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THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS OF CONCRETE PAVEMENT SYSTEM

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ABSTRACT: A three dimensional linear elastic finite element analysis is performed to analyse highway cement concrete pavement-soil system. 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. Effects of thickness and length of a concrete pavement on the pavement deflection, tensile stress and subgrade pressure under traffic wheel load are investigated. The similar effects of thickness of subbase and California bearing ratio (CBR) of subgrade are also analysed. The study revealed that under wheel loading, the maximum value of pavement deflection, tensile stress and subgrade pressure are reduced substantially with an increase in slab thickness. It is also observed that the magnitudes of pavement deflections and tensile stresses in concrete pavements are reduced with the use of a subgrade of higher CBR value.

KEYWORDS: Concrete pavements, finite element, subbase and subgrade

INTRODUCTION

Highway cement concrete pavement system involves complex slab-soil interaction. Various classical solutions in equation form aided by field testing of pavements involve very 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. This approach provides more realistic result than the case of Winkler foundation. But a major limitation of their study is that only one material can be considered in the subgrade. Also, their study did not cover detailed effect of parameters like pavement size, shape, subbase and subgrade properties. Therefore, further research study is

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required to be made for comprehensive understanding of the behaviour of pavement system.

SCOPE

A fully three-dimensional finite element study of concrete pavement system has been carried out in order to investigate the detailed behaviour of pavement system under the action of traffic wheel load. A parametric study has also been made to see the effects of various parameters like pavement slab thickness, pavement length, subbase thickness, subbase and subgrade CBR on the behaviour of pavements.

FINITE ELEMENT IDEALISATION

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 (Fig. 1) 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 (Sexana 1982). An extra 3 ft 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 insignificant (Hossain 1992).

Eight noded isoparametric brick element (Fig. 2) with three transitional degrees of freedom at each node is selected for finite element modelling 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 has been used in the present study. A 2x2 integration scheme is employed to calculate the stiffness and load matrices. The finite element model for a typical single concrete pavement with subbase and subgrade layers is shown in Figure 3. Some trial finite element meshes are studied in order to select an appropriate mesh for analysis. 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). A finite element mesh with 1176 nodes involving 840 brick elements (Fig. 3) is found to be providing reasonable accuracy in computing deflections (Hossain 1992) and hence, it is selected for analysing the pavement system.

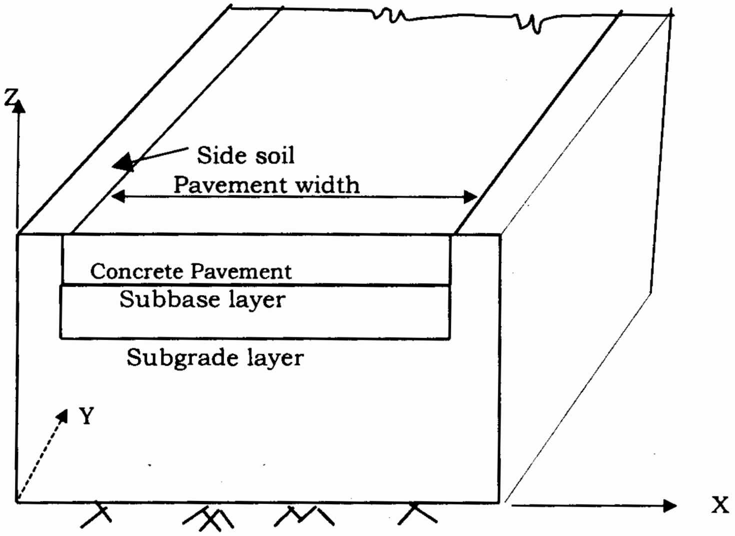
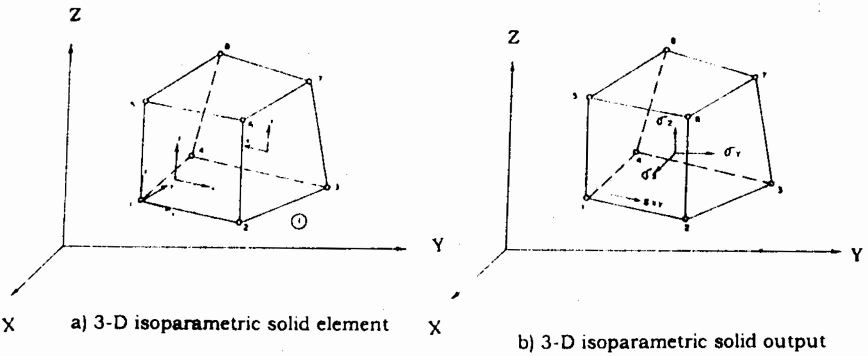


