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The Influence of Bonding between Layers on Pavement Performance, a Case Study of Malaysian Road

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Abstract. This paper summarizes a theoretical study undertaken to provide a better understanding of the consequences of poor bond on flexible pavement performance. The main objective of this paper is to investigate the influence of bond on the performance of Malaysian road. The pavement structure of Malaysian road was analyzed using a layered linear elastic program, BISAR 3.0 taking into account different state of the bond at the interfaces of the pavement layers and a static horizontal load in addition to the standard vertical dual load. The results indicate that the condition of the bond between the wearing and binder course can reduce the life of the pavement by up to 64%. On the other hand, the results also indicate that the condition of the bond between the binder and road base course, which was made up from asphaltic materials can reduce the life of the pavement by up to 68%.

1 Introduction

The issues on flexible pavement distress have been widely highlighted by several researchers for years. The causes are also varies depending on the type of distresses occurred. However, one of the main factors contributed to the pavement failures is poor interlayer bonding between the pavement structures. Based on many research that has been conducted in the past, the interlayer bond is responsible for ensuring all layers to behave as a single entity, thus reducing cracks and deformation of the pavement [1]. In most pavement design, the pavement layers are usually assumed to be fully bonded together and no displacement is developed between them. Through different discussion, the most effective method to ensure the interlayer bonding of pavement layers are by applying a thin bituminous bond coat (or tack coat) at the interfaces [2].

However, full bonding is not always achieved since many cases of pavement distresses caused by poor bonding between pavement layers has been reported in different countries. In 1980, Peattie [3] reported that 56 cases of premature bond failures between surfacing and

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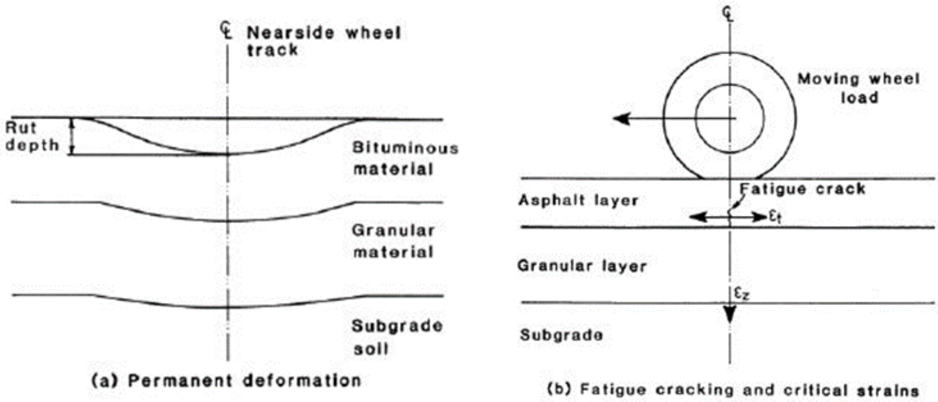
binder course of (mainly) newly constructed roads in the United Kingdom (UK) were reported. Shaat [4] reported that in Northern Ireland, some sections of newly constructed roads experienced bond failures soon after they were opened. Meanwhile, Hakim [5] stated in his research that de-bonding problem between bases was found in a three years old pavement structure in the UK [2]. In Malaysia, it was reported that delamination is the most common failures occurred in Malaysian road, caused by slippage at the interface between wearing and binder course [6]. From the cases reported, it can be observed that the failures commonly occur between wearing and binder course. In addition, location with high horizontal loading is more prone to failure.

In pavement engineering, a number of computer programmes have been developed in order to overcome the problems related to poor pavement bond. However, only a few of these computer programmes address different interface conditions [7]. Unlike other programmes, Bitumen Stress Analysis in Roads (BISAR) that was developed by Shell Research Gate in 1970 is most widely used software due to its capability to include shear spring compliance into the analysis [8]. Furthermore, BISAR analysis produces comprehensive calculations, produces strain and stress profile in a pavement structure resulting from different loadings and provides a value for the expected life of the pavement for each run.

