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# COMPARATIVE STUDY OF CONVENTIONAL REGULAR AND BOX SHAPE CONCRETE PAVEMENTS USING FINITE ELEMENT TECHNIQUE

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**ABSTRACT**: In this study, the behaviour of a uniformly thick conventional pavement and a thickened edge box shaped pavement with holes for utility services under traffic wheel load has been investigated using finite element technique. Four major distress causing phenomena of pavements are studied. These are vertical deflection, tensile stress, subgrade pressure and contact shear stress at slab-soil interface. The study revealed that the maximum deflections of box shaped pavements particularly with an equivalent subbase are much lower than the corresponding values for conventional regular shaped pavements. Also, significant reduction in maximum tensile stress and contact shear stress is possible when an equivalent subbase layer is used under box-shaped pavements. This paper provides a comparison of the behaviour of regular shaped and box shaped concrete pavements under traffic wheel loads.

**KEYWORDS**: Concrete pavements, finite element, conventional uniform thickness and thickened edge box shape pavements

## INTRODUCTION

Field performance of conventional regular shaped concrete pavements (Fig. 1a) was often not upto the level to justify their huge initial costs. In most cases, they need maintenance services at a fairly regular basis causing disruption to traffic flow. Saxena (1982), suggested some innovative proposals regarding the change of pavement shape in order to get a pavement type of higher durability and better performance. Initial analyses (Hossain 1992) have indicated that among the innovative pavement shapes suggested by Saxena (1982), the thickened edge box-shaped (Fig. 1b) concrete pavement might ensure a more durable and better performance pavement system although such a section will require little attention to detail in the preparation of the subgrade. Saxena (1982) claimed that box-shaped base will tend to confine the underlying layer and reduce pumping. It is also claimed that the often encountered temperature curling stress will be minimal in such a shape and the structure will maintain contact with the base or subgrade. A research study was therefore undertaken in order to make a comparison between the conventional and box-type pavements regarding the detailed behaviour of them upon traffic wheel loading.

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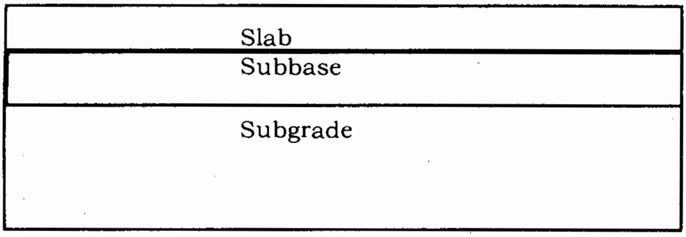
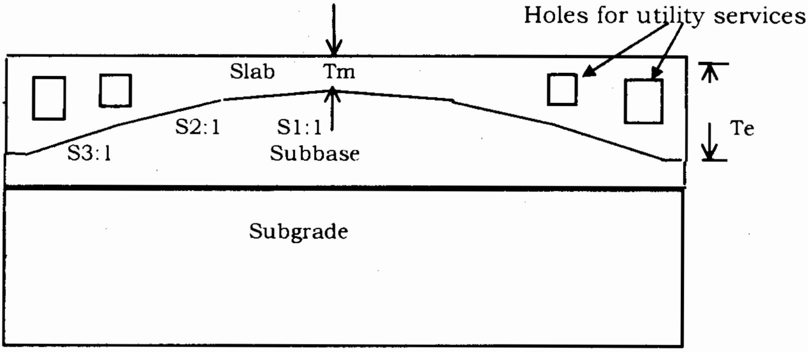


*a) uniform thickness conventional concrete pavement system*



Note: Tm = Mid-slab thickness, Te = edge thickness, S1, S2 & S3 are the three different slopes along the bottom surface of the pavement

