Effect of Vertical and Horizontal Load on Pavement Interface Shear Stress

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Abstract: **Pavement interlayer slipping in areas where the vehicle accelerates decelerates brakes or turns (e.g. toll gates, police check-points, and airport runways) are common in many developing countries. However conventional mechanistic empirical pavement designs do not consider the effect of horizontal shear load in their designs, rather they only consider vertical stress or normal load. This paper aims at exploring the effect of both vertical and horizontal shear load on the interface shear stress and subsequently the performance of pavements. The paper primarily two things: overloading and interface bonding state (contact state of pavement layers) on performance of pavement structures with respect to different loading conditions. Horizontal shear stress was considered as the main cause of pavement deformation in areas of constant vehicle braking. In this paper a stretch of 1km of Chengdu-Deyang-Nanbu expressway in Sichuan province of China was considered. This road section was a test section with three pavement configurations as follows: semi-rigid base pavement, flexible pavement and full depth asphalt pavement. Material properties of pavement layers were represented by layer thickness, elasticity of modulus and poison ratio. BISAR multilayer elastic theory computer programme was used to compute mechanical responses of pavements. EverFE (FEM) pavement software was also used to come up with graphical representations of overloaded pavements. It was concluded that the severe pavement damage in areas where vehicles accelerates or decelerates is as a result of both overloading and braking which increases level force at vehicle braking. Overloading crushes and densifies the aggregates in asphalt concrete mixture thereby reducing the air voids. Loss of air voids on the other hand result in loss of mixture stability and rutting due to build up of pore pressure in the mixture under traffic loading resulting in loss of strength and flow. Braking on the other hand increases shear stress at the interface hence rutting or permanent deformation occurs. When horizontal loading is applied by moving vehicle, a poor bond condition at the interface beneath the surface could cause slippage cracking or horizontal permanent deformations at the surfacing layer. Poor load transfer from the layer to the underlying layers caused by poor bond condition leads to a high stress concentration within the surfacing material. Slippage cracking will initiate at the top of the surface when the surfacing material is unable to withstand the induced horizontal stresses. The bonding condition was modeled with a range from weak bonding to strong bonding which represented the partial bonding condition as a realistic condition at interface between pavement layers. The standard shear spring compliance in BISAR software was used to represent this bonding condition. The results indicated that overloading coupled with poor bonding condition of pavement interface causes premature slipping of pavement layers. Better bonding condition at the interface between layers will decrease the strain responses while the opposite will increase the strain or deformation. Hence, better structural capacity can be achieved with better bonding between layers.**

Keywords – vertical load, horizontal shear load, full bond, partial bond, full slip, friction coefficient, shear stress

1.0 INTRODUCTION

Vertical load is the standard loading used in pavement design. However horizontal load is the main cause of pavement interlayer shear stresses in areas where the vehicle accelerates, decelerates, brakes or turns such as toll gates, police check-points, airport runways experience interlayer slipping due to the effect of horizontal shear stress [1].

In flexible pavements, the design of the pavement thickness for roads, airports and industrial yards is based on the calculation of stresses and strains, occurring within the structure due to the traffic loadings, and the comparison with the allowable stresses and strains. The linear elastic multi-layer theory is used to calculate the occurring stresses and strains [2]. Of course the traffic loading has to be known to enable the thickness design of the pavement structure to be determined. Finally the bonding between pavement layers should be adequate (or be in a state of full bond [ibid].

Bonding condition of pavement layers on the other hand plays a significant role in design and construction of pavement as ensures the required bearing capacity, strength and durability of asphalt pavement and hence poor bonding contributes to the slipping of pavements especially in places where vehicles brake [3]. Under sufficient bonding the asphalt layers function as a monolithic structure and the largest stresses from vertical load are concentrated at the bottom of the structure. When the bonding is insufficient each asphalt layer functions separately and such pavement is able to carry lower loads compared to the pavement, the layers of which are sufficiently bonded. Figure 1 shows the effect of horizontal shear load on pavement structures.

2.0 PAVEMENT MODEL

2.1 Pavement Structure Model

Three pavement structure models under investigation were semi-rigid base pavement which consisted of six chemically stabilised layers, flexible pavement which has seven layers and full depth asphalt pavement with six layers as shown in tables I, II and III. The subgrade was assumed to extend to infinity and all pavement layers were assumed to be infinite in the horizontal direction. The pavement was considered as an elastic multilayered system with varying interface condition. In addition, a horizontal load simulating friction forces combined with a standard dual load was considered.