2 Incorporating bond condition in pavement design

Nottingham Design Method is adopted for this study [9]. The method is based on the analytical pavement design approach. There are two modes of failures that were observed in pavement structure:

1. Development of permanent deformation (rut) shown in Fig. 1 (a), coming from the accumulated permanent strain in the pavement.
2. Fatigue cracking of the bituminous layer, shown in Fig. 1 (b) caused by load induced repeated tensile strain, which induced by each load.



(a) Permanent deformation

(b) Fatigue cracking and critical strains

Fig. 1. Failure modes and critical strains in flexible pavements (Source: [9])

BISAR program calculates stresses, strains, and displacements in a multi-layer elastic system, defined by the following configuration, material behaviour and few assumptions that have been introduced in this program:

1. Consisting of horizontal layers of uniform thickness placed on a semi-infinite base or half space.
2. Infinite extension of layers in horizontal directions.
3. The homogenous and isotropic material in each layer.
4. The materials are linear elastic.

In elastic layered system, two different interface conditions are considered: full bond (full friction) and full slip (frictionless). The interface condition is represented by Goodman's constitutive law:

$$\tau = K_s(\Delta U) \tag{1}$$

where τ denotes the interface shear stress, K_s is the horizontal shear (interface) reaction modulus and ΔU is the relative horizontal displacement at the interface.

Within BISAR programme, the slip between pavement layers is accounted for by employing the concept of shear spring compliance (standard or reduced). The physical definition of the standard shear spring compliance (also known as the inverse of the interface's horizontal shear reaction modulus), *AK*, is given as follows:

$$AK = \frac{\text{relathe tive horiontal displacement between layers}}{\text{interface}'\text{s stress}}\,[m^3/N] \tag{2}$$

which relation is expressed mathematically through the parameter α, defined as

$$\alpha = \frac{AK}{AK+\frac{1+v}{E}.a} \tag{3}$$

where a is the radius of the load (m), E is the modulus of the layer above the interface (Pa), v is the Poisson's ratio of that layer and α is the friction parameter, with $0 \leq \alpha \leq 1$ (α=0 means full friction, α=1 means complete slip). The reduced shear compliance, *ALK* (m), is defined as

$$ALK = \frac{\alpha}{1-\alpha}.a \tag{4}$$

According to Sutanto [2], among those aforementioned models to characterize the interface bond condition; the shear reaction modulus, K_s, seems to be the most widely used by researchers. Although the models incorporated into the Finite Element (FE) analysis might be more accurate in representing the bond conditions, the parameter K_s is less complicated and can be easily incorporated into BISAR programme to analyze the effect of bond on the state of stress, strain and deflection within the pavement structure.

3 Estimation of design life

Brown and Brunton [9] highlighted that the ultimate state of pavement at the end of their design life (usually 20 years) may either be one of a "failure" or of a "critical" condition. Failures indicate that the pavement is no longer suitable for use and, this state is distinguished when there is existence of about 20mm rut or extensive cracking in the wheel tracks. Meanwhile, the "critical" condition is defined by a 10mm rut or the first appearance of wheel track cracks.

The Nottingham Design Method estimates pavement's life according to critical strains and mixture characteristics, which can be expressed by the following equations:

Failure life due to fatigue:

$$\log N = 15.8\log\varepsilon_t - 46.06 - (5.13\log\varepsilon_t - 14.39)\log V_B - (8.63\log\varepsilon_t - 24.2)\log SP_i \tag{5}$$

Failure life due to deformation:

$$N = f_r \left[\frac{3.0\times10^9}{\varepsilon_z{}^{3.57}}\right] \tag{6}$$

where *N* is the number of load applications to failure, ε_t is the horizontal tensile strain, ε_z is the vertical compressive strain, V_B is the percentage of the binder by volume, SP_i is the initial softening point of bitumen and f_r is a rut factor (f_r = 1.56 for DBM). Values of V_B, SP_i and f_r are adopted from Brown and Brunton [9] and Jabatan Kerja Raya [10].

