical H-20 truck was considered for the detailed parametric study of the pavement systems.

3.6 Critical Wheel Load Case

Various wheel load positions suggested by Portland Cement Association (PCA) (Wright and Paquette 1979) (Fig. 3.10) were considered in the present study. Analysis was performed for the different wheel load positions. The different wheel load positions are referred as load case I, load case II and load case III. Maximum deflections and stresses for Box and conventional type of pavements were plotted in Fig. 3.11, and Fig. 3.12 respectively. From these figures it is observed that load case I is a critical one.
Fig. 3.10/ Truck load positions for stress analysis. (Courtesy Portland Cement Association)
Fig. 3.11 Maximum deflection for different load cases

Fig. 3.12 Maximum tensile stress for different load cases
For the rest of the study this wheel load case I will be used for pavement analysis. However, for 24 ft wide pavement a critical loading case of two truck axles at the same time along the same transverse line was considered. But this type of loading cases with two simultaneous high axle load were assumed to be very few in practical cases. Therefore, this double truck axle loading case will not be considered critical for design purpose.

3.7 Behavior of Concrete Pavements

3.7.1 General

The aim of the present study was to investigate the behavior of the conventional and Box-type reinforced concrete pavement and make necessary recommendations for having a rational and economic design guide for both of them. In order to establish the basis for such recommendations, interpretation of results obtained from finite element analysis was warranted. Four important distress causing factors in pavements namely vertical deflection, tensile stress, subgrade pressure and shear stress at contact surface of pavement and under lying layer were studied. However, the present study restricts its discussions to the single slab layered pavement system described in Fig.3.6a to Fig.3.6d. The layered three dimensional model was considered to be on roller type of support on all of its sides except the top surface. Both box and conventional type of pavement were analyzed for load case of I (Fig.3.10) using the finite element mesh shown in Fig.3.2 & Fig.3.4 respectively.
Both the conventional and box type of pavements taken for analysis have a width of 24 ft. So, there will be cases when two H-20 truck axle will be along the same transverse direction line. For this case the right truck was assumed to occupy the similar axle load position as the left truck. Now as the analysis was an elastic one principle of superposition was used to study the deflections and stresses in the pavement for this loading case. For the study of the behavior of conventional pavement a typical 8 inch thick (Fig.3.14) pavement was considered. In case of Box type pavement a typical pavement with a mid slab thickness of 5 inch and a Te/Tm (Edge thickness/Mid thickness) ratio of 2.8 (Fig.3.13) will have an equivalent uniform thickness of 7.83 inch which is nearly equal to 8 inch. Hence, for the purpose of comparison with the conventional pavement this typical box type pavement was used in the analysis. However, Both the condition of with subbase and with no subbase layer were considered for analysis. Based on these analyses discussions and subsequent comparisons of behaviors of the two pavement systems were made in the following sub articles.

3.7.2 Load deflection behavior of pavement systems

a) Box type pavement

Finite element analysis of box type pavement was performed for load case I (Fig.3.10) and the displacement fields were studied. This analysis of box type pavement reveals that horizontal deflections (UX & UY) are negligible in compared with the vertical deflections
Sub'grade layer depth = 30' 

SUBBASE AREA = 1843 in² 

(EQUIVALENT UNIFORM SUBBASE THICKNESS = 6.4")

Subgrade layer depth = 50'

Fig 3.13 Box Type Pavement System.

Subbase area = 1728 in²

SUBGRADE

SUBBASE THICKNESS = 6.4"

Fig 3.14 Conventional Pavement System.
Therefore, only the vertical deflected shape of Box-type concrete pavement was shown in Fig.3.15. This figure illustrates the general load-deflection behavior of Box-type concrete pavement. From the diagram it is observed that maximum deflections occur in the region under wheel load and deflection value gradually diminishes in the region away from the wheel load position. Variation of vertical deflection both in transverse and longitudinal direction is shown in Fig.3.17 and Fig.3.18 which illustrate that maximum deflection occurs under wheel load. These figures also reveal that without subbase layer larger portion of box type pavement exhibits the typical concentric deflection basin. Where as with a subbase layer almost the whole pavement reveals more cylindrical rather than spherical deflection patterns. This means that with the subbase layer the structural rigidity of the pavement system has been significantly improved. Saxena (1982) also obtained similar cylindrical deflection pattern for anchored pavement (Fig. 2.8). From Fig. 3.17 it is also observed that use of $E_{subbase}/E_{subgrade}$ value of 10 decreases maximum pavement deflection by 75 percent which implies that the use of subbase in case of box type pavement can significantly reduce the vertical deflection of the pavement. For two truck axle loading maximum deflection in box type pavement with a subbase increases by 55% from the corresponding values for single truck loading (Fig.3.19). But similar loading change in case of box type pavement without a subbase causes 65% increase in maximum deflection value.
b) Conventional pavement

The nodal displacements of conventional pavement (UX, UY & UZ) were computed in global x, y and z directions. For load case I, it was observed that transverse and longitudinal deflections (UX & UY respectively) are negligible in comparison with the vertical deflection (UZ). Therefore, only the vertical deflection values were taken into consideration. Vertical deflected shape of conventional pavement shown in Fig.3.16 illustrates the general load deflection behavior of conventional concrete pavement. Variation of vertical deflection both in transverse and longitudinal direction is shown in Fig.3.17 & Fig.3.18 which show that the maximum deflection occurs under wheel load positions. These figures also reveal that in both the cases of with or without subbase layer conventional pavement yields spherical type of deflection pattern. This means that the use of subbase layer does not significantly improve the structural rigidity of conventional pavement. Again in case of no subbase condition distribution of vertical deflection is not uniform. Saxena (1982) also obtained the similar deflection pattern for conventional pavement. Two truck axle loading increases maximum deflection values in conventional pavement significantly. Two truck axle in lieu of one axle causes increase in maximum deflection value by 85% when a subbase is used and by 75% when no subbase is used. As the grid of element meshes used for analyzing conventional pavement was unsymmetrical the deflection pattern (Fig.3.19) for conventional pavement was unsymmetrical.
c) Comparison between Conventional and Box type of pavement

Comparison of deflection pattern shown by box and conventional pavement (Fig 3.17 and Fig.3.18) reveals that a significant improvement in reducing maximum pavement deflection can be achieved by changing the pavement cross-section from conventional to box type section. While conventional pavement shows a spherical deflection pattern, box type of pavement shows a cylindrical deflection pattern which is a clear improvement in load deflection behavior in the case of later one. Because, spherical deflection pattern is characterized by localized high deflection values which indicates less rigidity of the structure. On the other hand, cylindrical deflection pattern is characterized by relatively low deflection values distributed over the length of the structure which indicates relatively higher rigidity of the structure. When no subbase layer is used 15% reduction in maximum pavement deflection is possible by using box type of pavement in lieu of conventional pavement. But similar modification of pavement with a subbase layer (Having 10 times higher CBR value than the underlying subgrade soil) reduces pavement deflection by 80%. So, box type of pavement with a subbase layer is highly effective in reducing pavement deflection. Conventional pavement experiences more increase in maximum deflection value than that of box type pavement when loading is changed from single truck to double truck axles.
Fig. 3.15  Vertical Deflection of Box-Type Pavement for Wheel Loading. (Vertical Deflection 100 times magnified.)
Fig. 3.16 Vertical Deflection of Conventional Pavement for Wheel Loading (Deflection Value 15 Times Magnified).
**Fig. 3.17** Transverse vertical deflection for wheel load

**Fig. 3.18** Longitudinal vertical deflection for wheel load
Fig. 3.19 Transverse vertical deflection for two truck axle
3.7.3 Tensile Stress in Pavement systems

a) Box type of pavement

Nodal stresses acting in x and y direction (shown as $\sigma_x$ and $\sigma_y$ in Fig. 3.1) act as tensile stresses in the pavement. Studying the variation of tensile stress in box type of pavement in both the transverse ($\sigma_x$) and longitudinal ($\sigma_y$) direction (Fig. 3.20 and Fig. 3.21) it is observed that the maximum tensile stress occurs under the wheel positions. Also it can be observed that from the loading edge to the longitudinal direction there is a sharp reduction in pavement tensile stress and after 1/5th of slab length from edge pavement experiences compressive stress. However, in the transverse direction loading edge region experiences maximum tensile stress which gradually diminishes to zero near mid slab region. Use of subbase which has modulus of elasticity 10 times greater than subgrade modulus reduces the flexural stress, $\sigma_x$, by 50 percent (Fig. 3.20). Without subbase the maximum tensile stress occurs about 3 ft away from the free edge and with a subbase layer the maximum tensile stress occurs near the center line of the pavement (Fig. 3.20). But flexural stress distribution in longitudinal direction (Fig. 3.21) shows that the maximum stress ($\sigma_y$) occurs at the edge of the pavement in both the cases of with or without subbase layer unlike the case of transverse direction. Figure 3.22 illustrates that box type pavement with a subbase experiences only 5% more maximum tensile stress for two truck axle
loading case than that for a single truck loading case. But for the similar condition box type pavement without a subbase experiences 12% increase in maximum tensile stress value.

