A non-linear approach for mechanistic empirical modelling of asphalt-granular base layers interface

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ABSTRACT

This paper proposes a mechanistic model for asphalt-granular base layers interface and an experimental procedure to assess the model parameters. The Mohr-Coulomb yield criteria was used to model interface shear strength and Goodman's law was used to relate the relative displacement and shear stress over the interface that bonds the investigated layers. Moreover, transversal reaction modulus was assumed to be stress dependent, which makes the model non-linear. Experimental results have shown agreement with model assumptions. Finally, a simulation of cracked area evolution was performed to verify the effects of the interface model on the structural response. For the materials studied, the interface mechanical behaviour seemed to be closer to a debonded condition.

Keywords: Interface, Prime Coat, Finite Element Method

1. INTRODUCTION

Prime coat in pavement systems can be defined as the application of a bituminous binder over the first subjacent granular layer underneath the asphaltic surface course, to assure that these two layers are bonded. Since the structural relevance of interface bonding conditions between layers have been studied and confirmed by many authors (Uzan, 1978; Mantilla & Button, 1994; Khweir & Fordyce, 2003; Ziarie & Khabiri, 2007; Hu & Walubita, 2011), prime coat modelling and its laboratory characterization become an important topic for pavement design.

Despite numerous experimental studies to characterize the surface coarse-base layer interface shear strength, existing models usually assume a constant value for the interface stiffness, i.e., the transversal reaction modulus. However, it is known that such assumption is not true for tack coat interface (Chen, 2010), which leads one to believe that it is also not true for prime coat.

This paper presents efforts to model and characterize asphalt coat-granular base interface considering friction and adhesion, within a non-linear approach. Additionally, a test is performed to assess prime coat model parameters, and a Finite Element analysis simulates the effect of the model on a pavement structural response.

2. INTERFACE MODELING AND CHARACTERIZATION

Studying rock mechanics, Goodman (1968) proposed a law to describe the slipping behavior of two adjacent layers (Figure 1). Equation 1 describes the relation between the layers relative displacement Δu and the shear stress through a constant K_t (kPa/mm) called shear reaction modulus.

$$\tau = K_t \Delta u \tag{1}$$

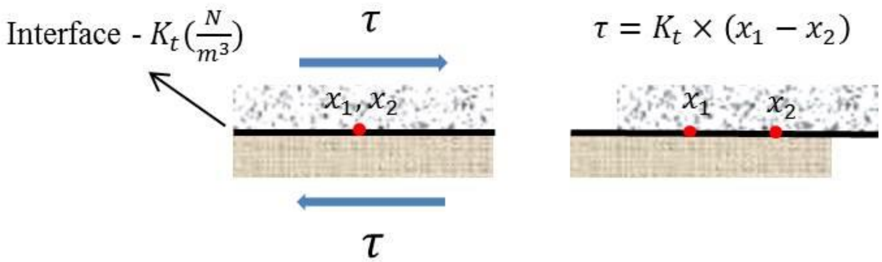


FIGURE 1: Goodman's Law

It is common to assume K_t with a constant value. However, if the bonding condition is also provided by aggregate friction (Lambe & Whitman, 1995), it is reasonable to consider K_t as a function of axial stresses on the interface. This assumption is important for pavement mechanics, especially for thin pavements, because compressive stresses along the interface are not uniform. Moreover, the bituminous binder applied as a prime coating also provides additional bonding. In this paper, K_t is described according Equation 2.

$$K_t = K_p + K_f \tag{2}$$

$$K_f = \alpha\sigma \rightarrow K_t = K_p + \alpha\sigma \tag{3}$$

Where K_p (kPa/mm) is the adhesion provided by the prime coat, K_f (kPa/mm) is the friction between layers due to the presence of aggregates, σ is the axial stress, and α (m^{-1}) is a friction constant. The transversal reaction modulus K_t is therefore a function of axial stress σ. Mohr-Coulomb yield criterion (Equation 4) is adopted. The angle φ represents the friction between aggregates, whereas cohesion C represents the bonding provided by the prime coat. Equation 5 resumes the K_t model proposed in this paper.

$$\tau_{max} = C + \sigma \tan\varphi \tag{4}$$

$$K_t(\sigma) = \begin{cases} K_p + \alpha\sigma, & \tau < \tau_{max} \\ 0 \quad , & \tau \geq \tau_{max} \end{cases} \tag{5}$$