4 Results and discussion

Table 1 and Table 2 show the properties and materials of pavement layers studied in this research, stiffness data refers to Jabatan Kerja Raya [10] and the effect of road geometry was not studied. The condition of the bond at the interfaces considered was evaluated by the horizontal shear reaction modulus, K_s. The interface is considered fully bonded when Ks ≥ 10,000 MN/m^3. While for K_s ≤100 MN/m^3, the interface can be considered as fully de-bonded.

From Table 1 below, since the bituminous layers of the pavement structure is comprised by 3 different layers (two interfaces), the effect of the bond at the base of respective bituminous layers will be analyzed separately. Firstly, the effect of the bond between the wearing course and binder course was being analyzed (Pavement 1A), then the effect of the bond between the binder course and first layer of road base was being analyzed further by using BISAR 3.0 (Pavement 1B).

Table 1. Properties and Materials of Pavement Layers in Bukit Mertajam (Pavement 1)

Layer	Layer number	Thickness (m)	Material	Stiffness, E (MPa)	Poisson's ratio, *ν*
Wearing course	1	0.05	AC14	1200	0.40
Binder course	2	0.06	AC28	1600	0.40
Road base	3	0.075	AC28	2000	0.35
	4	0.30	Crushed aggregate	400	0.35
Sub-base	5	0.15	Granular	50	035
Sub-grade	6	∞	-	50	0.35

Table 2. Properties and Materials of Pavement Layers in Jalan Orang Asli, Sungai Siput (Pavement 2)

Layer	Layer number	Thickness (m)	Material	Stiffness, E (MPa)	Poisson's ratio, v
Wearing course	1	0.06	AC14	1200	0.40
Binder course	2	0.06	AC28	1600	0.40
Road base	3	0.30	STB 1	1800	0.40
Sub-grade	4	∞	-	50	0.35

The results of the analysis using BISAR 3.0 are presented in Table 3. It shows the computed maximum horizontal tensile strain ε_t at the bottom of bituminous layers for

Pavement 1A, 1B and 2. The values range from 151.8 to 306.8 × 10^{-6}, 82.6 to 344.7 × 10^{-6} and 66.25 to 102.7 × 10^{-6} for Pavement 1A, 1B and 2 respectively. Similarly, the computed vertical compressive strains on top of the subgrade are 290.7 to 344.7 × 10^{-6}, 290.7 to 415.4 × 10^{-6} and 271.1 to 333.0 × 10^{-6} for the Pavement 1A, 1B and 2 respectively.

Table 3. Properties and Materials of Pavement Layers

State of Bond	**K_s (MN/m^3)**	**Horizontal tensile strain at the bottom of the asphalt layer, ε_t (× 10^{-6})**	**Vertical compressive strain at the bottom of the asphalt layer, ε_z (× 10^{-6})**	**Design life, N (msa*)**	
				N_f (see Eq. 5)	**N_d (see Eq. 6)**
Pavement 1A					
Full friction	100,000	151.8	-	4.44	-
		-	290.7	-	7.51
Intermediate case	10,000	245.1	-	0.58	-
		-	294.8	-	7.15
	1,000	304.1	-	0.27	-
		-	312.3	-	5.82
	100	305.3	-	0.26	-
		-	336.2	-	4.47
Full slip	10	306.8	-	0.26	-
		-	344.7	-	4.09
Pavement 1B					
Full friction	100,000	82.6	-	11.27	-
		-	290.7	-	7.51
Intermediate case	10,000	115.1	-	3.95	-
		-	302.4	-	6.52
	1,000	249.3	-	0.34	-
		-	348.6	-	3.93
	100	326.4	-	0.15	-
		-	400.7	-	2.39
Full slip	10	344.7	-	0.12	-
		-	415.4	-	2.10
Pavement 2					
Full friction	100,000	66.25	-	22.6	-
		-	271.1	-	9.64
Intermediate case	10,000	73.52	-	16.3	-
		-	276.9	-	8.94
	1,000	86.54	-	9.72	-
		-	298.3	-	6.85
	100	98.4	-	6.48	-
		-	323.8	-	5.11
Full slip	10	102.7	-	5.66	-
		-	333.0	-	4.63