Fig 1. Schematic diagram of highway concrete pavement system



a) 3-D isoparametric solid element

b) 3-D isoparametric solid output

Fig 2. Three Dimensional (3-D) isoparametric solid element (Desalvo and Swanson 1985)

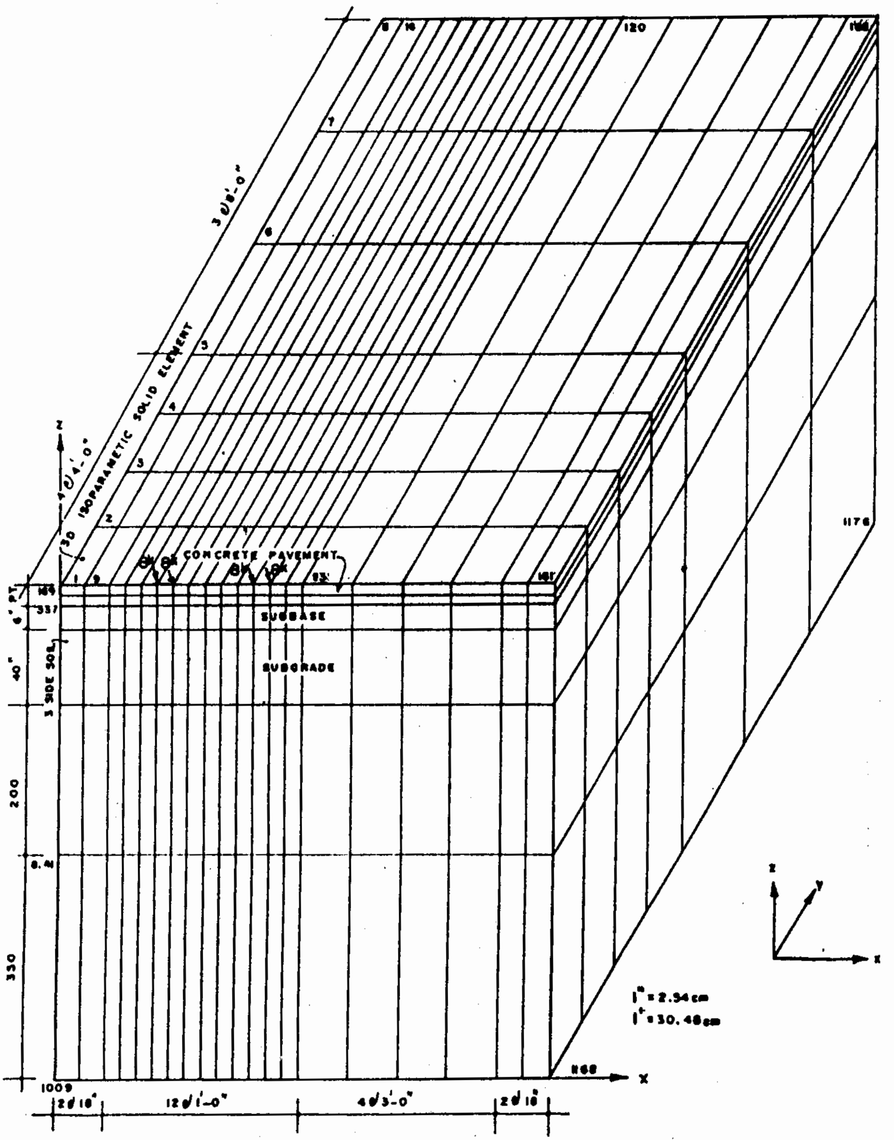


Fig 3. Finite element mesh for wheel load analysis of concrete pavement system (a typical pavement of 40ft by 24 ft is shown)

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 are considered to be on rollers so that no rigid body motion takes place (i.e. deflections along X,Y and Z directions in Fig. 2) are assumed to be zero. Also, no relative displacements are allowed at the interface of the two dissimilar material layers.

