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Effect of Horizontal Shear Load on Pavement Performance

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Abstract. Severe pavement damage often occurs in areas where vehicles brake, accelerate or decelerate such as toll gates and police check-points. BISAR 3.0 software was used to simulate the braking effect of vehicles. Theoretical calculations of mechanical responses of a six layered semi-rigid base asphalt pavement were obtained and results revealed that when normal load was applied without horizontal (shear) load, relative horizontal displacement was zero; this meant that normal stress does not induce pavement layer slipping. When both normal and horizontal (shear) load was applied, significant relative horizontal displacement values were obtained. This meant that where braking or horizontal shear load was applied, slipping of pavement layers was likely to occur. When overloading condition was simulated, critical strains such as tensile strains at the bottom of wearing surface and compressive strains at the top of subgrade increased significantly compared to a situation where a normal load condition was simulated. This meant that overloading could reduce fatigue life of pavements and increase chances of rutting. Overloading generally crushes and densifies the aggregates in asphalt concrete mixture and reduces air voids. Loss of air voids results in loss of mixture stability and rutting due to build up of pore pressure in the asphalt mixture under traffic loading resulting in loss of strength and flow. Overloading coupled with horizontal shear stress is the main cause of pavement damage in areas of vehicle braking or deceleration.

Keywords: vertical load, horizontal shear load, tensile strains, compressive strains, shear stress, relative horizontal displacement, overloading.

1. Introduction

Road sections where vehicles accelerate, decelerate, brakes or turns suffer extensive pavement damage [1]. For example areas such as airport runways, toll gates and police check-points due to excessive horizontal shear stress induced during braking or deceleration [2]. Braking or turning wheels often cause the pavement surface to slide and deform [3]. The resulting sliding and deformation is caused by a low-strength surface mix or poor bonding between the surface hot mix asphalt (HMA) layer and the next underlying layer in the pavement structure. When HMA surface bonds poorly to the layers below; the top pavement layer may slide as vehicles pass over it [4] and damage will inevitably follow. Unable to effectively transfer loads through the entire depth of the pavement structure, slipping top layers must absorb most of the stress, leading to rutting.

Bonding condition of pavement layers on the other hand plays a significant role in design and construction of pavement as it 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 [5]. De-bonding of pavement layers can also be explained by the Goodman’s constitutive law which explains how the pavement interface condition is affected by the braking effect of traffic [6]. When traffic decelerates, deformation of an elastic body caused by forces that tend to produce an opposite but

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parallel sliding motion of the body's planes occurs. Goodman's model describes the interface behaviour in multi-layered elastic systems and how shear stress is related to the pavement stiffness (Ks) shown in equation 1 [7]. When a vehicle brakes, the pavement layers tend to slip over each other and produce a relative horizontal displacement. The interface between two layers is called a shear stiffness modulus (Ks) which is related to shear stress (τ) and relative horizontal displacement (ΔU) as shown:

$$\tau = K_S\left(\Delta U\right) \tag{1}$$

The study investigated the effect of horizontal shear stress induced by braking traffic on the performance of pavements. The paper is important because it brings out the phenomenon behind pavement damage in areas of vehicle braking or deceleration.

2. Experiment and Method

2.1. Pavement Structure Modeling

The pavement structure model under investigation was semi-rigid base pavement which consisted of six chemically stabilised layers, as shown in Table 1. 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. BISAR 3.0 software was used to produce calculations. The road configuration under consideration had the following material properties shown in Table 1.

Table 1: Material Properties for Semi-rigid 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
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. Coefficient of friction between wheel and pavement surface was assumed in the range between 0 – 0.5, horizontal load was defined by multiplying this coefficient with the vertical load value. Horizontal loads found to be in the range between 0 – 12.5 KN for standard dual wheel loading and in the range up to 50 KN for overload condition. The horizontal load was generated by side friction from the vehicle braking which formed the following relationship with the vertical load as follows:

$$F = p\ x\ f \tag{2}$$

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 0.5.

The standard dual wheel load was taken to be 50 KN, while the tire contact pressure is 0.7 MPa. Contact of radius was taken to be 0.105m. Based on equation 2, F=horizontal load was calculated to simulate the horizontal load.