The paper analysed the effect of vertical and horizontal load on pavement interface shear stress. When shear stress was greater than normal stress, slipping of pavement layers become inevitable. Specifications for design of highway Asphalt Pavements in china, JTG D50-2006 was used in design of Chengdu, Deyang Nanbu expressway therefore was used for material properties in tables I, II and III

TABLE I. MATERIAL PROPERTIES FOR FLEXIBLE PAVEMENT

Structural Layer	**Material properties**		
	Thickness (cm)	***Elasticity of Modulus(MPa)***	***Poisson ratio***
SMA 13	4	1500	0.35
AC 20	6	1200	0.35
AC 25	8	1000	0.35
Asphalt Treated Base	10	3000	0.35
Gravel graded	20	350	0.4
Cement Stabilised Subbase	20	1000	0.25
subgrade		40	0.4

TABLE II. MATERIAL PROPERTIES FOR FLEXIBLE BASE PAVEMENT

Structural Layer	Material properties		
	Thickness (cm)	*Elasticity of Modulus(MPa)*	*Poisson ratio*
SMA 13	4	1500	0.35
AC 20	6	1200	0.35
AC 25	8	1000	0.35
Asphalt Treated Base	20	3000	0.2
Cement Stabilised Subbase	30	1000	0.25
subgrade	Infinite	40	0.4

TABLE III. MATERIAL PROPERTIES FOR SEMI-RIGID BASE ASPHALT PAVEMENT

Structural Layer	**Material properties**		
	Thickness (cm)	***Elasticity of Modulus (MPa)***	***Poisson ratio***
SMA 13	4	1500	0.35
AC 20	6	1200	0.35
AC 25	8	1000	0.35
Cement Treated Base	20	1200	0.2
Cement Stabilised Subbase	30	1000	0.25
subgrade		40	0.4

2.2 Load Configuration Model

Standard dual wheel configuration loads was used for this study. Coefficients of friction between wheel and pavement surface are assumed in the range between 0 - 1, horizontal load can be defined by multiplying this coefficient with the vertical load value. Horizontal loads are in the range between 0 – 25 KN for standard dual wheel loading and in the range up to 150 KN for overload condition. The horizontal load is generated by side friction from the vehicle braking which forms the following relationship with the vertical load as follows:

$$F = p \times f \qquad \text{[Eq.1]}$$

Where F = level force generated at vehicle braking (single wheel) KN
P= vertical load of a single wheel, KN,
f= friction coefficient, whose value ranges from 0 to 1.

The standard dual wheel load in China is taken to be 25KN, while the tire contact pressure is 0.7 MPa. Contact of radius is taken to be 0.105m. Based on equation 1, F=horizontal load was found to range from 0 to 150KN

2.3 Interface Condition

Two interface conditions have been provided as either full friction (i.e. full bond) or frictionless (i.e. full slip), which are only considered two extreme interface conditions and very unlikely in reality because interlayer friction may still exist. A method for the solution of elastic layered systems in between those two extreme conditions was introduced [4]. It adopted Goodman's constitutive law to explain the interface condition:

$$\tau = K_s(\Delta U) \qquad \text{[Eq. 2]}$$

Where τ = shear stress at the interface (MPa);
ΔU = the relative horizontal displacement between the two sides of the interface (mm)
Ks = shear reaction modulus at the interface (MPa).

Shear stiffness at the interface Ks (interlayer bond quality) spans from 105 MN/m3 (full bonding) to Ksi=10

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MN/m3 (no bonding) and was modeled in 3D FEM (EverstressFE) computer programme as shown in figure 7.

Using an elastic layered BISAR software which developed by SHELL, it is possible to make a model for the interface with partial condition. The designers of BISAR have developed the concept of Shear Spring Compliance to account for the relative displacements (slip) between pavement layers. The Shear Spring Compliance (AK) is the inverse of the shear reaction modulus at the interface between adjacent layers (Ks). The definition of the Shear Spring Compliance, AK, is given by:

$$AK = \frac{relative\ horizontal\ displacement\ of\ layers}{stress\ acting\ at\ the\ interface} \left[m^3 / N \right]$$

In this approach the interface between two (horizontal) pavement layers is represented by an infinite thin inter-layer of which the strength is described by means of spring compliance. Physically it assumes that the shear stresses at the interface cause a relative horizontal displacement of the two layers, which is proportional to the stresses acting at the interface. In BISAR software, the bonding condition was varied from full bond (α=0) to full slip (α=1). However it should be noted that full slip is assumed as 0.99 (not exactly 1) and full bond as 0.01 for calculation purposes.