b) Conventional pavement

The variation of tensile stresses in the conventional concrete pavement in the transverse ($\sigma_x$) and longitudinal ($\sigma_y$) direction are shown in Fig.3.20 and Fig.3.21 respectively. From these figures it appears that maximum tensile stresses in pavement occur under the loading points. Figure 3.20 illustrates that use of a subbase layer under conventional pavement which has modulus 10 times higher than the underlying subgrade material causes only 8% reduction in maximum tensile stress. In longitudinal direction (Fig. 3.21) effect of using a subbase layer is also the same. In transverse direction (Fig. 3.20) almost half of the pavement experiences higher tensile stress. Where as in the longitudinal direction tensile stress is reduced to zero within 1/6th of pavement length. For two truck axle loading conventional pavement with a subbase experiences 70% more maximum tensile stress than that of single truck axle loading case (Fig.3.22). But for the similar condition conventional pavement without a subbase experiences 75% more maximum tensile stress. The finite element grid of conventional pavement was unsymmetrical. Therefore, tensile stress distribution in case of conventional pavement was unsymmetrical.
c) Comparison between Box and Conventional pavements

Comparison of tensile stress acting in the two pavement systems was made using Fig.3.20 & Fig.3.21. It appears from Fig.3.20 that without a subbase layer tensile stress distribution in transverse direction in conventional pavement is more uniform than that of box type pavement. This is because, without a subbase layer the enhanced rigidity provided in the thickened edge region of box type pavement is not so active due to high deflection in underlying subgrade layer. But with the use of a subbase layer the performance of box type pavement improves significantly. When a subbase layer is used the use of box type pavement in lieu of conventional pavement can reduce the maximum tensile stress by almost 35%. Whereas without a subbase layer similar change in pavement type can cause 27% increase in maximum tensile stress. Therefore, only in presence of a subbase layer box type pavement experiences much less tensile stress than that of conventional pavement. For two truck axle loading the maximum tensile stress in conventional pavement increases significantly from the corresponding values of single axle loading. But two truck axle loading causes only a little increase in maximum tensile stress value of box type pavement.
- Box type with subbase
- Box type without subbase
- Conventional with subbase
- Conventional without subbase

**Fig. 3.20** Transverse distribution of tensile stress for wheel load

- Box type with subbase
- Box type without subbase
- Conventional with subbase
- Conventional without subbase

**Fig. 3.21** Longitudinal distribution of tensile stress for wheel load
Transverse distance from left to right (inch)

Pavement size: 40' x 24'
Subbase CBR = 20
Subgrade CBR = 2

Fig. 3.22 Transverse tensile stress distribution for two truck axle
3.7.4 Subgrade contact pressure under Pavement systems

a) Box type pavement

Subgrade contact pressure distribution (shown as $\sigma$, in Fig.3.1) under Box-type pavement upon application of wheel load was shown in Fig.3.23 & Fig.3.24. Studying transverse variation of subgrade contact pressure (Fig.3.23) under box type pavement it is observed that maximum subgrade pressure occurs under the wheel load and for the positions away from the wheel load it decreases rapidly. In longitudinal direction (Fig.3.24) subgrade pressure sharply diminishes to smaller value within 1/5th of the pavement length. From the above figures it is observed that subgrade under the Box-type pavement experiences a high contact pressure of around 19 psi when there is no subbase layer. If a subbase layer is used subgrade pressure can be reduced by almost 50%.

b) Conventional pavement

Variation of subgrade contact pressure under conventional concrete pavement in both transverse and longitudinal direction are shown in Fig.3.23 & Fig.3.24. In transverse direction maximum subgrade pressure occurs under wheel load and rapidly diminishes to right and left of it. In longitudinal direction subgrade pressure almost diminishes within 1/10th of pavement length. These figures also illustrates that if no subbase layer over subgrade layer is used maximum subgrade pressure under conventional concrete pavement
varies between 16 psi for load case I. But using a subbase layer it can be reduced by almost 70%.

c) Comparison between Box and Conventional pavement

Comparison of subgrade pressures under box and conventional type of pavement (from Fig. 3.23 and Fig. 3.24) reveals that box type pavement experiences relatively higher subgrade pressure. This is because box type pavement thickness in midslab region is lower than that of uniformly thick conventional pavement. Therefore, subgrade of this region under box type pavement experiences relatively higher subgrade contact pressure.

3.7.5 Shear Stress Under Pavement systems

a) Box type pavement

Shear stress (Shown as SXY in Fig. 3.1) distribution in transverse and longitudinal direction is illustrated in Fig. 3.25 and Fig. 3.26. Studying these figures it is observed that shear stress under Box-type concrete pavement can be as high as around 40 psi when there is no subbase. But using a subbase layer having modulus value 10 times greater than the subgrade modulus it can be reduced by almost 50%. Reduced shear stress in case of the box type pavement with subbase layer is due to the reduced deflection in this case. It is also observed from Fig. 3.25 that left corner and the midslab
Fig. 3.23 Transverse distribution of subgrade pressure

Fig. 3.24 Longitudinal distribution of subgrade pressure
region experience relatively higher shear stress. This is because, wheel loads are positioned in these regions.

b) Conventional pavement

Shear stress distribution in the transverse and longitudinal direction under conventional pavement were shown in Fig.3.25 and Fig.3.26 respectively. From Fig.3.25 it is observed that maximum shearing stress under conventional concrete pavement varies between 25-35 psi in both the cases of with or without a subbase layer. This is because, use of subbase layer below conventional type of pavement does not reduces pavement deflection considerably. It also appears from the figures (Fig.3.25 & Fig.3.26) that maximum shear stress occurs under the wheel load positions.

c) Comparison between Box and conventional pavement

Shear stress distribution under box and conventional type pavement, were compared here. Without a subbase layer box type pavement bottom experiences 33% higher (Fig. 3.25) shear stress than that of conventional pavement. But a subbase layer under box type pavement reduces shear stress significantly; whereas the same in case of conventional pavement has almost negligible effect in reducing shear stress. However, with a subbase layer box type pavement can reduce the shear stress by 20% from that of conventional pavement.
Fig. 3.25 Transverse variation of shear stress

Fig. 3.26 Longitudinal variation of shear stress
3.8 Parametric Study

3.8.1 General

In an attempt to investigate the relative importance of the geometric element and layer parameters of both the conventional and Box-type pavement, a parametric study has been carried out. The parameters considered in this study are:

a) Box Type Pavement
   i) Mid-slab thickness, $T_m$
   ii) Ratio of end thickness to mid-slab thickness ($T_e/T_m$)
   iii) Width of slab, $P_W$
   iv) Length of slab, $P_L$
   vi) Subbase thickness
   vii) Subbase CBR, $C_1$ 
   viii) Subgrade CBR, $C_2$

b) Conventional Pavement
   i) Thickness of pavement slab, $h$
   ii) Width of " slab, $P_W$
   iii) Length of " slab, $P_L$
   iv) Subbase thickness, $d_{sl}$
   v) Subbase CBR, $C_1$ &
   vi) Subgrade CBR, $C_2$

The relevant pavement parameters are shown in Fig. 3.27 & Fig.3.28
Fig. 3.27 Parameters of Box-Type Pavement

Subgrade Layer depth = 50'

Fig. 3.28 Parameters of Conventional Pavement

Subgrade Layer depth = 50'
3.8.2 Varying mid-slab thickness (Tm)

This parameter of box type pavement was varied from 4 inch to 6 inch with an increment of 0.5 inch considering the fact that the economic dimension of mid slab thickness of box type pavement will be within this range. Results of these analyses were presented in Table D.1 (Appendix D) and the corresponding variation in maximum vertical deflection, tensile stress and subgrade contact pressure were shown in Fig.3.29, Fig.3.30 and Fig.3.27 respectively. From Fig.3.29 it appears that in absence of subbase layer under the pavement slab a reduction of 30% in pavement deflection is possible by increasing the mid slab thickness from 4 inch to 6 inch. Similar reduction in pavement tensile stress is also possible with no subbase condition. However, in presence of a subbase layer, no such significant reduction in tensile stress as well as deflection is possible by increasing the mid slab thickness.