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 compressive strength of concrete generally varies in the range of 2500-3000 psi in Bangladesh construction practices. Based on this range, a modulus of elasticity value of $3x10^6$ psi 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. Modulus of elasticity (E) of soil is computed using Klomp (1962) suggested relationship between CBR and modulus of elasticity which is as follows,

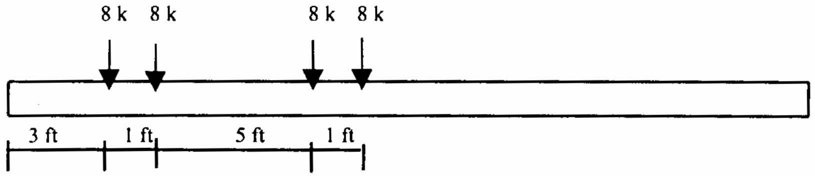
$$E = 1500 \times CBR \qquad \text{......(1)}$$

where, E is expressed in psi.

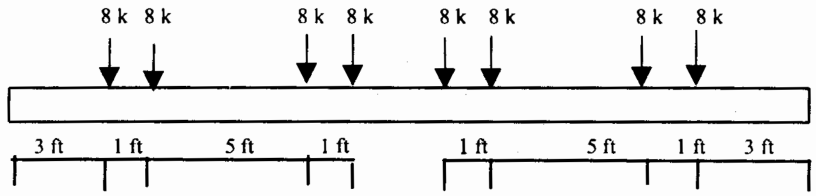
LOADING

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 representing a typical H-20 truck(with dual wheel single axle) is considered for the detailed parametric study of the pavement systems.

A comparative analysis (Hossain 1992) revealed that, out of three wheel load cases (Wright and Paquette 1979) suggested by Portland Cement Association (PCA), case-I results maximum tensile stress and deflection. Therefore, wheel load case-I is selected for the purpose of pavement analysis and the same is shown in Figure 4 for a typical H-20 truck loading. However, for pavements of more than one lane width (a lane width of 12 ft has been considered for this study), the possible two opposite flow truck axles are also considered simultaneously for analysis. The double truck loading is also shown in Figure 4.



a) Wheel loading for a H-20 truck (Note: k means kips)



b) Wheel loading for two H-20 trucks (Note: k means kips)

Fig 4. Wheel load arrangements for analysis

BEHAVIOUR OF CONCRETE PAVEMENTS

In order to study the detailed behaviour of concrete pavements, a typical pavement of 8 inch thickness has been analysed. The length and width of pavement slab are taken to be 40 feet and 24 feet respectively. The pavement system is 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. During the parametric study, the geometric and material parameters are varied within the practical range. Pavement length has been varied in the range of 30 ft to 100 ft while the constant slab thickness of 8 inch has been used. Pavement thickness has been varied in the range of 4 inches to 14 inches while the pavement length is taken as constant at 40 ft. The subbase layer thickness has been varied in the range of 6 inches to 12 inches while the CBR value of the same layer has been varied in the range of 20 to 50. And, study has also been made with varying subgrade CBR values within the range of 1 to 10. The behaviour of concrete pavements related to deflection, tensile stress, subgrade pressure and shear stress has been investigated using the results from finite element analysis of the pavement system.