*b) thickened edge box-shape concrete pavement system*

*Fig 1. Transverse cross-section of concrete pavement systems*

## METHOD OF APPROACH

Highway concrete pavement system involves complex slab-soil interaction. Various classical solutions in equation form aided by field testing of pavements involve simplified assumption of the complex problem (Yoder and Witczak 1975). With the advent of high-speed computers and powerful finite element technique, it is now possible to carry out more realistic and accurate analysis of concrete pavement system. Amir and Ernest (1980) used finite element method based on classical theory for medium-thick plates resting on Winkler media. The computer program developed by these researchers can handle only two-layered pavement systems: slab and subbase/subgrade. Huang and Deng (1983) considered concrete pavement as thin plate resting on elastic solid in their finite element analysis. The linear elastic approach provided more realistic result than the case of Winkler foundation. Again, Saxena (1982) suggested that a fully three-dimensional analysis of pavement system would yield more reliable results. It was, therefore, decided to make a fully three dimensional and linear elastic finite element analysis of the two highway concrete pavement systems in order to make a comparison between the two. Eight noded isoparametric brick element with three transitional degrees of freedom at each node is selected for finite element modelling (Hossain et. al. 1997) and discretization of the system.

Engineering Analysis System (ANSYS) is a generalised finite element program capable of handling arbitrary load on any shape of physical system (Desalvo and Swanson 1985). For its suitability to the present problem, ANSYS is used in the present study. A 2x2-integration scheme is employed to calculate the stiffness and load matrices. Some trial finite element meshes are studied in order to select an appropriate mesh for analysing the pavement systems. The accuracy level of any finite element mesh can be judged from the magnitude of variation in deflection values obtained from the analysis of trial meshes when the number of degrees of freedom are varied (Hossain 1992). For conventional pavement, a finite element mesh with 1176 nodes involving 840 brick elements (Hossain et al 1997) is found to be providing reasonable accuracy in computing deflections and hence, it is selected for analysing the pavement system. Similar considerations suggested a finite element mesh of 1176 nodes involving 816 brick elements for the box shape pavement (Hossain 1992). However, the net concrete area for both the conventional and box type pavement sections are taken to be the same.

## IDEALISATION OF THE PROBLEM

Considering the geometry of the pavement system and the arbitrary nature of loading, the pavement system is idealised as fully three-dimensional. A single pavement slab is taken for analysis and interaction with adjacent slabs (i.e. transfer of load and deflection along joints) is not considered in this analysis. Fifty feet subgrade soil depth is considered to be adequate for pavement analysis considering the soil depth influenced by wheel load[1]. An extra 3-ft (0.9 m) of subgrade soil on both sides of the concrete slab is also included in the system to be analysed. This is due to the fact that the deformation in soil beyond this three feet is found to be insignificant (Hossain 1992).

Smooth boundary conditions are applied along the bottom and side faces of the boundary. The objective of using smooth boundary conditions is to make the system as flexible as possible. The bottom surface as well as all other vertical sides is considered to be on rollers so that no rigid body motion takes place. Also, no relative displacements are allowed at the interface of the two dissimilar material layers.

Considering the possible variations in the geometry of the cross-section of box type pavement, it is required to take some of the variables as constant for the purpose of general analysis. End base width should be wide enough to avoid local punching of pavement. Again, wider end base width means higher amount of concrete requirement. Analyses are made with varying end base width; and it is found that increase in end base width over 18 inch (457 mm) only results in slight reduction in edge vertical stress (Hossain 1992). Starting from the centreline of the pavement three different slopes are used (S1, S2 and S3 in Fig. 1b) towards the edge along the bottom surface of the pavement. This shape will help to confine the underlying soil at the same time increasing the structural rigidity of the pavement due to its shell action. Hollow spaces are required to be provided at the thickened edge of the pavement in order to bring in the economy in material use. In the analysis, the width of the holes are varied in the range of 6 inch (150 mm) to 24 inch (600 mm) depending on pavement width and finite element mesh. No hollow space can be provided in the top 4 inch (100 mm) of pavement in order to keep provision for steel reinforcement, which according to British design practice (TRL 1970) should be placed 2.5 inch (63 mm) below the top surface of the pavement. Again, the holes should not be extended so much towards the bottom surface to cause stress concentration along the bottom corners of the holes. However, with the selected dimensions of the holes the magnitude of the stresses at the corner of the holes has been checked for any abrupt increase.