3.8.3 Varying the End Thickness (Te)

This parameter of box type pavement was varied from 10 inch to 16 inch at an interval of 2 inch and expressed in terms of te/tm ratio where tm is the constant mid slab thickness of 5 inch. Results of this variation were presented in Table D.2 (Appendix D). Also the effect of this variation on maximum vertical deflection, tensile stress and subgrade contact pressure were shown in Fig.3.32, Fig.3.33 & Fig.3.34 respectively. It is observed from Fig.3.32 that the effect of increasing edge thickness on maximum deflection
Fig. 3.29 Effect of mid slab thickness on pavement deflection

Fig. 3.30 Effect of mid slab thickness on maximum tensile stress
Fig. 3.31 Effect of mid slab thickness on subgrade pressure
of Box-type concrete pavement is not so significant. This is because the maximum deflection occurs in the mid slab region where thickness of pavement remains almost the same although the edge thickness varies. Figure 3.33 illustrates that increase in edge thickness can significantly reduce the flexural tensile stress. Increasing edge thickness from 10 inch to 16 inch (which increase only about 30% of material requirement) tensile stress can be reduced by 50% when there is a subbase layer and by 25% when there is no subbase layer. This proves the efficiency of box shape in reducing the pavement tensile stress. It also appears from Fig.3.34 that effect of increasing edge thickness on maximum subgrade pressure is not so significant. This is because, maximum subgrade pressure occurs in the region where thickness of pavement remains the same although the edge thickness varies.

3.8.4 Varying the thickness of pavement slab (h)

This parameter of conventional pavement shown in Fig.3.28 was varied from 4 inch to 14 inch at an interval of 2 inch. Results of this variation are presented in Table D.3 (Appendix D). Also the variation of maximum deflection, tensile stress and subgrade pressure with the variation of thickness are shown in Fig.3.35, Fig.3.36 & Fig.3.37 respectively. Studying Fig.3.35 which illustrates the effect of pavement thickness on pavement deflection it can be noted that increasing pavement thickness from 4 inch to 6 inch a sharp reduction in pavement deflection is possible and after 6 inch with the increase in pavement thickness a gradual
Fig. 3.32 Effect of increasing edge thickness on Pavement Deflection

Fig. 3.33 Effect of increasing edge thickness on tensile Stress
Fig. 3.34 Effect of increasing edge thickness on subgrade contact pressure.
Pavement size: 40'x24'
Subgrade CBR = 2
Subbase CBR = 20
Subbase thickness = 6"

Fig. 3.35 Effect of Pavement Thickness on Maximum Deflection

Fig. 3.36 Effect of Pavement Thickness on Tensile Stress
Fig. 3.37 Effect of Pavement thickness on subgrade contact pressure
reduction in deflection will occur. Increase in pavement slab thickness reduces the tensile stress in pavement slab. From Fig. 3.36 it is seen that every 2 inch increase in slab thickness results in about 15-20% reduction in tensile stresses.

3.8.5 Varying the width of slab (PW)

a) Box type pavement
The width of pavement depends on number of lanes and lane width. Considering standard lane width of 12 ft number of lanes was varied from one to four. Results of this variation are presented in Table D.4 and the corresponding variation in maximum vertical deflections and tensile stress are shown in Fig. 3.38 & Fig. 3.39. Figure 3.38 illustrates that maximum pavement deflection is decreased with increase in pavement width. Increasing pavement width from 12 ft to 48 ft maximum pavement deflection can be reduced by 63% in both the cases of with or without subbase layer. Similar increase of width results 53% reduction in maximum tensile stress when a subbase layer is used and 66% reduction in tensile stress when no subbase layer is used.

b) Conventional pavement

Results of pavement width variation in case of conventional pavement are presented in Table D.5 (Appendix D). The variation of maximum vertical deflection and tensile stress with the variation
of PW are shown in Fig.3.38 & Fig.3.39 respectively. These figures illustrate that using wider pavement maximum deflection and tensile stress can be significantly reduced in case of conventional pavement also. Increase of pavement width from 12 ft to 48 ft causes 80% reduction in maximum pavement deflection. Similar increase of pavement width results 50% reduction in maximum tensile stress value.

c) Comparison between Box and Conventional Pavement

It can be concluded from Fig.3.38 and Fig.3.39 that variation of width in both the cases of conventional and box type of pavement has almost the similar effect on pavement deflection and tensile stress.

3.8.6 Varying the length of slab (pL)

a) Box type pavement

This parameter was varied from 30 ft to 100 ft at an interval of 10 ft. The results of this variation are shown in Table D.6 (Appendix D) and the corresponding variation in maximum vertical deflections and tensile stress are shown in Fig.3.40 & Fig.3.41. Figure 3.40 and Fig.3.41 illustrates that using longer single pavement slab maximum deflection and flexural tensile stress can be significantly reduced. Increasing the length of box type pavement from 30 ft to 100 ft a reduction of 40%-45% in maximum deflection
value is possible. Similar increase in length causes 55%-60% reduction in maximum tensile stress. This is because, smaller pavement slabs experience higher vertical compressive stress and higher deflection in the layers; therefore higher tensile stress is resulted.

b) Conventional pavement

Results of similar variation in case of conventional pavement are presented in Table D.7 (Appendix D) and the corresponding variation of maximum deflection and tensile stress are shown in Fig.3.40 & Fig.3.41 respectively. From the study of Fig.3.40 and Fig.3.41 it is observed that deflection and tensile stress in pavement can be significantly reduced by using longer pavement. Increase of pavement length from 30 ft to 100 ft in case of conventional pavement causes 10-15% reduction in maximum pavement deflection. However, similar increase in length causes 50%-55% reduction in maximum tensile stress.

c) Comparison between Box and Conventional pavement

Comparison between box and conventional pavement was made regarding the effect of increase in pavement length using Fig.3.40 and Fig.3.41. It was observed that box type pavement was 3 times more effective than conventional pavement in reducing maximum pavement deflection for the increase of pavement length. This implies the higher longitudinal rigidity of box type pavement in compared with
Fig. 3.38 Effect of pavement width on maximum deflection

- Box type with subbase
- Box type without subbase
- Conventional with subbase
- Conventional without subbase

Pavement length = 40'
Subgrade CBR = 2
Subbase CBR = 20
Subbase thickness = 6''

Fig. 3.39 Effect of pavement width on maximum tensile stress

- Box type with subbase
- Box type without subbase
- Conventional with subbase
- Conventional without subbase

Pavement length = 40'
Conventional: 8'' thick
Box: Tm = 5'', Te = 14''
Subgrade CBR = 2
Subbase CBR = 20
Subbase thickness = 6''
Pavement width = 24'
Conventional: 8" thick
Box: $T_m = 5", T_e = 14"$
Subgrade CBR = 2
Subbase CBR = 20
Subbase thickness = 6"

Fig. 3.41 Effect of pavement length on maximum tensile stress

Fig. 3.40 Effect of pavement length on maximum deflection

Fig. 3.40 Effect of pavement length on maximum deflection
the conventional pavement. However, the effect of increase in pavement length on maximum tensile stress is similar in both the cases of box and conventional pavement.

3.8.7 Varying sub-base thickness (ds1)

a) Box type pavement

Subbase thickness under the box-type pavement was varied from 0 inch to 12 inch always keeping subbase CBR value as 20. Results of this variation are presented in Table D.8 (Appendix D). Also the effect of this variation on maximum deflection and tensile stress are shown in Fig. 3.42 & Fig.3.43. Studying Fig.3.42 it is observed that use of a subbase layer under Box-type concrete pavement has significant effect on pavement behavior. Use of subbase of 6 inch equivalent thickness result almost 75% reduction in pavement deflection. But further addition of subbase thickness has almost negligible effect on pavement deflection value. Using only 6" equivalent thickness of subbase layer under Box-type concrete pavement about 60% reduction in pavement tensile stress is possible. But increasing the thickness of subbase layer after that does not add any significant improvement in pavement performance.

b) Conventional pavement

Results of similar variation in case of conventional pavement are presented in Table D.9 (Appendix D). Also the effect of this variation on maximum deflection and tensile stress are presented...
in Fig.3.42 & Fig.3.43 respectively. From Fig.3.42 it can be observed that using 6 inch of improved subbase layer over subgrade soil reduces the maximum deflection by 5% only. Therefore, subbase is not so useful in reducing pavement deflection in case of conventional pavement. It also appears from Fig.3.43 that use of subbase under conventional pavement has no significant effect in reducing pavement tensile stress.

c) Comparison between Box and Conventional pavement

Figure 3.42 and Fig.3.43 illustrate that subbase layer under box pavement is highly useful in reducing pavement deflection and tensile stress. But the same for the conventional pavement is not so useful.