Load deflection behaviour

The nodal displacement 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, vertical deflections are only considered for the subsequent analysis of the pavement system. Variations of vertical deflection both in transverse and longitudinal directions are shown in Figure 5 & Figure 6 respectively. The transverse cross-section is taken along the line of wheel load application (Fig. 3) and the same for longitudinal direction is taken along the line through the point of maximum deflection. The figures illustrate that the maximum deflections occur in the region under wheel load and the magnitude of deflection gradually diminishes in the region away from the wheel load position. The maximum deflection of 0.19 inch and 0.17 inch can be observed (Fig. 5 and Fig. 6) for the conditions of without subbase and with subbase layers respectively. However, in cases of pavement width of more than one lane (a lane width of 12 ft has been considered for this study), the possible two opposite flow truck axles are also considered simultaneously for analysis. From Figure 5 and Figure 7, it can be observed that two truck axle loads (Fig. 4) in lieu of one truck axle results in an increase in maximum deflection value by 85% when a subbase is used and by 75% without any subbase. In Figure 8, the effects of pavement thickness on maximum deflection of pavement are shown. The pavement thickness are varied from 4 inches to 14 inches. The figure illustrates that with the increase in pavement thickness maximum deflection of pavement can be reduced; and, the significant reduction can be achieved by increasing the thickness from 4 inches to 6 inches, which suggests a minimum thickness of 6 inches to avoid deterioration from pavement deflection. Analysis of the pavement system are made varying the pavement length, subbase thickness, subbase CBR, and subgrade CBR values. The effects of respective variations on maximum pavement deflection are shown in Fig. 8, Fig. 9 and Fig.10 respectively. Figure 8 shows that maximum deflection can only be slightly (i.e. 10% to 15%) reduced by increasing the pavement length. Similar results have also been found when analyses are made with increased subbase thickness and subbase CBR (Fig. 9). The reduction resulted in the maximum deflection values are 20% for increasing the subbase thickness from 0 inch to 12 inch and 15% for increasing the subbase CBR from 20 to 50 respectively (Fig. 9). But it is revealed from the study that subgrade CBR value has significant influence on maximum pavement deflection values (Fig. 10). By increasing the subgrade CBR value from 1 to 4, maximum deflection value can be reduced by about 50%. However, the increase of subgrade CBR values above 4 only resulted in a gradual reduction in maximum deflection values.

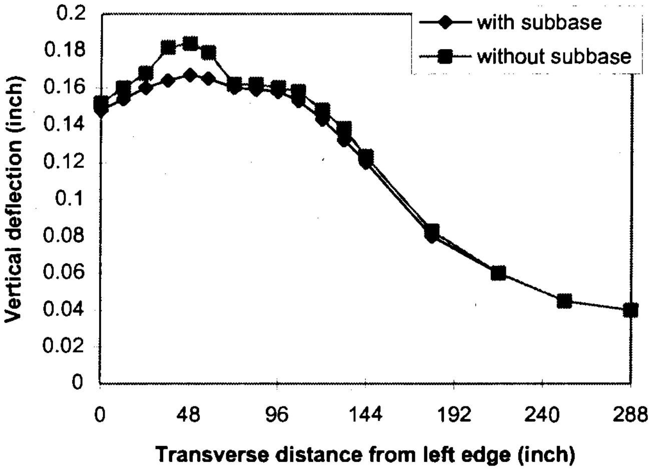


Fig 5. Transverse deflection pattern upon wheel loading

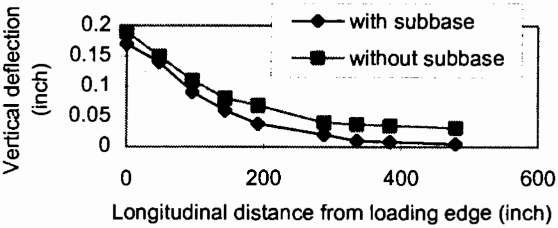


Fig 6. Longitudinal deflection pattern upon wheel loading

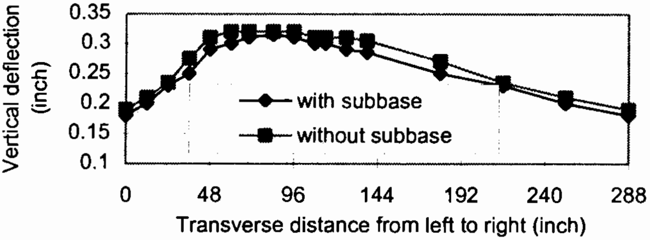
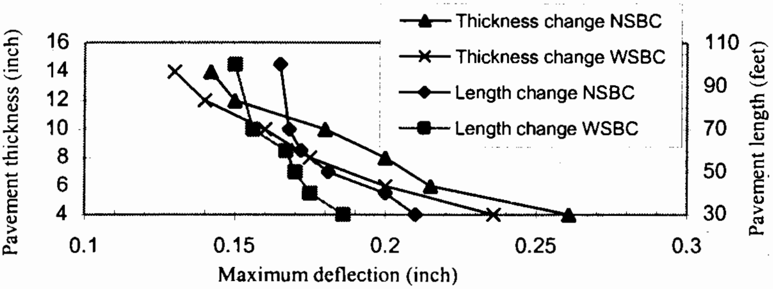