2.3. Interface Condition

Two interface conditions were provided as either full friction (i.e. full bond) or frictionless (i.e. full slip). BISAR 3.0 pavement computer programme provided for modeling the pavement interface through the reduced shear spring compliance ALK is expressed as follows:

$$ALK = \frac{\alpha}{1-\alpha}\cdot\alpha \tag{3}$$

Where, ALK = reduced shear spring compliance a= radius of the load, m

α= friction parameter $0 \le \alpha \le 1$ (α=0 means full friction; α-1 means full slip)

The interface friction parameter depends on the diameter of the applied load. A numerical variation in ALK from zero to, say, 100 times the radius of the loaded area covers the range from full friction to (practically) full slip (α = 0.99). Based on equation 3, an interface condition was calculated and used as input in the software.

3. Analysis and Discussion

3.1. Influence of Horizontal Forces on Critical Strain for a Normal Load Condition

Table 2: Influence of Horizontal Forces on Pavement Mechanistic Response

Pavement Structure	**Bonding state**	**Critical Strains**	**Normal load with horizontal force**			**Normal load without horiz. force**		
			Critical strain ε	**Displacement Ux**	**Shear Stress τ**	**Critical strain ε**	**Displacement Ux**	**Shear Stress τ**
SMA 13	Full bond	ε_{t_1}	1.75E-04	1.30E-04	3.07E+05	1.75E-04	0.00E+00	3.02E+05
AC 20	Full slip	ε_{t_2}	2.68E-04	1.58E-04	4.76E+05	2.68E-04	0.00E+00	4.68E+05
AC 25	Full bond	ε_{t_3}	-5.79E-05	3.10E-05	3.97E+04	-5.79E-05	0.00E+00	3.89E+04
Base (CTB)	Full bond							
Subgrade	Full bond	ε_c	-2.63E-04			-2.63E-04		

As can be seen in Table 2, when a normal load was applied with horizontal force, horizontal displacement at the interface of the asphalt layers occurred while when a normal load was applied without horizontal force, horizontal displacement did not occur. This shows that horizontal load has an effect on horizontal displacement between pavement layers. Horizontal displacement at the pavement interface was as a result of horizontal shear stress induced by the braking force or traffic deceleration. This causes the pavement to slip due to high shear stress generated at pavement interface. Horizontal load had no effect on critical strains because the results revealed that mechanical responses remained the same when normal force was applied with and without horizontal load.

3.2. Influence of Horizontal Forces on Critical Strain for a Overload Load Condition

Table 3: Influence of Horizontal forces to Pavement Mechanistic Response in overloading condition

Pavement Structure	**Bonding state**	**Critical Strains**	**Over load with horizontal force**			**Over load without horizontal force**		
			Critical strain ε	**Displacement Ux**	**Shear Stress τ**	**Critical strain ε**	**Displacement Ux**	**Shear Stress τ**
SMA 13	Full bond	ε_{t_1}	3.50E04	2.60E-04	6.12E+05	3.50E-04	0.00E+00	6.04E+05
AC 20	Full slip	ε_{t_2}	5.35E-04	3.03E-04	9.52E+05	5.35E-04	0.00E+00	9.35E+05
AC 25	Full bond	ε_{t_3}	-1.16E-04	6.21E-05	7.95E+04	-1.16E-04	0.00E+00	7.77EE+04
Base (CTB)	Full bond							
Subgrade	Full bond	ε_c	-5.26E-04			-5.26E-04		

Table 3 shows pavement behavior under conditions of overloading. Comparing results of Table 2 and Table 3 revealed that relative horizontal displacement increased with the increase in wheel load. Furthermore compressive strains at the subgrade top and tensile strains at the bottom of asphalt layers increased significantly with the increase in vehicular load. These results reaffirm the position that overloading accelerates pavement damage because it reduces fatigue life and increases chances of rutting.

3.3. Effect of Loading Condition on Critical Strains

Table 4: Effect of loading condition on compressive strains

Critical Strains	**Normal load with horizontal load**	**Overload with horizontal load**
Compressive strains ε_c top of subgrade	-2.63E-04	-5.26E-04
Tensile strains ε_{t_3} bottom of wearing surface	-5.79E-05	-1.16E-04

Table 4 compared the effect of loading on critical strains. When an overload combined with horizontal load was simulated and compared with a combined normal load with horizontal load, results revealed that compressive strains increased with the increase in load. It was further observed that adding horizontal loads to normal forces makes the stress-strain conditions in the pavement more severe. Since deformation at the top of subgrade is related to rutting at the pavement surface, an increase in compressive strains at the top of subgrade will accelerate likelihood of rutting at the surface of pavement because 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 occurs due to build up of pore pressure in mixture under traffic loading resulting in loss of strength and flow.