3.8.8 Varying subbase CBR (Cl)

a) Box type pavement

Subbase CBR was varied from 20 to 50 at an interval of 5 upto the subbase CBR value of 30 and later 10. With this variation analyses were made taking a constant equivalent subbase thickness of 6 inch. Results of this variation are shown in Table D.10 (Appendix D). Also the effect of this variation on maximum vertical deflection and tensile stress are shown in Fig. 3.44 & Fig.3.45. It appears from Fig.3.45 that increasing subbase CBR by 2.5 times causes 50% reduction in pavement deflection. Figure 3.45 illustrates that
improvement of subbase CBR has no such significant effect on pavement stress condition. Increasing subbase CBR value from 20 to 50 results only 8% reduction in tensile stress.

b) Conventional pavement

The results of similar variation in case of conventional pavement are presented in Table D.11 (Appendix D) and are also shown in Fig.3.44 & Fig.3.45 respectively. Figure 3.44 illustrates that increase in subbase CBR value from 20 to 50 reduces pavement deflection only by about 10%. Figure 3.41 illustrates the effect of subbase CBR value on tensile stress of pavement slab. It was observed from this figure that increasing subbase CBR value from 20 to 50 only 16% reduction in maximum tensile stress value is possible.

c) Comparison between Box and Conventional pavement

Comparison between box and conventional type of pavement was made regarding the effect of subbase CBR value on maximum pavement deflection and tensile stress value. From Fig.3.44 it was observed that box type pavement was 5 times more effective in reducing the pavement deflection by the increase of subbase CBR than the conventional pavement. However, studying Fig.3.45 it was observed that conventional pavement was 2 times more effective in reducing
Fig. 3.42. Effect of Subbase Thickness on Pavement Deflection

Fig. 3.43. Effect of Subbase Thickness on Maximum Tensile Stress
**Fig. 3.44** Effect of subbase CBR on pavement deflection

**Fig. 3.45** Effect of subbase CBR on maximum tensile stress
tensile stress by the increase of subbase CBR value than the box type pavement.

3.8.9 Varying subgrade CBR (C2)

a) **Box type pavement**

Subgrade CBR was varied from 1 to 10 with an increment of 1 upto CBR value of 4 and later 2. Results of this variation are presented in Table D.12 (Appendix D). Effect of this variation on maximum deflection, tensile stress and subgrade pressure are shown in Fig.3.46, Fig.3.47 and Fig.3.48 respectively. Figure 3.46 illustrates that without a subbase layer 75% reduction in maximum pavement deflection is possible by increasing the subgrade CBR value from 1 to 10. But in presence of a subbase layer similar increase in subgrade CBR causes only 25% reduction in maximum pavement deflection. Figure 3.47 illustrates that using subgrade of high CBR value flexural tensile stress in Box-type pavement can be significantly reduced. Increase of subbase CBR value from 1 to 10 causes 45% reduction in tensile stress when there is no subbase layer and 35% reduction in tensile stress when there is a subbase layer. This is because of the reduced pavement deflection by using high strength subgrade layer.
b) **Conventional pavement**

Results of similar variation in case of conventional pavement are presented in Table D.13 (Appendix D). Also the effect of this variation on maximum deflection, tensile stress, and subgrade contact pressure are presented in Fig. 3.46, Fig. 3.47 & Fig. 3.48 respectively. Figure 3.46 illustrates that increasing subgrade CBR value from 1 to 10 maximum pavement deflection can be reduced by 75% - 80%. Studying Fig. 3.46 it is also observed that increasing subgrade CBR value up to 4 a significant reduction in pavement deflection is possible. After that a gradual reduction in pavement deflection occurs with increase in subgrade CBR. From Fig. 3.47 illustrating the effect of variation of subgrade CBR value upon tensile stress it is observed that increasing CBR value from 1 to 2 a sharp reduction in stress value is possible. In subgrade CBR band of 2-4 a gradual reduction in stress value is possible and above the CBR value of 4 improving the quality of subgrade does not significantly reduces the stress value. However, increasing subgrade CBR value from 1 to 10 pavement tensile stress can be reduced by 60% (Fig. 3.48).

c) **Comparison between Box and Conventional pavement**

The effect of subgrade CBR value on pavement behavior is significant in both the cases of box and conventional type of pavement. Although in case of box type pavement presence of subbase
layer reduces the effect of subgrade CBR value on pavement behavior, in case of conventional pavement effect of subgrade CBR is almost the similar in both the cases of with or without subbase layer. However, in both the cases of box and conventional pavement subgrade pressure is increased gradually with the increase of subgrade CBR.
Fig. 3.46 Effect of subgrade CBR on pavement deflection

- Box type with subbase
- Box type without subbase
- Conventional with subbase
- Conventional without subbase

Pavement size: 40'x24'
Conventional: 8" thick
Box: Tm=5", Te= 14"
Subbase CBR= 20
Subbase thickness= 6"

Fig. 3.47 Effect of subgrade CBR on maximum tensile stress

- Box type with subbase
- Box type without subbase
- Conventional with subbase
- Conventional without subbase

Pavement size: 40'x24'
Conventional: 8" thick
Box: Tm=5", Te= 14"
Subbase CBR= 20
Subbase thickness= 6"
Pavement size: 40'x24'

Conventional: 8" thick
Box: Tm=5", Te=14"
Subbase CBR=20

Subgrade CBR

Fig. 3.48 Effect of Subgrade CBR on subgrade pressure
CHAPTER 4

A NEW DESIGN RATIONALAE

4.1 General

With the results of analysis presented in Chapter 3 along with discussions on each of the items, attempts were made to summarize the different important features of the behavior of both conventional and Box-type concrete pavement in the following articles. Proposal for a new design guide for both of the above mentioned types of concrete pavement will also be made.

4.2 Behaviour of Concrete Pavement upon Wheel Loading

In both the cases of Conventional and Box-type pavement load case I (Fig:3.10) i.e. edge loading results maximum flexural tension and deflection. Among the parameters pavement slab size, thickness, subbase thickness, and subgrade CBR value have considerable effect on pavement stress and deflection. In conventional pavement use of a subbase layer results no such remarkable improvement in pavement behaviour. But use of a subbase layer under the Box type concrete pavement makes a significant improvement in pavement behavior. Box type concrete pavement yields relatively higher subgrade pressure
than the conventional pavement. It is due to less amount of pavement thickness in middle portion of box type pavement. Use of a subbase layer does not decrease shearing stress in case of a conventional pavement. But in case of box type pavement shearing stress can be significantly reduced by using a subbase layer under the pavement slab.

4.3 Proposal for a Design Guide of Pavement Thickness

4.3.1 General

In view of the above characterization of the behavior of concrete pavement proposal for a design guide is formulated here. Flexural tensile stress upon wheel loading obtained from finite element analysis is taken as basic design parameters for design of pavement thickness. Widely used California Bearing Ratio (CBR) has been taken as subbase and subgrade evaluation measure. Subgrade pressure and deflection of pavement will also be checked to remove the possibility of any permanent deformation in subgrade and resulting loss of support and harmful tensile stress in pavement. To control pumping distress in pavement it is required to control shearing stress between pavement bottom and subbase or subgrade. It is expected that inclusion of checking of the above three parameters
will remove the possibility of pavement distress during design period and thus will result a very low maintenance concrete pavement which was the basic objective of this research.

Fatigue failure of concrete is taken as design basis to cover repetitive traffic load and stress ratio vs. allowable load repetition table prepared by PCA (Table 4.1) is included in the design proposal for use in pavement analysis.

In the following articles guidelines for ascertaining design flexural stress, deflection, subgrade pressure and shearing stress are proposed. Conventional and Box type pavement are considered separately for this purpose.