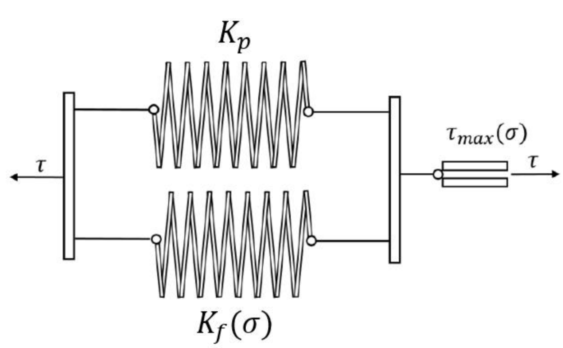
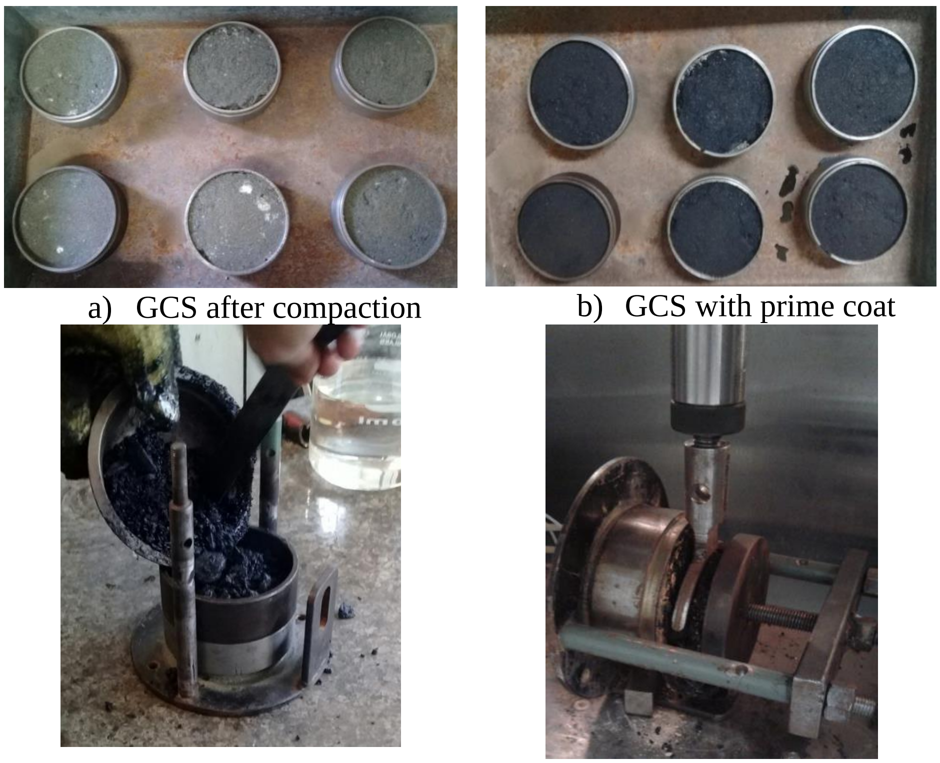


FIGURE 2: Interface model

The interface shear test developed to assess the parameters of the proposed model (K_p, φ, α and C) is analogous to the direct shear test used for soils characterization, except for the specimen size (10cm diameter and 6cm height) and its fabrication process. The first step (Figure 3a) consists in compacting the granular base material (Modified Proctor), followed by a prime coat application (1L/m²) on top of the referred material (Figure 3b). Over the prime coat, the asphaltic mixture is compacted according to the Marshall procedure (Figure 3c). At the end, the specimen contains the three materials, simulating field conditions, e.g., Graded Crushed Stone (GCS), CM-30 cutback and Hot Mix Asphalt, respectively. A 20kPa/s monotonic shear stress is applied (Figure 3d) at three levels of axial stress: 0, 50 and 100kPa (Figure 3a). Higher axial stress should have been applied, but there were experimental limitations during the process. A lubricant is used to mitigate friction between the steel plate and the asphalt concrete portion of the specimen.



a) GCS after compaction

b) GCS with prime coat

c) Asphalt coat application

d) Stress application

FIGURE 3: Interface shear test

3. STRUCTURAL RESPONSE: CRACKED AREA PREDICTION

Once interface model parameters are known, their effect over the estimated pavement Cracked Area (CA) is determined by a procedure typically found in mechanistic-empirical pavement design methodologies. The transfer function used in this paper is presented by Nascimento (2015).

$$CA(\%) = A \times (D_{red})^B \quad (4)$$

$$D_{red} = D \times S \quad (5)$$

$$D = \frac{N}{N_f} \tag{6}$$

Where CA is the Cracked Area, A (7272.68) and B (8.663) are regression coefficients, D_{red} is the reduced damage, D is the mean damage, and S is a fitting function. Damage D is the reason between the current load repetitions N and the maximum load repetitions N_f, which is calculated from the principal tensile strain ε and fatigue life parameters Y (20749123), Δ (-1.43), β (-0.30), α (3.23), C11 (0.000626), C12 (0.617111), according Nascimento (2015).