Fig 7. Transverse deflection pattern for double truck loading (for pavement wider than one lane)



Note: NSBC means without subbase condition and WSBC means with subbase condition

Fig 8. Effect of pavement length and thickness on maximum deflection

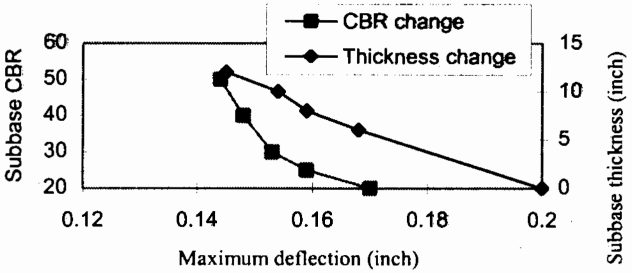


Fig 9. Effect of subbase thickness and CBR on maximum pavement deflection

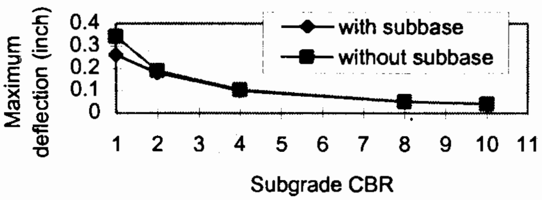


Fig 10. Effect of subgrade CBR on maximum pavement deflection

Tensile stress in concrete pavements

Nodal stresses acting in X and Y direction (shown as σ_x and σ_y in Fig. 2) act as tensile stresses in the pavement. The variation of tensile stresses in the transverse (σ_x) and longitudinal (σ_y) direction are shown in Figure 11 and Figure 12 respectively. The transverse cross-section is taken along the line of wheel load application (Fig. 3) and the same for longitudinal direction is taken along the line through the point of maximum tensile stress. From these figures, it appears that the tensile stresses in pavement are maximum under the loading points. The figures also illustrate that use of a subbase layer under concrete pavement results in only 8% reduction in maximum tensile stress. For pavements wider than a lane, when two truck axle loading (Fig. 4) are considered simultaneously, it is found that maximum tensile stress is increased by 70% (Fig. 13) from that of a single truck axle loading case. But for the similar condition concrete pavement without a subbase experiences 75% more maximum tensile stress. In Figure 14, the effect of increasing the pavement thickness on maximum tensile stress is illustrated. From this figure, it is observed that every 2 inch increase in pavement thickness results in about 15-20% reduction in tensile stress. The effect of pavement length on the maximum tensile stress of the pavement is also investigated and plotted in Figure 14. It is found that the effect of pavement length on maximum tensile stress is significant; an increase of pavement length from 30 ft to 100 ft results in around 50% reduction in maximum tensile stress. Figure 15 illustrates the effect of increased subbase thickness and subbase CBR values on maximum tensile stress of pavement. These figures reveal that increase in subbase thickness and subbase CBR value has little effect on maximum tensile stress of pavement. In Figure 16, the effect of increase in subgrade CBR value on maximum tensile stress is illustrated. From this figure, it can be observed that increase in the subgrade CBR values results in significant decrease in maximum tensile stress value for subgrade CBR values of 1 to 4 (Fig. 16); and beyond that only gradual reduction in maximum tensile stress occurs. However, with an increase in subgrade CBR values from 1 to 10 pavement tensile stress can be reduced by 60% (Fig. 16).