4.3.2 Conventional Pavement

Entering with specific wheel load and subgrade CBR flexural maximum tensile stress in pavement can be found from Fig. 4.1 for no subbase condition and from Fig. 4.2 for with 6 inch of subbase condition. Obviously, the two figures were prepared from the analysis of a 40 ft by 24 ft single pavement slab. For the specific pavement size and subbase CBR the above stress value can be modified using the corresponding parametric study table (Appendix D) and diagrams for conventional pavement presented in Chapter 3.
### Table 4.1: Stress Ratios Allowable Load Repetitions

<table>
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<th>Stress Ratio</th>
<th>Allowable Repetition</th>
<th>Stress Ratio</th>
<th>Allowable Repetition</th>
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<td>360</td>
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<tr>
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<td>42,000</td>
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<td>24,000</td>
<td>0.79</td>
<td>160</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>0.68</td>
<td>3,500</td>
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<td></td>
</tr>
</tbody>
</table>

*a From Portland Cement Association.

*b Load stress divided by modulus of rupture.

*c Unlimited repetitions for stress ratios of 0.50 or less.
Fig. 4.1 Stress Chart of Conventional Pavement for Single Axle Dual Wheel.
Fig. 4.2 Stress Chart of Conventional Pavement for Single Axle Dual Wheel.
4.3.3 Box-type Pavement

Flexural tensile stress upon various wheel loading on a 40 ft by 24 ft pavement slab are arranged in Fig. 4.3 for no subbase condition and in Fig. 4.4 for 6 inch of equivalent uniform thickness of subbase condition. A mid pavement thickness of 5 inch was used in both Fig. 4.3 and Fig. 4.4. Stress value obtained from the above two figures can be modified with the help of parametric study table (Appendix D) and diagrams for Box-type concrete pavement presented in chapter 3 to suit the specific design problem.

4.4 Design of pavement thickness

Finding flexural tensile stress from the design chart allowable repetition from the PCA table (Table 4.1) is found out and then percent used is calculated. Cumulative sum of % used is expected to be under 100 percent for a suitable thickness. For selected thickness subgrade pressure and pavement deflection is checked and necessary modification is done either by increasing thickness or by using a subbase layer. Allowable subgrade pressure limit of 12-15 psi suggested by Chou (1983) has been included in this design method as a criterion. After the frictional shearing stress is checked for that thickness final selection of pavement thickness is done. A pavement thickness design example was attempted using the design proposal suggested by this author. Salient features of the
Fig. 4.3 Stress Chart of Box-Type Pavement for Wheel Loading.

Box Type Pavement
No Subbase Layer

\[ \frac{t_e}{t_m} = 2 \]

\[ \frac{t_e}{t_m} = 2.4 \]

\[ \frac{t_e}{t_m} = 2.8 \]

\[ \frac{t_e}{t_m} = 3.2 \]

Subgrade: 1.5

Pavement Size: 40' x 24'

Wheel Load (Kips)
Fig. 4.4 Stress Chart of Box Type Pavement for Single Axle Dual Wheel.
design problem are mentioned below while details of thickness design procedure were described in appendix C.

Design Example:

A typical road section between Comilla Feni on Dhaka-Chittagong National Highway is taken as a design example to be designed by the guidelines proposed by this researcher. Traffic volume and axle load distribution on this highway along with other necessary data are collected from final report on road traffic submitted by Road Master Plan Project, 1991 (Ref 11). The design parameters are as follows:

Traffic count year 1990
Truck traffic growth rate = 7.3%  
Bus traffic growth rate = 7.2%  
Minibus traffic growth rate = 7.2%

Traffic Classification:
----------------------
Truck = 2300  
Bus = 560  
Minibus = 140  
Pick up = 60  
Car/Taxi = 180
Axle Load Classification:

<table>
<thead>
<tr>
<th>Load</th>
<th>Number</th>
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<tbody>
<tr>
<td>18k</td>
<td>1316</td>
</tr>
<tr>
<td>20k</td>
<td>573</td>
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<td>27k</td>
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</tr>
<tr>
<td>16k</td>
<td>560</td>
</tr>
<tr>
<td>13k</td>
<td>140</td>
</tr>
</tbody>
</table>

Number of lane = Two
Lane width = 12 ft
Subgrade CBR = 1
Subbase CBR = 20
Design Suggestions

With 6 inch of equivalent uniform subbase thickness the following pavement thickness can be suggested for the above problem:

<table>
<thead>
<tr>
<th>Slab size</th>
<th>Design thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Box</td>
</tr>
<tr>
<td>60' x 24'</td>
<td>6.8&quot; (Uniform)</td>
</tr>
<tr>
<td>40' x 24'</td>
<td>6.8&quot; (Uniform)</td>
</tr>
<tr>
<td>40' x 12'</td>
<td>7.5 (&quot; )</td>
</tr>
<tr>
<td>30' x 24'</td>
<td>6.8&quot; &quot;</td>
</tr>
<tr>
<td>30' x 12'</td>
<td>7.8&quot; (Uniform)</td>
</tr>
</tbody>
</table>

From the above suggestions it can be concluded that for smaller slab size box type pavement becomes more economical than the conventional pavement in terms of pavement thickness. But in case of larger slab size box type pavement shows no superiority in terms of less pavement thickness requirement. However, selecting the box type option maximum deflection in pavement can be kept very low which ensures pavement safety from distress resulting from high pavement deflection.
4.5 Potential of Hollow Space in Box type pavement

Optimum use of hollow spaces provided in Box type pavement will result an efficient integrated transportation system. The hollow space on two sides can be used for electricity, telephone, gas and water supply line. Addition of transportation of the supply system will make the Box type pavement economically potential.
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 General

In this chapter conclusions derived from the present study are presented. A guideline for future study in this area is also included.

5.2 Conclusions

On the basis of the analysis carried out the following main conclusions are drawn.

a) Behavior of Conventional pavement

i) The maximum values of tensile stress, deflection and subgrade pressure are found to decrease with an increase in slab thickness. The presence of a subbase layer also reduces the above values among which the maximum subgrade pressure is substantially reduced.

ii) The maximum values of tensile stress and deflection are reduced with an increase in pavement width and length within a reasonable limit. These values are marginally decreased due to the presence of a 6 inch subbase layer.

iii) With the use of a subbase layer of higher strength, an appreciable reduction in maximum tensile stress and deflection value were noticed.

iv) With the increase of subgrade CBR value the value of maximum deflection and tensile stress are reduced. The presence of a subbase layer reduces the maximum deflection and tensile stress value marginally but substantially reduces the maximum subgrade
contact pressure.

b) **Behavior of Box Type Pavement**

Substantial reduction in maximum pavement deflection and tensile stress values occurs due to the use of a subbase layer.

c) **Comparison between Conventional and Box Type Pavement**

i) The pavement deflections (transverse and longitudinal) for a box type pavement, with or without an equivalent subbase, are lower than the corresponding values of a conventional pavement. When an equivalent subbase layer is used the reduction in deflection of a box type pavement is much higher than that of a conventional pavement.

ii) The tensile stresses in a box type pavement with a subbase are significantly lower than those for a conventional pavement. For pavements without a subbase tensile stresses in transverse direction for a box type pavement are lower than those for a conventional pavement for most of the slab width except near the edge.

iii) The shear stresses under box type pavement (transverse and longitudinal direction) are lower than those of conventional pavement when a subbase layer is used.

iv) The higher the value of subgrade CBR the lower are the deflections and stresses in the both the pavement systems for the same loading. The most significant changes take place for CBR values increasing from 1 to 4.

v) The maximum tensile stress reduces considerably for increase in pavement length up to about 70 feet in both the cases of box and conventional pavement.
vi) The type of the pavement, either conventional or box-type, is much more important in reducing pavement deflection and stresses than the quality of subbase expressed in terms of the CBR value.

d) The Suggested Design Method

Based on the finite element analysis a new design method has been suggested. Using this it is observed that box type pavement is more economical than the conventional pavement in terms of less pavement thickness requirement. This economy is more pronounced when pavements with an equivalent subbase layer are considered. Also, this design method is more rational than the available methods through inclusion of the important pavement parameters such as pavement length, width, subbase thickness, subbase and subgrade CBR in the design process.