## PROPERTIES OF MATERIAL

The highway concrete pavement is normally composed of more than two different layers of materials: concrete slab, subbase aggregate (if used) and subgrade soil. All the materials are assumed to be linearly elastic, homogenous and isotropic. The properties of material in each layer used in the analysis are described below:

i) **Concrete**: The properties of concrete required for analysis are modulus of elasticity (Ec), density and Poisson's ratio. The practical experience of construction industry in developing countries such as Bangladesh suggests a compressive strength of concrete around 3000 psi (20.7 MPa) considering the poor quality of available cement and aggregate and also due to the lower assurance of infield quality control. Based on this value, a modulus of elasticity value of $3x10^6$ psi ($20.7x10^3$ Mpa) as obtained using the ACI suggested empirical relationship (Winter and Nilson 1986) and a Poisson's ratio of 0.15 are assumed in this analysis.

**ii) Subbase material**: Due to the shortage of natural stone aggregate, brick aggregates are widely used as subbase material in Bangladesh. The California Bearing Ratio (CBR) of brick aggregate varies in the range of 20 to 50. Considering the worst situation of saturated condition a CBR value of 20 is selected for the analysis.

**iii) Subgrade material**: CBR is widely used to measure the strength of subgrade among highway engineers. Most of the naturally occurring and improved subgrade CBR values are in the range of 1-10. Subgrade CBR values taken in the analysis are in this range.

In the present study, modulus of elasticity (E) of subbase and subgrade layers are estimated on the basis of their respective CBR values although modulus of subbase is known to be dependent on the subgrade modulus (Yoder and Witczak 1975). The following relationship suggested by Heukelom and Klomp (1962) has been used for the estimation of modulus,

$$E = 1500 \times CBR \tag{1}$$

Where, E is expressed in psi.

## LOADING

Gross weight of vehicle, number of repetitions, axle and wheel arrangements are the main factors required to be considered in selecting representative vehicle load. An axle load of 32 Kips (14515 kg) representing a typical H-20 truck (with dual wheel single axle) is considered for the detailed parametric study of the pavement systems.

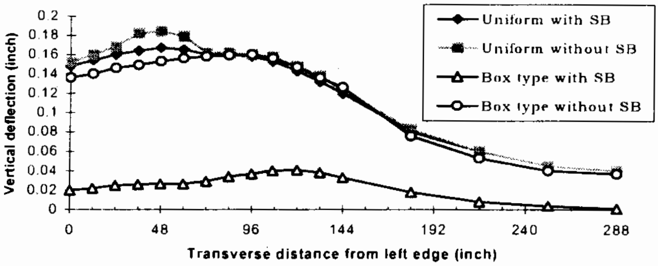
Most truck drivers drive with their outside wheels placed about 2 ft (0.6 m) from the pavement edge (Wright and Paquette 1987). And, analyses (Hossain 1992) reveal that corner loading rather than midway edge loading (as suggested by PCA (Wright and Paquette 1987)) results both critical stress and deflection for the single slab model in the current study. Considering these, a typical H-20 truck axle load position as shown in Fig. 3 and Fig. 4 is selected for the purpose of pavement analysis. However, the wheel loads are taken as concentrated point loads at nodes during analysis and similar wheel load idealisation is also used by other researcher (Saxena 1982).