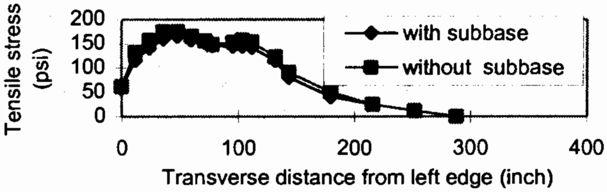


Fig 11. Transverse distribution of tensile stress for wheel load

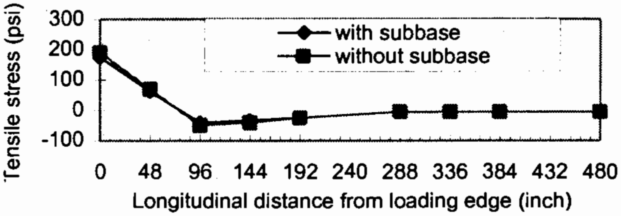


Fig 12. Longitudinal distribution of tensile stress

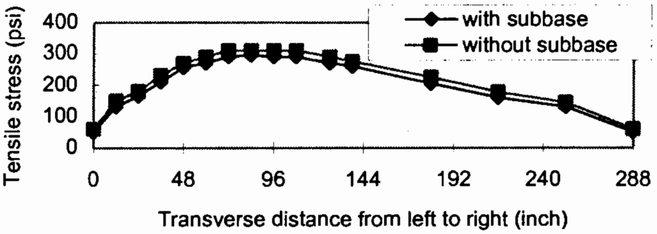


Fig 13. Transverse distribution of tensile stress for double truck loading

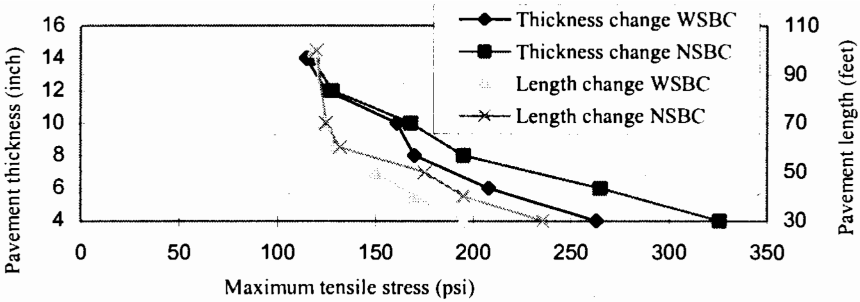


Fig 14. Effect of increasing pavement thickness and length on maximum tensile stress

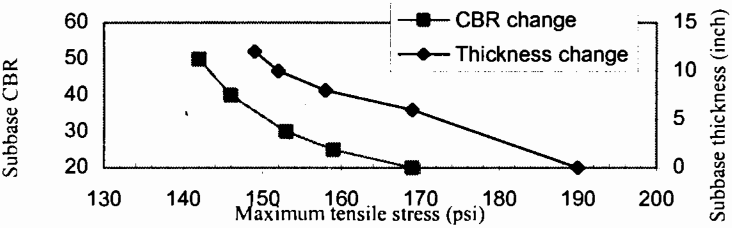


Fig 15. Effect of increasing subbase thickness and subbase CBR on maximum tensile stress

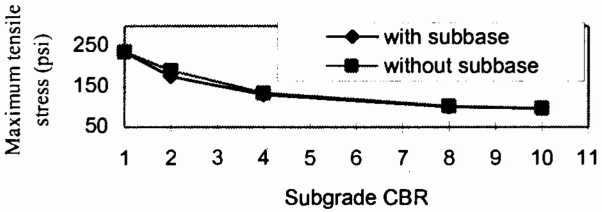


Fig 16. Effect of subgrade CBR on maximum tensile stress

Subgrade pressure under the pavement

Variation of subgrade pressure under concrete pavement in transverse and longitudinal direction are presented in Figure 17 and Figure 18 respectively. The transverse cross-section is taken along the line of wheel load application (Fig. 3) and the same for longitudinal direction is taken along the line through the point of maximum subgrade pressure. In transverse direction maximum subgrade pressure occurs under wheel load and rapidly diminishes to its right and left. In longitudinal direction subgrade pressure almost diminishes within 1/10th of pavement length (Fig. 18). The maximum subgrade pressure is found to be 16 psi; and using a subbase layer it can be reduced by 70%. The effect of varying the slab thickness on maximum subgrade pressure is also investigated. It is found that with the increase in slab thickness subgrade pressure decreases considerably (Fig. 19); and its variation is similar in both the cases of with or without subbase layer.