Fig. 2, 3 and 4 show the pavement's life to failure condition of different de-bonded interfaces. The life to failure due to fatigue and life to failure due to deformation is referred to as N_f and N_d, respectively. In Fig. 2 and 4, the analysis is observed at the partially bonded interface between layer 1 and layer 2 (wearing and binder course) while analysis for Fig. 3 is observed at the partially bonded interface between layer 2 and 3 (binder and road base course).

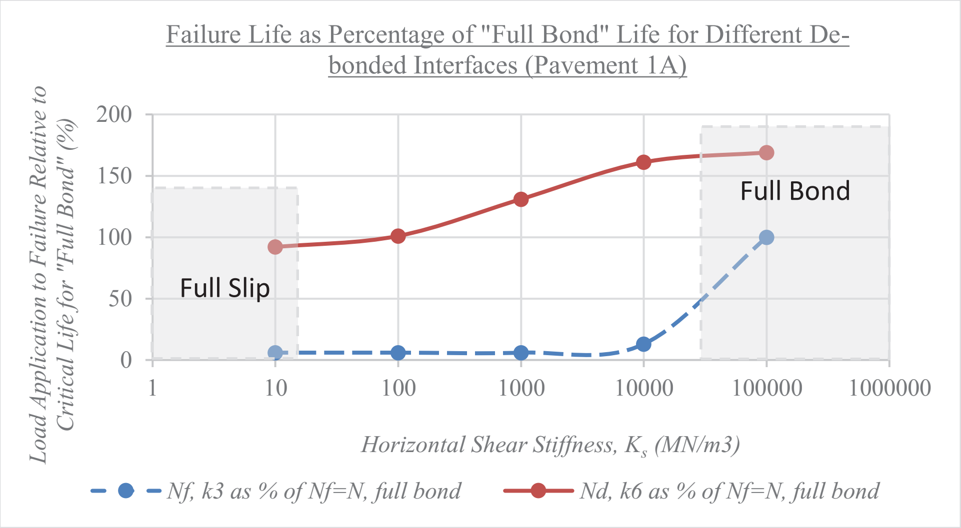


Fig. 2. Influence of bond condition on failure life as a percent of "full bond" life for different de-bonded interfaces (between wearing course and binder course)

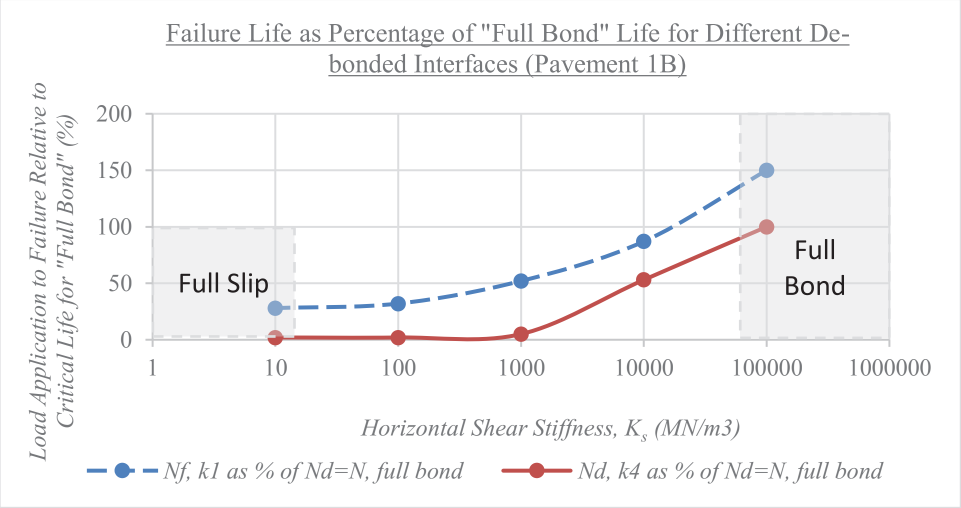


Fig. 3. Influence of bond condition on failure life as a percent of "full bond" life for different de-bonded interfaces (between binder course and road base course)