## ANALYSIS AND INTERPRETATION OF RESULTS

The present study is designed to compare the behaviour of conventional pavement with that of the box type pavement under the action of traffic wheel load. For the purpose of comparison, both conventional and box type pavement should have an equivalent pavement thickness. Analyses are made varying the thickness of uniform conventional pavement to see the effect of such variation; and it is observed that for increasing pavement thickness above 8 inch (203 mm) there is no sharp change in maximum deflection and tensile stress values for the selected wheel load[2]. Therefore, a typical conventional pavement of 8-inch (203-mm) uniform thickness is selected for analysis. In order to select an equivalent box type pavement, analyses are made varying the mid-slab thickness and edge thickness and it appears that a mid slab thickness of 5 inch (127 mm) and a Te/Tm (Edge thickness/mid thickness) ratio of 2.8 can be taken for further analysis as there is no substantial change in behaviour beyond this dimension (Hossain 1992). A typical box-type pavement with these dimensions has an equivalent uniform thickness of 8-inch (203-mm). The pavement systems are analysed for both the condition of 'with a subbase layer' and 'without a subbase layer'. When a subbase layer is considered, the thickness of the layer is taken to be 6 inches (150 mm) for the conventional pavement system and the same for the box-type pavement is taken to be such that the equivalent uniform thickness of the layer is as close as possible to 6 inch (150 mm). The behaviour of concrete pavements related to deflection, tensile stress, subgrade pressure and shear stress is investigated using the results from finite element analysis of the pavement system.

**Load deflection behaviour**

The nodal displacements of pavement slab (UX, UY & UZ) are computed in global X, Y and Z directions. It is observed that transverse and longitudinal deflections (UX & UY respectively) are negligible in comparison with vertical deflection (UZ). Therefore, only vertical deflections are considered for the subsequent analysis of the pavement system. Under traffic wheel loading, variations of vertical deflection both in transverse and longitudinal directions are shown in Fig. 2 & Fig. 3 respectively. Comparison of deflection pattern shown by box and conventional pavement (Fig. 2 & Fig. 3) revealed that with a subbase layer box type pavement showed a cylindrical deflection pattern, while the other pavement system showed a spherical deflection pattern. This is a clear improvement of load deflection behaviour with the introduction of thickened edge box type pavement. Because, spherical deflection pattern is characterised by localised high deflection values indicating less rigidity of the structure. On the other hand, cylindrical deflection pattern is characterised by relatively low deflection values distributed over the length of the structure indicating higher rigidity of the structure. When no subbase layer is used a 15% reduction in maximum pavement deflection is possible by introducing a box-shape pavement in place of a conventional regular shape pavement. But similar modification of pavement shape with a subbase layer (having 10 times higher CBR value than the underlying subgrade soil) reduces maximum deflection values by around 80%. Considering this significant impact of subbase layer on pavement deflection, analyses are made for varying subbase thickness and CBR; and, the results are presented in Fig. 4 and Fig. 5 respectively. Fig. 4 reveals that use of a subbase layer of 6 inch (150 mm) thickness under box type pavement results in a significant reduction in maximum deflection. However, further increase beyond 6-inch (150-mm) results in only little reduction in maximum deflection. On the other hand, in case of conventional pavement, only little reduction in maximum deflection is possible by using a subbase layer of 6 inch (150 mm) or more thickness (Fig. 4). But Fig. 5 reveals that subbase CBR values have little effect on maximum deflection values both in cases of conventional and box-type pavement.



Note: Uniform means uniform thickness conventional pavement, SB means subbase. The mid-slab thickness (Tm) of box type pavement = 5 inch and Te/Tm ratio for the same = 2.8