5.3 Recommendations for Future Study

Based on the experience gathered from the present study the following recommendations for future study in this field can be suggested:

i) A field or laboratory test of repeated wheel loading on reinforced concrete pavement model may be carried out to monitor adequacy of the present study.

ii) Tensile stress charts for concrete modulus of elasticity (Ec) value of $3 \times 10^6$ has been prepared in the present study. Stress charts for other Ec value can be prepared.

iii) From the suggested seven pavement systems anchored system of pavement was studied by Saxena (1982) and the box type was studied by this researcher. The other pavement types can be taken for further study.

iv) Tensile stress chart for air field load application can also be developed.
REFERENCES


Analysis Period - the period of time for which the economic analysis is to be made: ordinarily will include at least one rehabilitation activity.

Drainage Coefficients - factors used to modify layer coefficients in flexible pavements or stresses in rigid pavements as a function of how well the pavement structure can handle the adverse effect of water infiltration.

Equivalent Single Axle Loads (ESAL) - summation of equivalent 18,000-pound single axle loads used to combined mixed traffic to design traffic for the design period.

Maintenance - the preservation of the entire roadway, including surface, shoulders, roadside, structures, and such traffic control devices as are necessary for its safe and efficient utilization.

Modulus of Subgrade Reaction (k) - Westergard's modulus of subgrade reaction for use in rigid pavement design (the load in pounds per square inch on a loaded area of the roadbed soil or subbase divided by the deflection in inches of the roadbed soil or subbase psi/in”.

Pavement Performance - the trend of serviceability with load
applications.

Pavement Structure - a combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed.

Pumping - the ejection of foundation material, either wet or dry, through joints or cracks, or along edges of rigid slabs resulting from vertical movements of the slab under traffic.

Reinforcement - Steel embedded in a rigid slab to resist tensile stresses and detrimental opening of cracks.

Resilient Modulus - a measure of the modulus of elasticity of roadbed soil or other pavement material.

Rigid Pavement - a pavement structure which distributes loads to the subgrade, having as one course a portland cement concrete slab of relatively high-bending resistance.

Roadbed - the graded portion of a highway between top and side slopes, prepared as a foundation for the movement structure and shoulder.

Roadbed Material - the material below the subgrade in outs and
embankments and in embankment foundations, extending to such depth as affects the support of the pavement structure.

Serviceability - the ability at time of observation of a pavement to serve traffic (autos and trucks) which use the facility.

Single Axle Load - the total load transmitted by all wheels whose centers may be included between two parallel transverse vertical planes 60 inches apart extending across the full width of the vehicle.

Subbase - the layer or layers of specified or selected material of designed thickness placed on a subgrade to support a base course (or in the case of rigid pavements the portland cement concrete slab).

Subgrade - the top surface of a roadbed upon which the pavement structure and shoulders are constructed.

Tandem Axle Load - the total load transmitted to the road by two consecutive axles whose centers may included between parallel vertical planes spaced more than 40 inches and not more than 96 inches apart extending across the full width of the vehicle.
B.1 General Features of ANSYS

The ANSYS computer program is a large-scale, general purpose computer program for the solution of several classes of engineering problems. Analysis capabilities include static and dynamic; elastic, plastic, creep and swelling; buckling; small and large deflections; steady state and transient heat transfer, electrostatics, magnetostatics, and fluid flow.

The matrix displacement method of analysis based upon finite element idealization is employed throughout the program. The library of finite elements available numbers more than forty for static and dynamic analyses, and twenty for heat transfer analyses. This variety of elements gives the ANSYS program the capability of analyzing two and three dimensional frame structures, piping systems, two-dimensional plane and axisymmetric solids, three-dimensional solids, flat plates, axisymmetric and three-dimensional shells and nonlinear problems including interfaces and cables.

Loading on the structure may be forces, displacements, pressures, temperatures of response spectra. Loadings may be arbitrary functions of time of linear and nonlinear dynamic analyses. Loadings for heat transfer analyses include internal heat
The ANSYS program used the wave-front (or "frontal") direct solution method for the system of simultaneous linear equations developed by the matrix displacement method, and gives results of high accuracy in a minimum of computer time. The program has the capability of solving large structures. There is no limit on the number of elements used in an analysis. There is no "band width" limitation in the analysis definition; however, there is a "wave-front" restriction depends on the amount of core storage available for a given problem. Up to 3000 degrees of freedom on the wave-front can be handled in a large core. For extremely large problems an out-of-core wave-front procedure (which effectively removes the "wave-front" limit with an increased run time penalty) is available. But ANSYS version 4.4A on IBM RISC-6000 computer though takes minimum amount of computer run time it can handle only 200 degrees of freedom at a time on the wave front.

The input data for the ANSYS program has been designed to make it as easy as possible to define the problem to the computer. A preprocessor (PREP7) contains (real constants, material properties, constraints, loads etc) as well. Geometry plotting is available for all elements in the ANSYS library, including isometric, perspective, section, edge, and hidden-line plots of three-dimensional structures.
ANSYS is capable of generating substructures (or superelements). These substructures may be stored in a library file for use in other analyses. Substructuring portions of a model can result in considerable computer-time savings for nonlinear analyses.

Postprocessing routines are available for algebraic modification, differentiation, and integration of calculated results. Root-sum-square operations may be performed on seismic model results. Response spectra may be generated from dynamic analysis results. Results from various loading modes may be combined for harmonically loaded axisymmetric structures. Post routines also plot distorted geometries, stress contours, safety factor contours, temperature contours, mode shapes, time history graphs, and stress-strain curves.

B.2 Brief Description of 3-D Isoparametric Solid Element

This 3-D isoparametric solid element is used for the three-dimensional modelling of solid structures. The element is defined by eight nodal points having three degrees of freedom at each node; translation in the nodal x, y and z directions.

The element has plastic, creep, swelling, stress stiffening and large rotation capabilities. A generalized plain strain option is also available. Other options are also available to suppress the extra displacement shapes and to define the printout locations.
B.3 Element Input Data

The geometry, nodal point location, face numbers, loading and the coordinate system for this element are shown in Figure A.1. The element is defined by eight nodal points and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. Properties not input are taken as default values described in ANSYS.

The element loading may be input as any combination of nodal temperatures, nodal fluences and face pressures. Six key options are available to control input and output. A typical input file for the analyzing box type of pavement was included at the end of this appendix.

B.4 Theoretical background of ANSYS 45 Element

The element theory is based upon a formulation which includes incompatible displacement shapes. A 2x2x2 lattice of integration points is used with the numerical (Gaussian) integration procedure. Additional theoretical details of this element are described in section 2.45 of ANSYS theoretical manual (Ref.5).
B.5 Assumptions and Restrictions

Zero volume elements are not allowed. Elements may be numbered either as shown in Figure A.1 or may have the planes IJKL and MNOP interchanged. Also the element may not be twisted such that the element has two separate volumes. This occurs most frequently when the elements are not numbered properly.

All elements must have eight nodes. A prism-shaped element may be formed by defining duplicate K and L and duplicate O and P node numbers. A tetrahedron shape is also available. The extra shapes are automatically detected for tetrahedron elements. Nonlinear material properties must be isotropic. Material properties are evaluated at the average of the nodal temperatures.

B.6 Solution Printout

The solution print out from a execution run consists of the nodal solution and element solution. The nodal solution from a structural analysis consists of displacements and stresses at the direction of degrees of freedom. Nodal solutions may be taken either in nodal coordinate systems or in global coordinate system. A typical output file consisting of analysis result of box type pavement was included at the end of this appendix.
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/title, load analysis of box type pvt

kan,0
et,1,45
keyopt,1,5,2
mp,ex,1,3e6
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mp,ex,3,cr
mp,ex,4,cr
mp,ex,5,cr
mp,ex,6,cr
mp,nuxy,1,.15
mp,nuxy,2,.35
mp,nuxy,3,.35
mp,nuxy,4,.35
mp,nuxy,5,.35
mp,nuxy,6,.35
mp,dens,1,.0
mp,dens,2,0
mp,dens,3,0
mp,dens,4,0
mp,dens,5,0
mp,dens,6,0
te=14.0
tm=4
tm1=6
tm2=9
h1=6.5
h2=3
s1=18
s2=36
s3=48
s4=42
pl=480
pw=288
ps=36
ds1=2
ds2=40
ds3=200
ds4=350
pd=(te+ds1+ds2+ds3+ds4)
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n,5,-(ps+pw/2),192,pd
fill,1,5
n,7,-(ps+pw/2),p1,pd
fill,5,7
ngen,2,7,1,7,1,0,0,-4.0
ngen,2,7,8,14,1,0,0,-h1
ngen,2,21,1,7,1,0,0,-te
ngen,2,28,1,7,1,0,0,-(te+ds1)
gen,2,35,1,7,1,0,0,-(te+ds1+ds2)
gen,2,42,1,7,1,0,0,-(te+ds1+ds2+ds3)
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gen,2,56,113,168,1,s1
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ngen,2,7,288,294,1,0,0,-h2
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nset, x, (pw/2+ps)
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nset, y, pl
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nall
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f, 281, fz, -w
f, 449, fz, -w
f, 505, fz, -w
lprint, 1
prdisp, 1, 1, 1176, 1
prnstr, 1
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/input, 27
finish
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prnstr, all
finish
/eof
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VV/SP CONVERSATIONAL MONITOR SYSTEM