3.4. The Effect of Vertical and Horizontal Load in Semi-Rigid Base Pavement Structures

Fig. 1 shows a scenario where a vertical or normal load was applied in the software without the horizontal load. Results reveal that vertical load has a significant effect on performance of pavements relative to horizontal loads shown in Fig. 2. As the load increased shear stress also increased at the pavement interface. Because of this significance, pavements are often designed with vertical or normal load without considering horizontal load. ***However it is worth noting that horizontal shear load only becomes critical when vehicle braking or deceleration is expected at a given point on the highway such as toll- gates, police check points, railway crossing or even airport runways in which case combined normal and horizontal loads should be considered during design.*** It can also be seen that when the pavement interface was in the state of full slip(FS) shear stress increased, however when the pavement interface was in a state of full bond (FB) shear stress reduced significantly. Bonding condition is very important in pavement construction because if the pavement is not fully bonded, the pavement is likely to suffer from premature cracking.

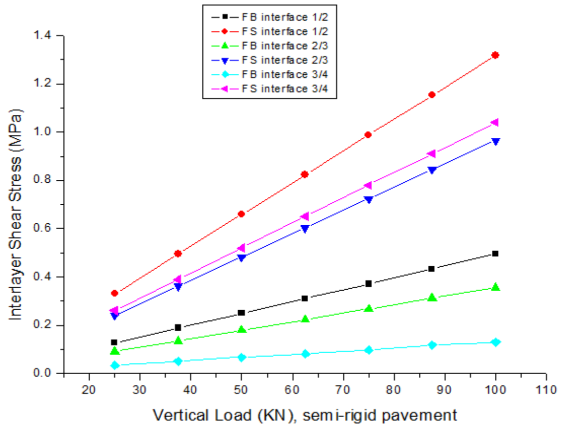

Fig. 1. Effect of vertical load on pavement performance

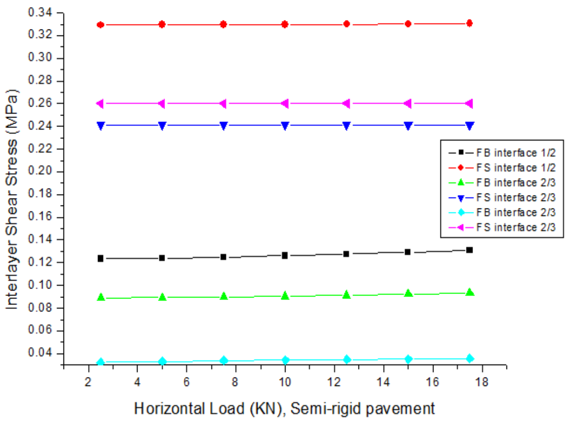

Fig. 2. Effect of Horizontal Load vs. interface shear stress

4. Conclusion

Based on BISAR 3.0 pavement simulations of a semi-rigid base pavement structure, it was concluded that severe pavement damage often occurs in areas of vehicles braking, acceleration or deceleration, was caused by a combination of excessive horizontal shear stress induced by the braking effect of vehicles and overloading. Theoretical calculations of mechanical responses further revealed that when vertical load was applied without horizontal (shear) load, relative horizontal displacement was found to be zero, implying that vertical stress does not induce pavement layer slipping. However when both vertical and horizontal (shear) load was applied in the software, significant relative horizontal displacement values were obtained. This meant where braking or horizontal shear load was applied, slipping of pavement layers and subsequently slippage cracking was likely. When overloading condition was simulated, critical strains such as tensile strains at the bottom of wearing surface and compressive strains at the top of subgrade increased significantly compared to a situation where a standard load condition was simulated. Overloading showed potential to reduce fatigue life of pavements and increased chances of rutting. Overloading generally crushes and densifies the aggregates in asphalt concrete mixture and reduces air voids. Loss of air voids results in loss of mixture stability and rutting due to build up of pore pressure in the asphalt mixture under traffic loading resulting in loss of strength and flow. Bonding condition of pavement interface was found to be critical to performance of pavement structures. When the bonding condition was simulated in the software, results showed high stress concentration within the surfacing material. Slippage cracking was likely to initiate at the top of the surface when the surfacing material was unable to withstand the induced horizontal stresses. It should be stressed that vertical stress is very critical in design of pavements. Because of this significance, pavements are designed with vertical load without considering horizontal loads. ***However it is worth noting that horizontal load only becomes critical when vehicle braking or deceleration is expected at a given point on the highway such as toll- gates, police check points, railway crossing or even airport runways. In that respect a combination of vertical and horizontal loads should be considered to avoid excessive rutting on highway sections.***

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