*Fig 2. Transverse deflection pattern upon wheel loading*

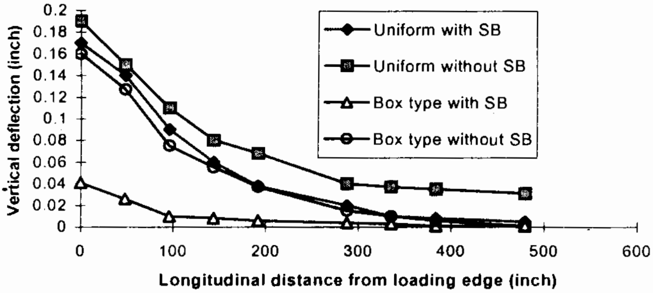


*Fig 3. Longitudinal deflection pattern upon wheel loading*

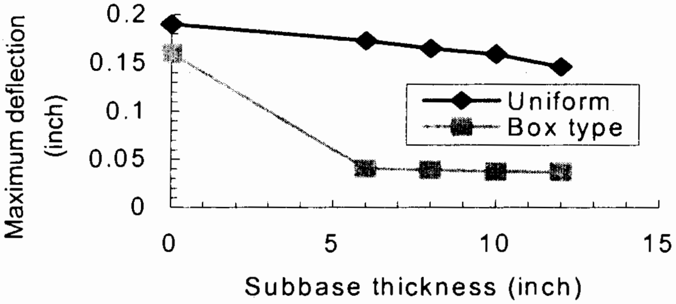


*Fig 4. Effect of increasing subbase thickness on maximum deflection*

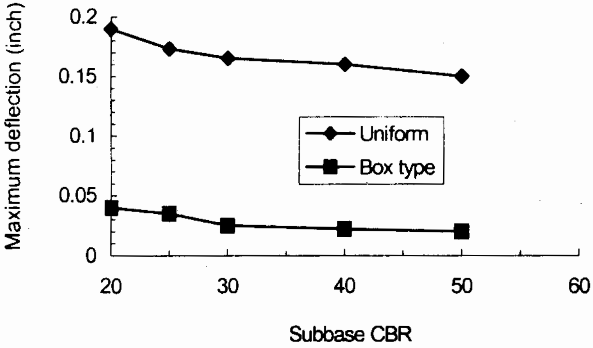


Fig 5. Effect of increasing subbase CBR on maximum deflection

**Tensile stress in pavement system**

The variation of tensile stresses in the transverse and longitudinal direction are shown in Fig. 6 and Fig. 7 respectively. From these figures, it appears that the tensile stresses in pavement are maximum under the loading points. Fig. 6 reveals that without a subbase layer tensile stress distribution in conventional pavement in the transverse direction is more uniform in nature than that of box type pavement. This is because, without a subbase layer the high stiffness provided in the thickened edge region of box type pavement is not so useful due to high deflection in underlying subgrade layer. But with the use of a subbase layer (having 10 times higher CBR value than the underlying subgrade soil) the performance of box type pavement improves significantly. From Fig. 6 and Fig. 7, it can be observed that when a subbase layer is used maximum tensile stress in box type pavement is 35% lower than that of conventional pavement. Whereas without a subbase layer the maximum tensile stress in box type pavement is rather 27% higher than that of conventional pavement. Considering the significant influence of subbase layer on tensile stress, analyses are made for varying subbase thickness and CBR; and, the results are presented in Fig. 8 and Fig. 9 respectively. Fig. 8 reveals that use of a subbase layer of 6 inch (150 mm) thickness under box type pavement results in a significant reduction in maximum tensile stress. However, further increase beyond 6-inch (150 mm) results in only little reduction in tensile stress. On the other hand, in case of conventional pavement, only little reduction in maximum tensile stress is possible by using a subbase layer of 6 inch (150 mm) or more thickness. Again, Fig. 9 reveals that subbase CBR value has little effect on maximum tensile stress for the box type pavement; but the same value has significant effect on maximum tensile stress for conventional pavement.

