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Impact of contact stress distribution on skid resistance of asphalt pavements

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HIGHLIGHTS

- Introduction of mathematical model for tire-pavement stress distribution.
- Estimation of surface fractal dimension via improved projective covering method.
- Evaluation of the dispersion and concentration of contact stress by Weibull index.
- Confirmation of the critical separation value of tire-pavement contact stress.
- Correlation of friction coefficient and average effective stress.

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ABSTRACT

In order to obtain the actual contact area and stress distribution between tire and asphalt pavement, a pressure-sensitive film was conducted and adopted for measuring radial tire contact stress. In this study, the fractal dimension of the fracture surface was estimated to describe the surface roughness of four types of track boards in terms of utilizing the improved projective covering method. The results showed that Weibull distributions were applicable to describing the contact stress distribution between tire and pavement, and the Weibull expectation could effectively characterize the stress level. In addition, it was found that greater stress expectations indicated more significant stress concentration effects on the pavement surface. The stress distribution increased with an increase of pavement texture depth or tire load or a decrease of the tire inflation pressure. The influence of pavement roughness and tire load was more significant than tire inflation pressure on the stress concentration. Compared to the general pavement texture depth (sand patch method), the surface fractal dimension adequately described the surface roughness including macro-texture and micro-texture, and it was directly affected by the proportion of coarse aggregate. The pavement skid-resistance performance was mainly influenced by its high stress regions (>1.8 MPa) at the top of asperities. The skid-resistance performance of asphalt pavement was proved to be better with a high-level average effective stress.

1. Introduction

Traffic accidents can be reduced if safety improvements are provided by analyzing parameters that affect pavement friction. Experimental measurements have shown that the friction force at tire-pavement interface is influenced by many factors, including vehicle factors (load, speed, slip ratio, slip angle, and camber angle), tire factors (tire type, inflation pressure, tread design, and rubber composition), pavement conditions (roughness, micro- and macro-texture, dryness and wetness), and environmental factors (temperature and contamination) [1,2]. From a pavement perspective, the properties such as the hardness, shape, angularity and surface texture of aggregates are important for skidding resistance, as well as the design method for asphalt mixtures [1–5]. A main safety criterion for asphalt pavements is the tire-pavement interaction [6].

The actual pattern between tire and asphalt pavement was close to an elliptical shape, but some studies simply considered the contact area of tire on the pavement to a circle shape. However, the research showed that the contact surface is not round and the contact pressures are generally non-uniform over both the width and length of contact [7]. The contact stresses developed at the tire-pavement surface are important because they determine the

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stresses caused in the pavement structure. The tire-pavement interfacial contact stresses may cause a complex stress-state near the pavement surface and increase the potential for pavement damages, such as top-down cracking, "near-surface" cracking, and instable rutting in the upper HMA layer [8–10]. Besides that, the tire-pavement contact plays an important role in the skidding resistance performance. Many aspects, such as the transient contact with nonlinear frictional properties at the tire-pavement interface, make the rolling contact problem more difficult than it may appear at first glance [11]. The use of finite element method (FEM) is a popular choice to explore this issue. Al-Qadi et al. developed tire-pavement interaction model using the FEM and analyzed the tire-pavement contact stress distributions at various conditions [8,10,12,13], but these studies considered the pavement as a smooth flat surface and the macro- and micro-texture on asphalt pavement were not adequately considered.

Developing an effective detection technology to measure the contact area and stress distribution between tire and pavement is an appropriate choice. Currently, the main techniques of pressure measurement include pressure plate method, pressure-sensitive membrane, light absorption, and pressure sensors et al. [14–16], but there are several shortcomings, such as low accuracy and poor stability, which may result in some obvious measure errors. Cheli developed equipment that could predict the force between tire and pavement by measuring the deformations of the rim's three directions during tire-rolling [17]. Liang used the Tekscan system to measure tires' radial grounding performance and described the geometric characteristics with geometrical parameters [18]. However the contact stress distribution cannot be accurately acquired because of the low accuracy measurement.

In this paper, the high sensitivity pressure film was adopted to measure the contact stress distribution between automobile tires and pavement, which was explored to establish evaluation indices that can describe the dispersion and concentration of the stress distribution. Finally, the impact of the stress distribution on pavement skid-resistance performance was revealed.

2. Objective and scope of this study

The objectives and the scope of this study are as follows:

(1) The objective of this study is to measure the effective contact area and stress distribution between tire and asphalt pavement, and come up with a mathematical method to describe contact stress distribution of different pavements. Meanwhile, this study also aims to propose an indicator that describes surface roughness including macro- and micro-texture of asphalt pavement.

(2) In the research, four types of track boards were selected and a smooth steel plate was employed as a reference. Their friction coefficients and pavement texture depth were measured. Based on the measurement of a 3D laser scanner, the fractal dimension of the surface was estimated by using the improved projective covering method. Pressure-sensitive films were used to measure the effective contact area and stress distribution between tire and track boards.

3. Materials

The styrene-butadienestyrene (SBS) modified asphalt and granite aggregate were used to design four forms of asphalt pavement, and basic properties are as shown in Tables 1–3.

4. Methodology

4.1. Mechanisms of pavement friction

According to the Tabor theory of tribology, the friction force at the contact interface of the pavement and tire is coming from two parts, adhesion, F_a, and hysteresis, F_h, as shown in Fig. 1. The macro-texture of pavement mainly results in viscoelastic deformation resistance, F_h; in contrast, hysteresis F_h contributes approximately 10% of the tire-pavement friction [19]. Adhesive friction occurs mainly at the contact interface between the micro-texture and the rubber tire referred to adhesion, F_a, which is a function of the maximum tangential stress and the contact area. As a result, the adhesive friction force at a single asperity is expressed by the following formula:

$$F_a = \tau_i \times A_i = \varphi \times \sigma_i \times A_i = \varphi \int\int_{A_i} \sigma(x,y)dxdy, \qquad (1)$$

where F_a is the adhesive friction force at a single asperity (N); $\sigma(x,y)$ is the normal stress distribution at the contact interface (MPa); φ is the adhesion coefficient between tire and road, which is related to pavement materials, pavement conditions, tire material, tread pattern, and vehicle speed [20].

When there is much non-rigid material on the road surface, such as snow, water, or soft plastic asphalt material, the pavement

Table 1
Basic properties of SBS.

Type of test		Specification requirement	Test results	Evaluation
Needle penetration 25 °C, 100 g, 5 s, 0.1 mm		40–60	53	Passed
PI	Min	0	0.3	Passed
Ductility 5 °C, 5 cm/min, cm	Min	20	28.7	Passed
Softening point $T_{R\&B}$ (°C)	Min	60	76	Passed
Flash point (°C)	Min	230	282	Passed
Solubility (%)	Min	99	99.6	Passed
Elastic recovery 25 °C, %	Min	75	94	Passed
Kinematic viscosity (Pa s)	135 °C Max	3	2.47	Passed
	165 °C	–	–	–
PTFOT	Quality variation (%)	±1.0	−0.19	Passed
Residue	Ductility 5 °C, 5 cm/min, cm Min	15	40.2	Passed
(163 °C, 85 min)	Penetration ratio (%) Min	65	76.4	Passed

Table 2
Basic properties of aggregates.

Apparent density (g/cm^3)	Crushing value (%)	Abrasion (%)	Water absorption (%)	Friction coefficient (BPN)
2.668	14.3	18.6	0.49	42.2