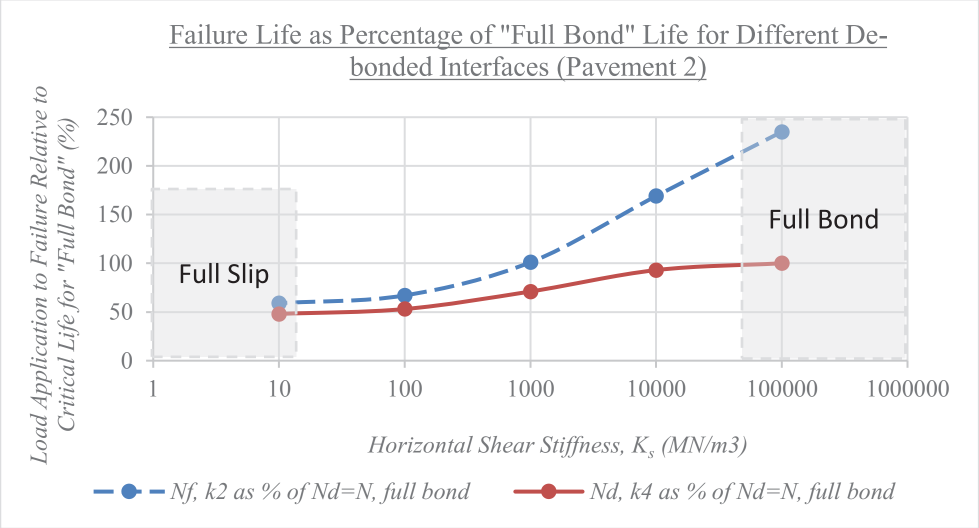


Fig. 4. Influence of bond condition on failure life as a percent of "full bond" life for different de-bonded interfaces (between wearing course and binder course)

The life to failure is determined by comparing the lower number of the deformation and the fatigue lives. The data presented in Fig. 2 and 4 show that the lowest pavement failures lives correspond to the single partially bonded interface between the wearing course and binder course. While in Fig. 3, the lowest pavement failures life corresponds to the single partially bonded interface between binder course and road base. If this interface is partially bonded, the failure life for Pavement 1A is the fatigue life and the partial bond life values range from 6% to 92% of the full bond life. The failure lives for Pavement 1B and Pavement 2 are the deformation lives, the life values range between 2% to 48% for horizontal shear stiffness of 10 MN/m3 (full slip condition) and 53% to 93% for horizontal shear stiffness of 10,000 MN/m3 (full bond condition) for both pavements respectively.

According to the cases reported in different countries, the interface between the wearing course and binder course is the most important element, since most incidents reported due to bond failures mostly occur at these two interface layers. Based on this study, the reduction in failure life for full slip can amount up to 94% to 98%, combining two different cases.

4 Conclusions

As a conclusion, it can be concluded that:

1. The worst pavement performance can be experienced for a de-bonded interface between the wearing course and binder course (Pavement 1A and Pavement 2) and the interface between binder course and road base (Pavement 1B) with reduction of life up to 94% to 98% respectively.
2. The bond condition between the layers in the surfacing is important with respect to its overall structural performance as well as the serviceability of the road and the ride quality.
3. Flexible pavement plays a very important role in contributing role to the country. The usage of flexible pavement has been predicted to increase in coming years and more complications will come in the future if the current problems cannot be solved in a very effective way, which aimed to prolong the pavement life and to provide better service to the public.

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