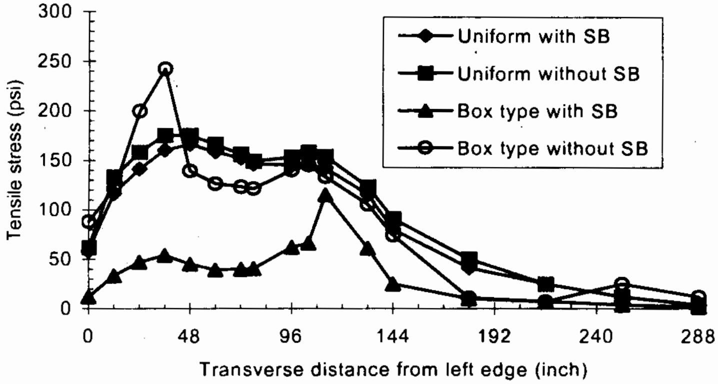


*Fig 6. Transverse distribution of tensile stress*

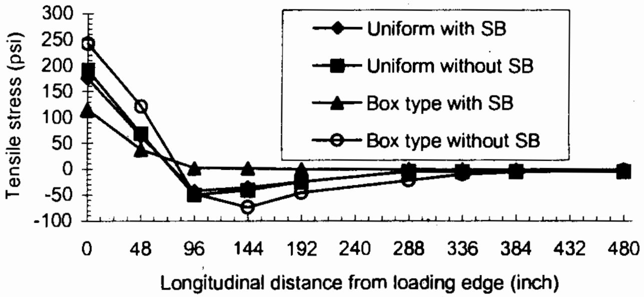


*Fig 7. Longitudinal distribution of tensile stress*

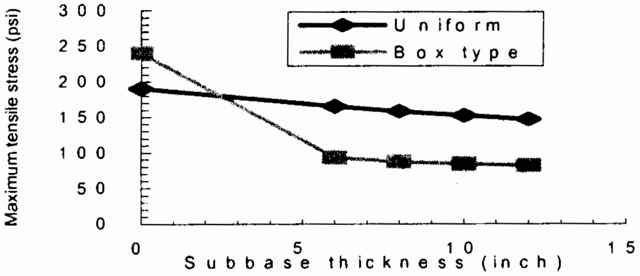


*Fig 8 Effect of increasing subbase thickness on maximum tensile stress*

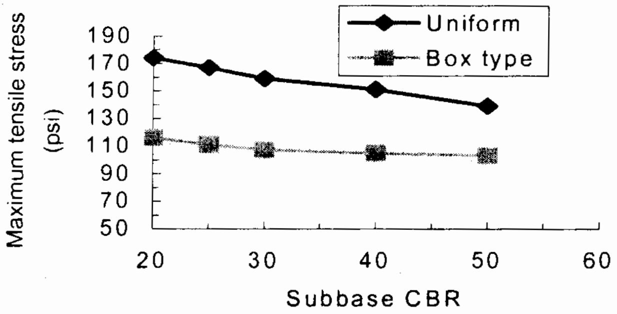


Fig 9. Effect of increasing subbase CBR on maximum tensile stress

**Subgrade pressure under concrete pavements**

Subgrade pressure distribution under pavement systems is shown in Fig. 10 and Fig. 11 in the transverse and longitudinal directions respectively. The figures reveal that box type pavement experiences relatively higher maximum subgrade pressure. However, when a subbase layer is considered the maximum subgrade pressure under box type pavement is reduced considerably (Fig. 10 and Fig. 11).