1173 -732712E-04 -242942E-03 3000000E+00

ANSYS - ENGINEERING ANALYSIS SYSTEM REVISION 4.4 A 94 BANGL

NDES UNIV. MAY 1, 1990


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12.2575 JUL 28, 1992 CP= 57.730

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***** DISPLACEMENT SOLUTION *****

TIME = 00000E+00 LOAD STEP= 1 ITERATION= 1

NODE UX UY UZ

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1175 -497632E-04 -275135E-03 000000E+00
1176 -666975E-04 -189000E+00 000000E+00

MAXIMUMS

NODE VALUE
589 559599E-02 590 395044E-02 512 -393799E-01

INTEGER STORAGE REQUIREMENTS FOR BACK SUBSTITUTION

TIME = 12.2575 CP= 57.730

FIXED DATA = 7013 TEMPORARY DATA = 7064 TOTAL = 14092

FIXED AVAL= 4000000 TEMPORARY AVAL= 4000000 TOTAL AVAL= 4000000

***** POST 1 MODAL STRESS LISTING *****

LOAD STEP 1 ITERATION= 1 SECTION= 1

TIME= 000000E+00 LOAD CASE= 1

THE FOLLOWING X, Y, Z STRESSES ARE IN GLOBAL COORDINATES

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2 11898E-01 -11755E-01 -2325 2218
3 19096E-02 -6436E-02 -1451 -1411
4 13514E-01 -20806E-01 -12579E-02 5958E-02 3405E-03 9390E-02 313
5 1366E-01 -1015E-01 -4145E-01 3638E-01
6 -6094E-02 -2652E-01 -3196E-02 -7588E-02 3113E-03 -4261E-03 232
7 3205E-02 -7464E-02 -3609E-01 3197E-01
8 -394E-03 -1402E-01 -233B-02 -4678E-02 2923E-03 -1458E-02 154
9 -295E-02 -726E-02 -1939E-01 -5266E-01
10 -6515E-02 -4715E-02 -2481E-03 -1107E-02 -392E-03 -2241E-03 505
11 -2966E-02 -6844E-02 -1190E-01 -1034E-01
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APPENDIX-C

Design Example

A typical road section between Comilla Feni on Dhaka-Chittagong National Highway is taken as a design example to be designed by the guidelines proposed by this researcher. Traffic volume and axle load distribution on this highway along with other necessary data are collected from final report on road traffic submitted by Road Master Plan Project, 1991. The design parameters are as follows:

Traffic count year: 1990
Truck traffic growth rate = 7.3%
Bus traffic growth rate = 7.2%
Minibus traffic growth rate = 7.2%

Traffic Classification
----------------------

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Axle Load Classification
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<td>13k</td>
<td>140</td>
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Number of lane = Two
Lane width = 12 ft

Solution:
---------

Design Traffic

Weighted average projection factor for 40 years = \((1+i)^n/40\)

So, for truck traffic growth rate of 7.3% 40 years projection factor = 5.787
For Bus traffic growth rate of 7.2% 40 years projection factor = 5.657

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| Bus axle load, kips  | 560  | 46.25                             |

| Minibus axle load, kips | 140  | 11.56                             |

Thickness design

Modulus of rupture of concrete = \( \frac{8f'c}{\nu} \) = \( 8 \times 2770 = 421 \) psi (Yoder and Witczak 1975)

Considering the no. of repetitions of traffic load it is required to keep the stress ratio always below 0.50 i.e. maximum tensile stress allowable = 210.5 psi.

The critical axle load which will result maximum stress in the pavement is 27k. Using a load safety factor of 1.15 the critical axle load is obtained as 31 kips. So, the design calculation based on 31k axle load will exclude the need for checking the tensile stress for other lower axle loads.

Considering Conventional Concrete Pavement (40′x24′)

Without Subbase layer

11 inch slab thickness with subgrade CBR of 1 can maintain tensile stress level below 210.5 psi (Fig. 4.1)

With subbase layer

With a subbase layer of 6 inch thickness 10 inch slab thickness with subgrade CBR of 1 can maintain tensile stress level below 210.5 psi (Fig. 4.2).

Now, without a subbase layer subgrade contact pressure exceeds allowable range of 12-15 psi. With a 6" subbase layer subgrade pressure = 4 psi.

Therefore use of a 6 inch subbase layer will make the pavement system safe from pavement distress resulting from excessive subgrade pressure and associated pumping phenomenon.
Use of a subbase layer will reduce shearing stress significantly which will produce lower amount of finer material and thereby pumping distress will be minimized.

**Considering Box-type Pavement (40’X24’)**

maximum tensile stress allowable = 210.5 psi (Explained earlier)

**Without subbase layer**

A \( \frac{te}{tm} \) ratio of 3.2 (Fig.4.3) can be selected where \( tm = 5" \), which is equivalent to 9 inch of uniform thickness.

**With subbase layer**

A \( \frac{te}{tm} \) ratio of 2.0 (Fig.4.4) can be selected where \( tm = 5" \), which is equivalent to 6.8 inch of uniform pavement thickness.

Again to keep the subgrade pressure below the allowable range use of subbase layer is necessary.

Use of a subbase layer will minimize contact shearing stress and will thereby minimize pumping distress.

So, with 40’x24’ pavement slab size no significant amount of saving in material quantity is possible by changing the pavement section from conventional shape to box shape.

**Now, Considering 30 ft by 12 ft pavement slab**

**Conventional Pavement**

For reduced length multiplying factor= 1.11 (Fig.3.41 or Table D.5)

For reduced width multiplying factor = 1.21 (Fig.3.39 or Table D.6)

So, reducing the allowable tensile stress of concrete by these factors, we get allowable tensile stress of concrete in this case = \( \frac{210.5}{(1.11 \times 1.21)} = 156.8 \) psi.

**Without Subbase layer**

with subgrade CBR = 1

Thickness required = 15 inch (Fig. 4.1)

**With Subbase Layer**

Subgrade CBR = 1

Pavement thickness reqd. = 12 inch (Fig. 4.2)
Subgrade CBR = 1

Box-type Pavement

For reduced length multiplying factor = 1.18 (Fig. 3.41 or Table D.5)
For reduced width multiplying factor = 1.16 (Fig. 3.39 or Table D.6)
So, reducing the allowable tensile stress of concrete by these factors, we get allowable tensile stress of concrete in this case
= \frac{210.5}{(1.16 \times 1.18)} = 154 \text{ psi}

With subbase layer

a \frac{te}{tm} \text{ ratio of } 2.8 \text{ will meet the requirement (tm } = 5"
(Chart Fig 4.4) Which has an equivalent 8" uniform pavement thickness.

Without subbase layer box type pavement as well as conventional pavement will not be durable due to high subgrade contact pressure and resulting large deflection in subgrade layer which will ultimately lead to pumping distress.

Therefore, using the same procedure design suggestions for other pavement size can also be estimated.
### APPENDIX D

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**Table D.1 Results of variation of mid slab thickness (tm) for Box type Pavement**

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<td>(kips)</td>
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</tr>
<tr>
<td>40'x24'</td>
<td>32 S.A.</td>
<td>2</td>
<td>4</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.5</td>
<td>111</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>6</td>
<td>108</td>
</tr>
</tbody>
</table>

**Table D.2 Results of Variation of Edge thickness (te) for Box-type Pavement**

*tm= Mid slab thickness=5"

<table>
<thead>
<tr>
<th>Pavement Load</th>
<th>Subgrade</th>
<th>Subbase</th>
<th>te/te*</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ratio)</td>
<td>With Subbase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(6.4&quot; thick)</td>
<td></td>
</tr>
<tr>
<td>40'x24'</td>
<td>32 S.A.</td>
<td>2</td>
<td>2</td>
<td>184</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.4</td>
<td>152</td>
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<td>116</td>
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<td>82</td>
</tr>
</tbody>
</table>

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Table D.3 Results of variation of thickness (t) of conventional pavement.