Bonding condition can also be represented by the Shear Reaction Modulus (Ks). Bonding condition is classified in some ranges of Ks values [5]; partial bonding on the values less than 1,060 MPa/m and full bonding on the values more than 1,060 MPa/m. For the partial condition, there are weak bonding condition on the values less than 405 MPa/m, medium bonding condition on the range between 405 MPa/m and 620 MPa/m, and strong bonding on the range between 620 MPa/m and 1,060 MPa/m. Following Table IV shows the AK value as the inverse of Ks value which are used for this study:

TABLE IV. STANDARD SHEAR SPRING COMPLIANCE VALUES

Bonding Parameter	**Medium bonding**			
Ks (MPa/m)	450	500	550	600
AK (m3/N)	2.22E-9	2.00E-9	1.82E-9	1.67E-9
Ks (MPa/m)	**Strong Bonding**			
	700	750	800	850
AK (m3/N)	1.43E-9	1.33E-9	1.25E-9	1.18E-9

3.0 ANALYSIS OF THE EFFECT OF VERTICAL AND HORIZONTAL LOAD ON PAVEMENT INTERFACE SHEAR STRESS

3.1 Effect of vertical and horizontal load on pavement semi-rigid base pavement

The results of BISAR computer programme as shown in figures 2 and 3 revealed that in a semi-rigid base pavement, the effect of horizontal shear load on shear stress is insignificant under conditions of standard dual load. Vertical load proved to have greater impact on shear stress in this respect. Further that when the interface is in the state of full slip (FS), shear stress increases unlike when the interface is in the state of full bond (FB).

When horizontal loading is applied by moving vehicle, a poor bond condition at the interface beneath the surface is developed and could cause slippage cracking or horizontal permanent deformations at the surfacing layer. Poor load transfer from the layer to the underlying layers caused by poor bond condition leads to a high stress concentration within the surfacing material. Slippage cracking will initiate at the top of the surface when the surfacing material is unable to withstand the induced horizontal stresses

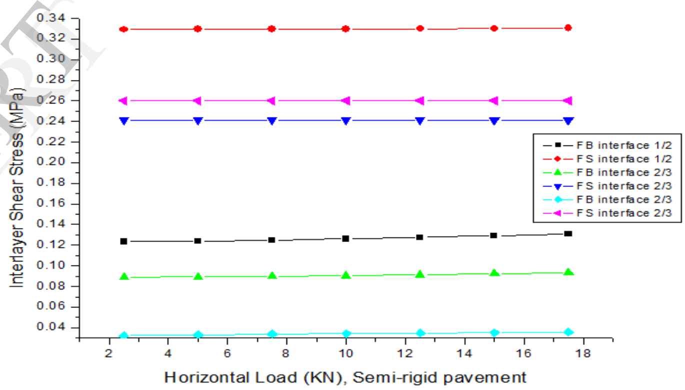

Fig. 1. Effect of horizontal shear load in semi-rigid base pavement structures

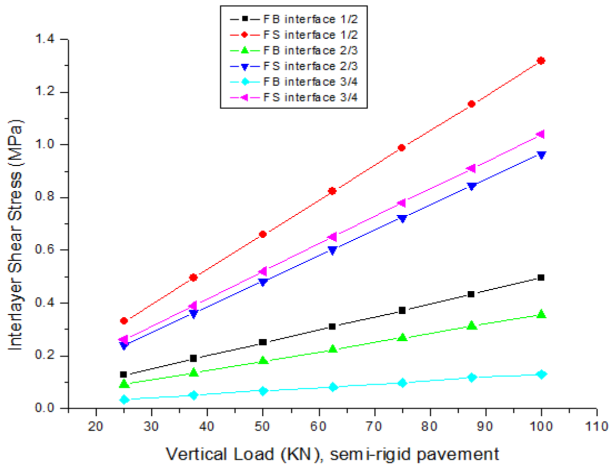

Fig. 2. Effect of vertical load in semi-rigid base pavement structures

3.2 *Effect of vertical and horizontal load in Flexible pavement structures*

In comparison with semi-rigid base pavement, flexible pavement was found to have increased shear stress on the interface when both pavements are in the state of full bond which also increases tensile strain at the bottom of wearing course or interface between top two layers (1/2 layers) thereby making the pavement more susceptible to fatigue cracking:

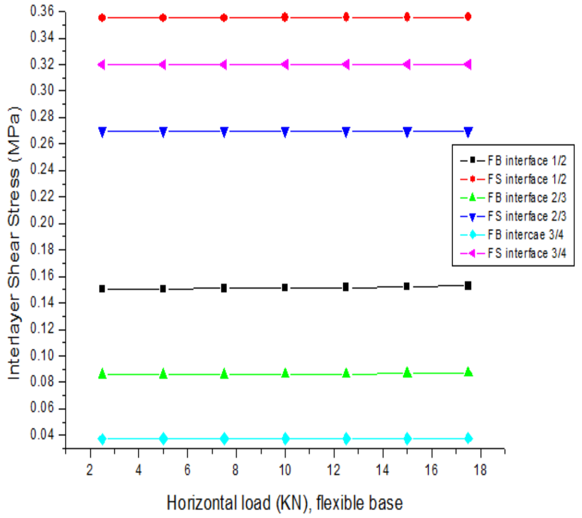

Fig. 3. Effect of horizontal shear load in flexible base pavement structures

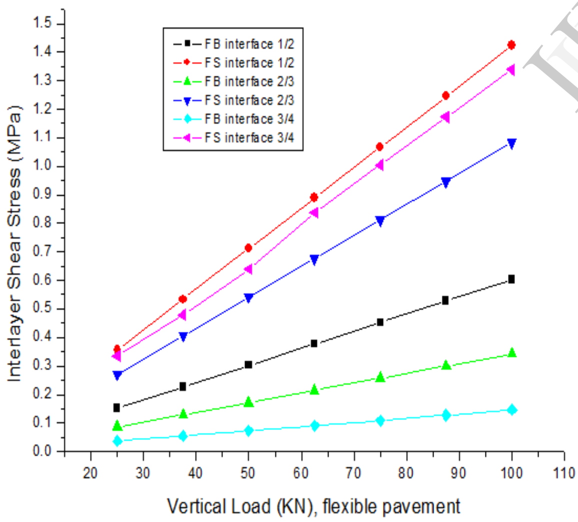

Fig. 4. Effect of vertical load in flexible pavement structures

3.3 *Effect of vertical and horizontal load on pavement full depth asphalt pavement*

The results of full depth asphalt pavement show that there's linear relationship between vertical and interlayer shear stress. Further, it can be deduced that although horizontal shear stress is considered insignificant in pavement design, its effect is severe in areas where vehicles brake or decelerates such as police check-points, railway-highway crossings and/ or toll gates, therefore appropriate designs need to be developed.

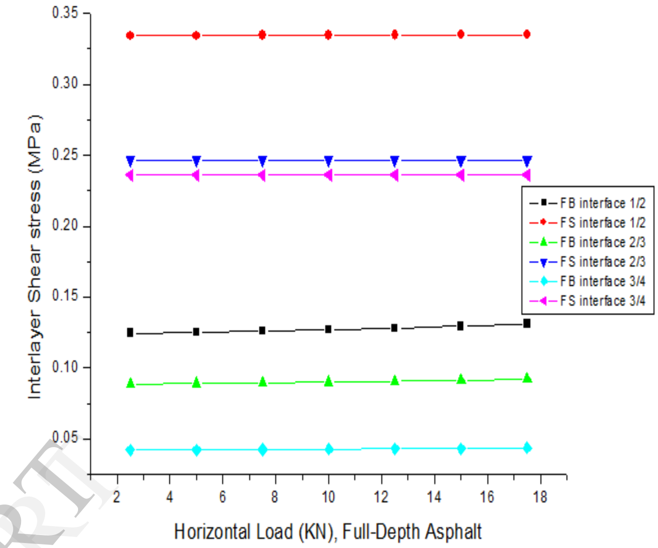

Fig. 5. Effect of horizontal shear load in f ull depth Asphalt pavement structures

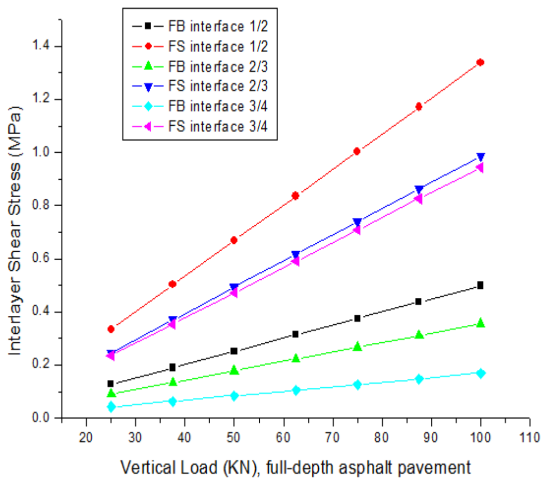

Fig. 6. Effect of vertical load in full dept asphalt pavement structures

The results further show that layer bonding plays a vital in pavement performance regardless of the loading condition. Pavements modeled with full bond interface experienced lower shear stress compared with those modeled with full slip bond condition. This was manifest in three layer interface and for three pavement structures analysed