The theoretical structure analyzed (Table 1) is subjected to 1.93×10^7 standard axle load (10.8cm radius and 550kPa vertical loading) repetitions over 180 months. The structure is considered axisymmetric and all layers (except the interface) are linear-elastic. Because of the non-linearity caused by the considered interface model, the Finite Elements Method was used. Cracked Area evolution was simulated for a 10-year period.

TABLE 1: Structure analysed

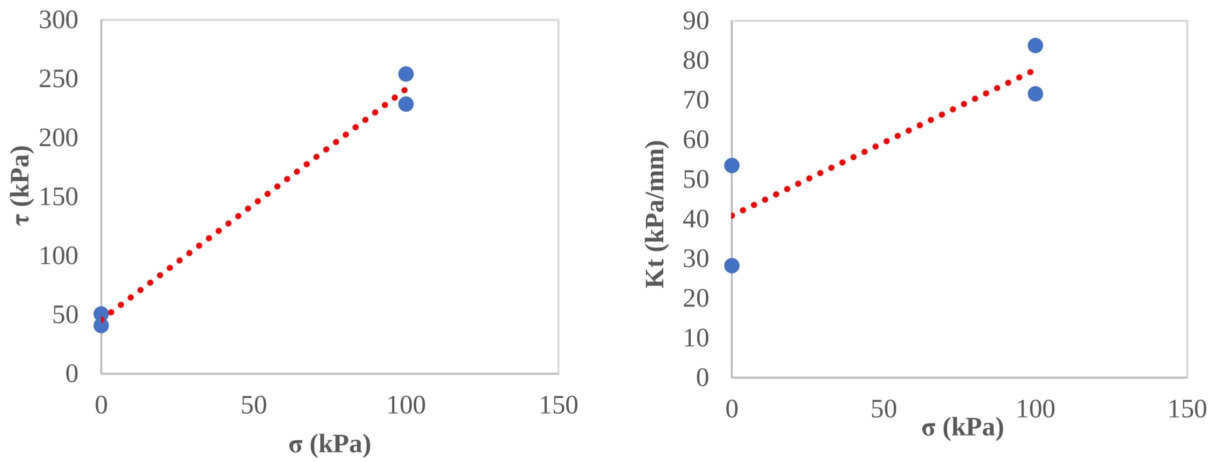
Layer	Thickness	E (MPa)	Poisson
Asphalt Coat	5	3000	0.30
Interface	--------	--------	--------
Base Course	15	478	0.35
Subbase	15	493	0.40
Subgrade	∞	407	0.40

4. RESULTS AND DISCUSSION

4.1. Interface Shear Test

Figure 4 shows that both shear strength (τ_{max}) and the transversal reaction modulus (K_t) are stress dependent. Such results reinforce the hypothesis that the adhesion provided by prime coat and the aggregates friction must be considered to model asphalt surface coarse-granular base interface.

Table 2 presents interface model parameters. Mantilla & Button (1994) performed direct shear tests on asphalt coat-granular base interfaces. Friction angle ranged from 52° to 73°, and cohesion from 0 to 160kPa. The referred authors did not present transversal reaction modulus results. The values encountered in the present research are within values reported in the literature. Uzan (1978) states that if $K_t < 100kPa/mm$, the layers can be considered debonded. Under such assumption, the interface studied in this paper presents itself as debonded.



a) Interface Mohr-Coulomb envelope   b) Tranversal reaction modulus function

FIGURE 4: Interface shear test results

TABLE 2: Interface model parameters

σ (kPa)	Kt (MPa/m)	T (kPa)	K_{imp} (kPa/mm)	A (mm^{-1})	C (kPa)	Φ (°)
0	28	41	40.86	0.37	45.77	62.93
0	54	51				
100	72	229				
100	84	254				

4.2. Cracked Area Prediction

An example of the cracked area evolution for the systems considered in Table 1 is shown in Figure 4. Results demonstrate that the interface studied in this paper has a behavior approximate to the debonded condition. Such result agrees with Uzan (1978), once K_t along the asphalt coat-granular base interface maximum value is 135kPa/mm when the interface model proposed is used.

It should be noted that the load was assumed to be vertical, without a longitudinal or transversal component. Such simplification may underestimate the interface structural role, once it works mainly on transversal and longitudinal directions. To properly consider these load directions, a 3D model would be necessary, which increases computational cost, especially because the phenomenon is nonlinear.