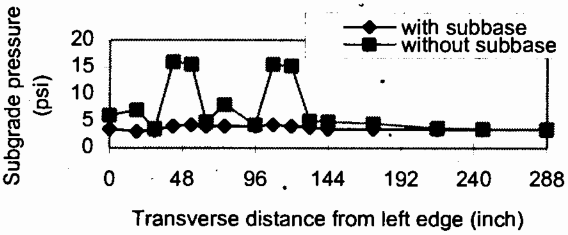


Fig 17. Transverse distribution of subgrade pressure

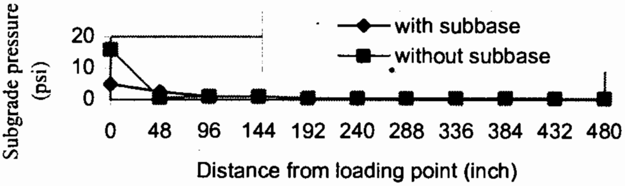


Fig 18. Longitudinal distribution of subgrade pressure

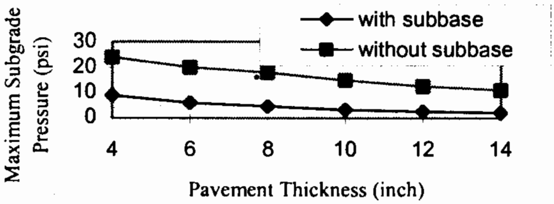


Fig 19. Effect of pavement thickness on maximum subgrade pressure

Shear stress at slab-soil interface of concrete pavement

Shear stress distribution (shown as SXY in Fig. 2) in the transverse and longitudinal direction at the slab-soil interface are presented in Figure 20 and Figure 21 respectively. The figures reveal that maximum shear stress at the interface is around 30 psi for both the cases of with or without subbase layer. **This means use** of a subbase layer cannot reduce the contact shear stress at **the slab-soil interface**.

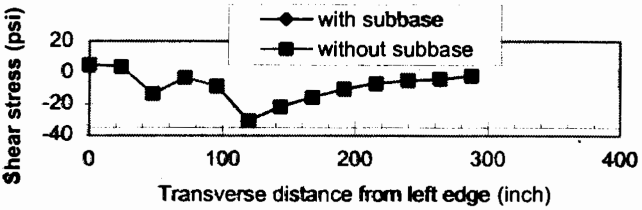


Fig 20. Transverse distribution of shear stress at slab-soil interface

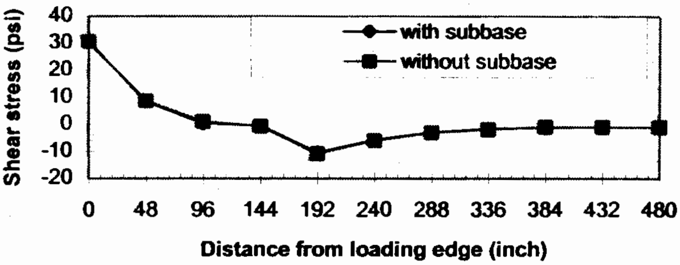


Fig 21. Longitudinal distribution of shear stress at slab-soil interface

CONCLUSIONS

A three-dimensional finite element method is adopted for analysing highway concrete pavement system. Major distress causing phenomena in concrete pavement are carefully examined. It is found that the maximum values of tensile stress, deflection and subgrade pressure decrease with an increase in slab thickness. While their values decrease with the increase in slab thickness, the reduction is more significant for the slab thickness of 4 inch to 8 inch. The presence of a subbase layer also reduces the above values among which the maximum subgrade pressure is substantially reduced. The values of maximum deflection and tensile stress are not reduced considerably with the increase of subbase thickness and subbase CBR values. However, A better quality subgrade (of higher CBR value in this case) can significantly reduce the maximum deflection and tensile stress values in concrete pavements; and, the most significant reduction takes place for the increase of CBR values in the range of 1-4. For example, by improving the subgrade CBR value from 1 to 4 about 50% and 40% reductions are possible in the maximum deflection and tensile stress values respectively.

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