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3.4 Effect of overloading on pavement performance

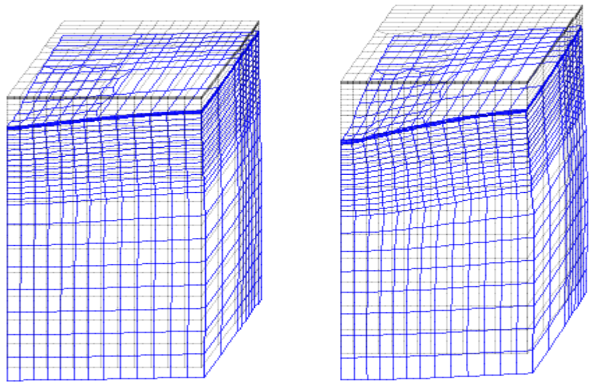

Fig. 7. *(a) standard dual wheel load of 25KN (b) Overload of dual wheel load 50KN*

Overloading coupled with vehicle braking generates level force generated at vehicle braking accelerates rutting or plastic deformation as shown in figure 8. The maximum horizontal shear stress under standard single wheel load can only be 25KN (since friction coefficient f, ranges from 0 to 1). The effect in this case is the same as vertical normal stress.

3.5 Effect of layer thickness on interlayer shear stress

In this study, top layers only were varied from 4cm, 5cm, 6cm,7cm 8cm,9cm upto 10cm. the other pavement layers were held constant. The friction coefficient of wheels and AC layer at emergent braking was taken as f=0.5 and BISAR software was used in computations

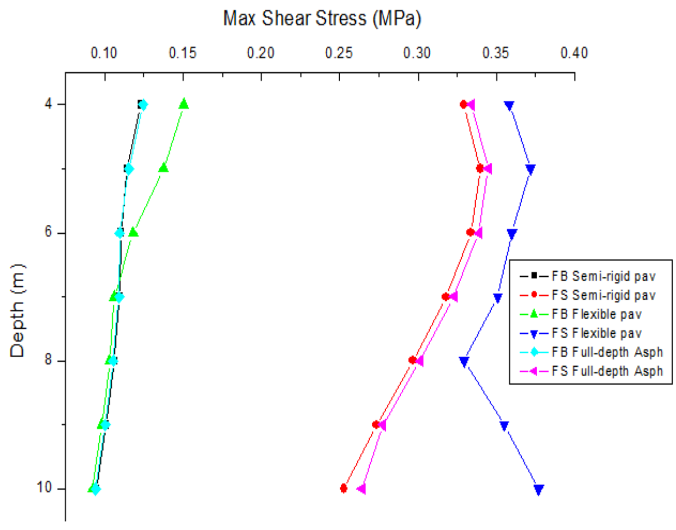

Fig. 8. Effect of surface layer thickness on the interlayer shear stress

The results indicate that the Surface layer thickness has an effect on the shear stress of the interface. The interlayer shear stress decreases with an increase in surface Further the two assumes a linear relationship, for every 1cm thickness addition, the interlayer shear stress will be reduced. In addition the maximum shear stress at the interface occurs directly under the wheel or tire pressure and in the top layer.

4.0 CONCLUSION

It can therefore be concluded that the severe pavement damage at police check-points is as a result of both overloading and braking which increases level force at vehicle braking. Overloading crushes and densifies the aggregates in asphalt concrete mixture thereby reducing the air voids. Loss of air voids on the other hand result in loss of mixture stability and rutting due to build up of pore pressure in the mixture under traffic loading resulting in loss of strength and flow. Braking on the other hand increases shear stress at the interface hence rutting or permanent deformation occurs.

When horizontal loading is applied by moving vehicle, a poor bond condition at the interface beneath the surface is could because slippage cracking or horizontal permanent deformations at the surfacing layer. Poor load transfer from the layer to the underlying layers caused by poor bond condition leads to a high stress concentration within the surfacing material. Slippage cracking will initiate at the top of the surface when the surfacing material is unable to withstand the induced horizontal stresses

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