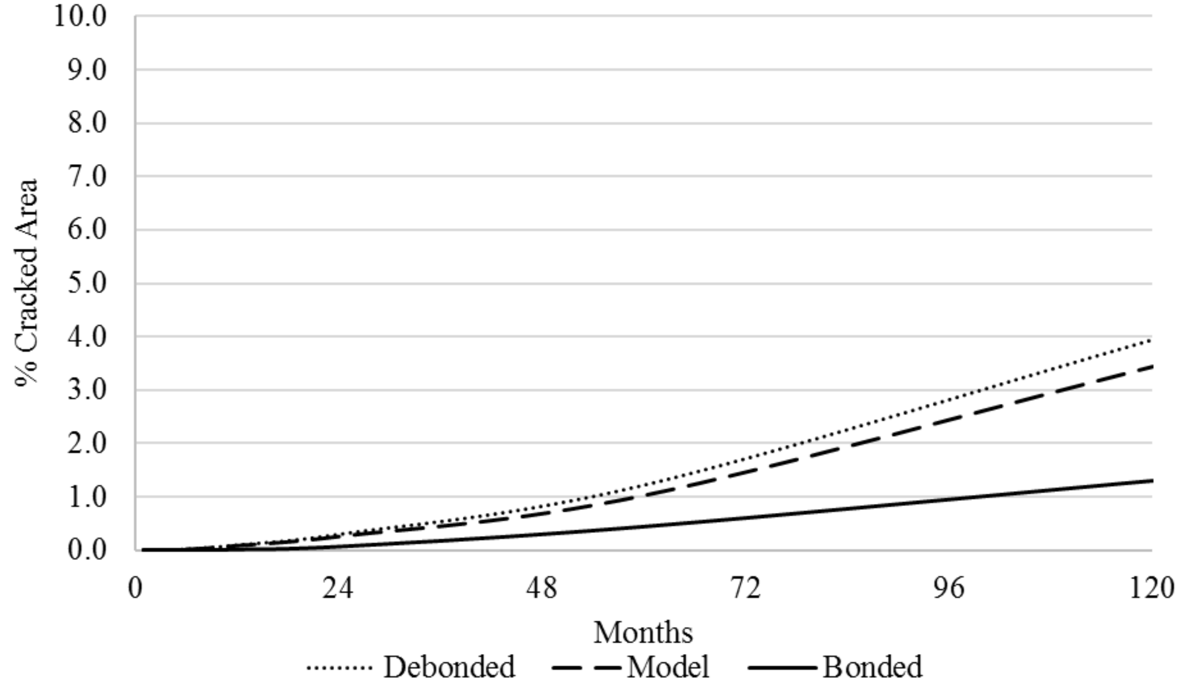


FIGURE 5: Cracked Area evolution

5. CONCLUSIONS

An interface shear experimental test is presented with a corresponding mechanistic model. Both shear strength and transversal reaction modulus are stress dependent according experimental results. However, it is necessary to perform more tests to verify if this phenomenon occurs at higher stress levels and for other materials. Structural analysis has shown that the interface studied presents a debonded behavior, therefore for simplification purposes it would be reasonable to consider that the bonding between layers is null. Nevertheless, this conclusion is limited to the tested materials and experimental conditions adopted. Further studies are necessary for a better understanding of asphalt coat-granular base interface mechanical behavior.

REFERENCES

[1] Uzan, J.; Livneh, Moshe; Eshed, Y. Investigation of adhesion properties between asphaltic concrete layers. In: Association of Asphalt Paving Technologists, Proc 47, pp. 495-521, 1978.

[2] Mantilla, C.A.; Button, J.W. Prime coat methods and materials to replace cutback asphalt. FHWA Research Report, v. 01, n. 1334, pp.1-156, 1994.

[3] Khweir, K.; Fordyce, D. Influence of layer bonding on the prediction of pavement life. Proceedings of The Institution of Civil Engineers - Transport, [s.l.], v. 156, n. 2, pp.73-83. 2003.

[4] Ziari, H.; Khabiri, M. Interface condition influence on prediction of flexible pavement life. Journal of Civil Engineering and Management, v. 13, n.1, pp. 71-76, 2007.

[5]HU, Xiaodi; Walubita, Lubinda F. Effects of Layer Interfacial Bonding Conditions on the Mechanistic Responses in Asphalt Pavements. Journal of Transportation Engineering, [s.l.], v. 137, n. 1, pp.28-36, 2011.

[6] Goodman, R., Taylor, R., & Brekke, T. A model for the mechanics jointed rock. Transportation Research Board, pp. 637-659. 1968.

[7] Lambe, T. W; Whitman, R. Soil Mechanics. 2.ed. New York: John Wiley & Sons Inc, 1995.

[8] Nascimento, L. A. H. (2015) Implementation and Validation of the Viscoelastic Continuum Damage Theory for Asphalt Mixture and Pavement Analysis in Brazil. PhD Thesis. North Carolina State University. Raleigh-USA.