<table>
<thead>
<tr>
<th>Axle length</th>
<th>Width</th>
<th>t</th>
<th>Subgrade CBR</th>
<th>Subbase CBR</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.A.</td>
<td>ft</td>
<td>ft</td>
<td>inch</td>
<td>With Subbase</td>
<td>No Subbase</td>
</tr>
<tr>
<td>4&quot;</td>
<td>32k</td>
<td>40</td>
<td>24</td>
<td>6&quot;</td>
<td>2</td>
</tr>
<tr>
<td>8&quot;</td>
<td></td>
<td></td>
<td></td>
<td>174</td>
<td>189</td>
</tr>
<tr>
<td>10&quot;</td>
<td></td>
<td></td>
<td></td>
<td>165</td>
<td>170</td>
</tr>
<tr>
<td>12&quot;</td>
<td></td>
<td></td>
<td></td>
<td>128</td>
<td>133</td>
</tr>
<tr>
<td>14&quot;</td>
<td></td>
<td></td>
<td></td>
<td>113</td>
<td>117</td>
</tr>
</tbody>
</table>

Table D.4 Results of variation of Pavement width for Box-type Pavement

<table>
<thead>
<tr>
<th>Length</th>
<th>Load</th>
<th>Subgrade CBR</th>
<th>Subbase CBR</th>
<th>Width ft</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft</td>
<td>kip</td>
<td>With Subbase</td>
<td>No Subbase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>32 S.A.</td>
<td>12</td>
<td>116</td>
<td>56</td>
<td>164</td>
</tr>
<tr>
<td>24</td>
<td>116</td>
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<td></td>
</tr>
<tr>
<td>12</td>
<td>122</td>
<td>299</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>116</td>
<td>239.5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>12</td>
<td>122</td>
<td>299</td>
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</tr>
</tbody>
</table>
### Table D.5 Results of variation of Width of Conventional Pavement

<table>
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<tr>
<th>Length (ft)</th>
<th>Load (kips)</th>
<th>Subgrade CBR</th>
<th>Subbase CBR</th>
<th>Width (ft)</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>32</td>
<td>2</td>
<td>20</td>
<td>12</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>24</td>
<td>174</td>
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<td></td>
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<td></td>
<td>36</td>
<td>154</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>48</td>
<td>114</td>
</tr>
<tr>
<td><strong>S.A.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>32</td>
<td>2</td>
<td>20</td>
<td>24</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>36</td>
<td>154</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>48</td>
<td>114</td>
</tr>
</tbody>
</table>

With Subbase / No Subbase (6" thick)

<table>
<thead>
<tr>
<th>Length (ft)</th>
<th>Load (kips)</th>
<th>Subgrade CBR</th>
<th>Subbase CBR</th>
<th>Width (ft)</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>140</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>32</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>239.5</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>20</td>
<td>S.A.</td>
<td>50</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>73</td>
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<tr>
<td></td>
<td></td>
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<td>70</td>
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<td></td>
<td></td>
<td></td>
<td>100</td>
<td>48</td>
</tr>
<tr>
<td><strong>S.A.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>30</td>
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<td>32</td>
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<td></td>
<td></td>
<td></td>
<td>239.5</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>20</td>
<td>S.A.</td>
<td>50</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>60</td>
<td>162</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>70</td>
<td>148</td>
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<td></td>
<td></td>
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<td>122</td>
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</table>

### Table D.6 Results of variation of pavement length for Box-type pavement

<table>
<thead>
<tr>
<th>Width (ft)</th>
<th>Subgrade CBR</th>
<th>Subbase CBR</th>
<th>Load (kips)</th>
<th>Length (ft)</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>140</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>239.5</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>20</td>
<td>S.A.</td>
<td>50</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>162</td>
</tr>
<tr>
<td></td>
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<td>70</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td>100</td>
<td>122</td>
</tr>
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</table>

With Subbase / No Subbase (6.4" thick)
Table D.7 Results of variation of Length of Conventional Pavement

<table>
<thead>
<tr>
<th>Width (ft)</th>
<th>Load (kips)</th>
<th>Subgrade CBR</th>
<th>Subbase CBR</th>
<th>Length (ft)</th>
<th>Max. Flexural Tension (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>32</td>
<td>2</td>
<td>20</td>
<td>40</td>
<td>195</td>
</tr>
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<td></td>
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<td>50</td>
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<td>143</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>131</td>
</tr>
</tbody>
</table>

With Subbase, No Subbase (6" thick)

<table>
<thead>
<tr>
<th>Length (ft)</th>
<th>Max. Flexural Tension (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>232</td>
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<tr>
<td>40</td>
<td>189</td>
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<tr>
<td>70</td>
<td>138</td>
</tr>
<tr>
<td>100</td>
<td>110</td>
</tr>
</tbody>
</table>

Table D.8 Results of variation of Subbase thickness for Box-type pavement

<table>
<thead>
<tr>
<th>Length (ft)</th>
<th>Width (ft)</th>
<th>Subgrade CBR</th>
<th>Load (kips)</th>
<th>Subbase CBR</th>
<th>Subbase thickness (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>32 S.A.</td>
<td>20</td>
<td>239.5</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>2</td>
<td>32 S.A.</td>
<td>20</td>
<td>116</td>
</tr>
<tr>
<td>40</td>
<td>24</td>
<td>2</td>
<td>32 S.A.</td>
<td>20</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>88</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>84</td>
</tr>
</tbody>
</table>

D4
Table D.9  Results of variation of Sub-base thickness for Conventional pavement

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Subgrade</th>
<th>Subbase CBR</th>
<th>Load</th>
<th>Subbase CBR</th>
<th>Flexural Tensile Stress, psi (Max.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>24</td>
<td>2</td>
<td>20</td>
<td>32</td>
<td>4</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.A. 6</td>
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<td></td>
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<td>178</td>
</tr>
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<td></td>
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<td></td>
<td>174</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>168</td>
</tr>
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<td>12</td>
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<td></td>
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<td>159</td>
</tr>
</tbody>
</table>

Table D.10  Results of variation of subbase CBR for Box type Pavement

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Load</th>
<th>Subgrade</th>
<th>Subbase CBR</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
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<td>S.A. 2</td>
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</tr>
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<td>32</td>
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<td></td>
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<td>106</td>
</tr>
</tbody>
</table>
Table D.11 Results of variation of subbase CBR for conventional pavement

<table>
<thead>
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<th>Length</th>
<th>Width</th>
<th>Subgrade</th>
<th>Subbase</th>
<th>Load</th>
<th>Flexural Tensile Stress, psi (Max.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft</td>
<td>ft</td>
<td>CBR</td>
<td>CBR</td>
<td>kips</td>
<td></td>
</tr>
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<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>174</td>
</tr>
<tr>
<td>25</td>
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<td></td>
<td></td>
<td></td>
<td>169.6</td>
</tr>
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<td>24</td>
<td>2</td>
<td>30</td>
<td>32 S.A.</td>
<td>162.6</td>
</tr>
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<td>40</td>
<td></td>
<td>151.5</td>
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<td>50</td>
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<td></td>
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<td></td>
<td>142</td>
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</tbody>
</table>

Table D.12 Results of variation of subgrade CBR for Box-type Pavement

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Subbase</th>
<th>Load</th>
<th>Flexural tensile stress, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft</td>
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<td>kips</td>
<td>CBR</td>
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<td>116</td>
<td>216</td>
</tr>
<tr>
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<td>24</td>
<td>20</td>
<td>32 S.A.</td>
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</tr>
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</table>

With subbase No subbase
(6.4" thick)
Table D.13 Variation of Subgrade CBR for Conventional Pavement

<table>
<thead>
<tr>
<th>Length (ft)</th>
<th>Load (kips)</th>
<th>Subbase Load (kip)</th>
<th>Subgrade CBR</th>
<th>Maximum Flexural Tension, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Subbase</td>
<td>No Subbase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
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<tr>
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<td>135</td>
<td>106.7</td>
<td>113</td>
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