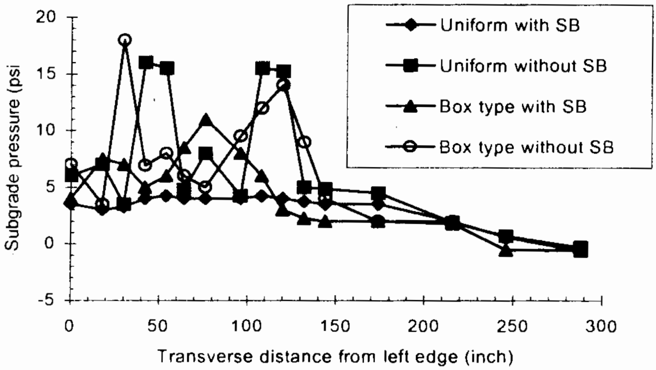


*Fig 10. Transverse distribution of subgrade pressure*

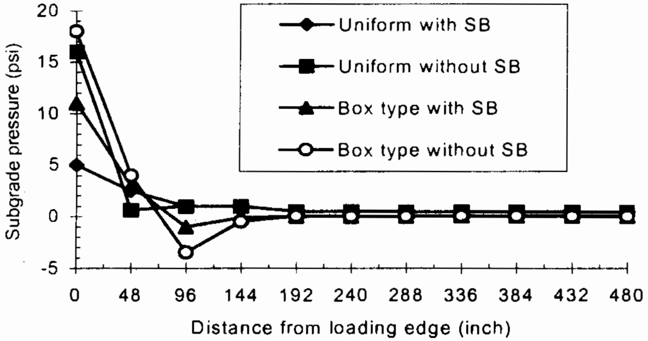


*Fig 11. Longitudinal distribution of subgrade pressure*

**Contact shear stress at slab-soil interface**

Shear stress distribution in the transverse and longitudinal direction at the slab-soil interface are presented in Fig. 12 and Fig. 13 respectively. The figures reveal that maximum shear stress at the interface is around 30 psi (0.21 Mpa) for conventional pavements; and, the same for box type pavements are around 20 psi (0.14 Mpa) and 40 psi (0.28 Mpa) for the condition of with and without subbase layer respectively. This means use of a subbase layer cannot reduce the contact shear stress at the slab-soil interface of conventional pavements; but similar use of a subbase layer in case of a box type pavement can reduce the maximum shearing stress by 50%.

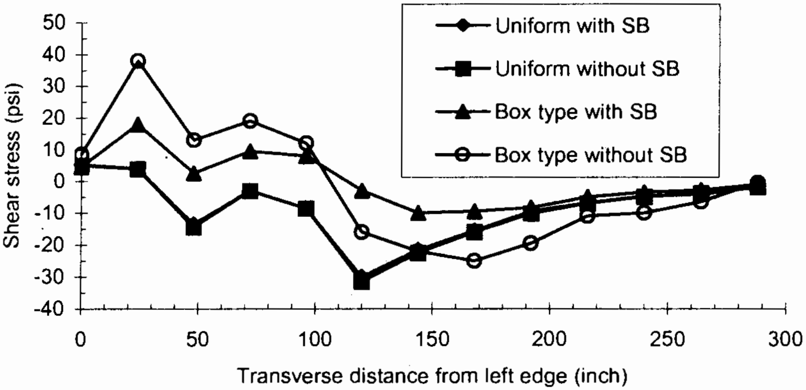


*Fig 12. Transverse distribution of shear stress at slab-soil interface*

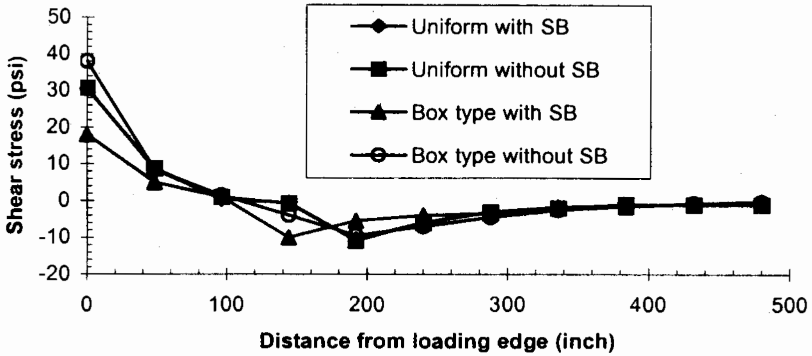


*Fig 13. Longitudinal distribution of shear stress at slab-soil interface*

## CONCLUSIONS

A comparative study of uniform and box shape pavement system has been undertaken using finite element technique. In comparison with uniform thickness pavement, box shape pavements show higher rigidity, especially, when used along with a subbase layer. When no subbase layer is used, box type pavement undergoes 15% less maximum deflection than the uniform pavement. But with a subbase layer box type pavement shows 80% less maximum deflection than the corresponding value of uniform pavement. The tensile stresses in a box type pavement with a subbase layer are also significantly lower than those for a uniform pavement. But without a subbase layer box type pavement experiences higher maximum tensile stress than that of the uniform pavement. The shear stresses under box type pavement are lower than those of uniform pavement when a subbase layer is used.

Considering the significant reductions in most of the distress causing elements, the potential of the box-shape pavement is considerable as a low-maintenance pavement suitable for important and busy city corridors.

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