A Novel Study of Contact Characteristics between Tire and Paved Road Surface using Pressure Film Technology

Nie Wen 1, Bo Chen 2*, Li Wei-Xiong 1,2, Zhang Xiao-Ning 2, Zhou Pei 1, Xiong Chun-Long 1*

1 Guangzhou Xiaoning Institute of Roadway Engineering Co., Ltd., Guangzhou, China.
2 School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China.

Abstract - Traffic safety is affected by the vital technical problem of skid resistance of asphalt paved road surface: the word Pavement is often mistakenly used for convenience in the literature. The tire to paved surface contact characteristic is a key to the study of skid resistance performance. In our project we studied the contact characteristics between tire and paved road surface by using a high-precision pressure film to obtain the contact footprint and the stress matrix of tire-road through different combinations of air pressure and load. The variation of the effective contact area and stress distribution was analyzed comprehensively. The results showed that pressure film measurement technology is suitable in reflecting the real contact characteristics between tire and road surface. The impression rectangular index k1 and effective contact rectangular index k2 were presented to describe the degree of full contact between tire and road. As the load increases, or the tire pressure decreases, the geometric shape of the tire contact mark changes from circular to rectangular, and the rectangular index k1 increases to 1.0. The stress concentration mainly occurs at the edge of tire pattern blocks of the grounded impression, especially at the toe of tire pattern. With the increase of load, the peak value of tire to paved-surface contact pressure increases significantly. The effect of single wheel load on stress concentration is greater than tire air pressure.

Keywords - Paved-surface, Contact Characteristics, Pressure Film, Effective Contact Area, Stress Concentration

I. INTRODUCTION

The paved-surface skid-resistant performance is the key to ensure traffic safety, and the essence of the skid-resistance is the friction mechanism of the interface between the tire and the paved-surface [1-2]. Surface texture of asphalt paved-surface mainly includes macroscopic texture and microscopic rough peak texture on its surface, as shown in figure 1. When the car is moving, the tire is directly in contact with the road surface to form a tribological system, which includes factors such as tire, paved-surface, tire and paved-surface medium and external environment. These factors interact with each other and have important influence on the friction between tire and paved-surface [3]. Tire is made of rubber material with elastic characteristics, which can be regarded as a cylinder. If the tire is not deformed completely, the contact interface between the tire and the smooth dry paved-surface is a line. However, due to the characteristics of tire (inflatable structure, viscoelastic material) under large loads, the contact interface between tire and paved-surface is similar to ellipse or rectangle [4]. To be fair, contact between tire and paved-surface is actually the occlusion of tire rubber and the bulge of paved-surface. That is, the real contact area is much smaller than the macro contact area between tire and paved-surface [5]. Judging from stress state of stable driving, start and brake process, the effect of the contact between tire and paved-surface is mainly reflected in the effective contact area between tire and paved-surface, and the degree of their interlocking [6].

Due to the complex surface structure of asphalt paved-surface, smooth interface such as steel plate was used to simulate the paved-surface in the past testing of tire performance. The real situation of the contact between tire and paved-surface was simplified, which had great influence on the experimental results. Suffering from testing instrument, problems such as the effective contact area, pressure distribution and concentration degree of real contact between tire and paved-surface have not yet received a satisfactory understanding, resulting in a slow research progress.

To study the real contact characteristics between tire and paved-surface, this paper select different influence factors, such as different measure ranges of pressure film, various axle loads, and diverse road surface roughness to develop experimental research. By placing pressure film between tire and paved-surface, this study selected evaluation indicators from geometrical morphology and mechanical characteristics. The contact distribution characteristics under different measurement conditions were compared. The impression pressure image and evaluation indicators were combined to represent the contact area and pressure distribution characteristics. By doing this, the tire-paved-surface stress distribution characteristics and the feasibility of further research on paved-surface skid resistance performance can be explored.
II. MATERIALS AND METHODS

A. Test Materials

Aggregate gradation of different paved-surface mixtures causes the roughness of the road surface. The graduation of AC16, which is coarse-grain dense-suspended type, is shown in table I.

<table>
<thead>
<tr>
<th>Gradation type</th>
<th>Mesh (mm) and Aggregate Mass Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-16</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

B. Selection of Working Conditions

According to “Technical Standard of Highway Engineering” (JTG B01-2003), the convert coefficient of passenger car (coach with less than 19 seats or truck with less than 2 tons) is 1.0. Hence, this study selected a light truck of Nissans ZN1021U2G with radial tire DUELER A/T 215/75R15, static load on the left rear wheel and the AC16 HMA for analysis purposes. Selection of working conditions is shown in table II.

<table>
<thead>
<tr>
<th>Pressure Load</th>
<th>600kPa</th>
<th>500kPa</th>
<th>400kPa</th>
<th>300kPa</th>
<th>250kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3kN</td>
<td>√</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>5.2kN</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>7.0kN</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>9.5kN</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>×</td>
</tr>
</tbody>
</table>

Note: √ represents the conditions are numbered; × represents the conditions have not been tested.

C. Measuring Technique

The effective detection technology of effective contact area, pressure distribution between tire and paved-surface mainly include pressure board method, pressure sensor method, light-absorption method, etc [4, 6-8]. It is difficult to test with high measurement precision and easy to test with low measurement precision according to the measurement technology of contact characteristics between tire and paved-surface at present. All of these methods place the tires on the glazed bearing facilities (rubber plate, steel plate or glass plate), which can’t be used to measure the contact between tire and paved-surface with rich structure. It's very critical and important to find a method with high measurement precision, easy operation, and can measure the contact surfaces of various roughness. Recently, a pressure film sensing technology has developed rapidly, which overcomes the shortcomings of the above methods and meets the research needs of this project (hereinafter, pressure film) [9].

There are two types of pressure film, mono-sheet type and two-sheet type. Mono-sheet type apply to high pressure situations and two-sheet type apply to low pressure situations. The underlying substrate material of the pressure film is polyester film, which is coated with the color forming layer and the color developing layer (Consisting of microcapsules containing the color of the material). The principle is shown in figure 2. When pressure is applied, the microcapsules are broken and the color forming material transfers to the color developing material, thereby generating a red color. The size of microcapsule is related to the strength and pressure of the cell wall.

![Diagram](image-url)
The thickness of pressure film is less than 200μm (100μm×2), and its minimum measuring area can be accurate to 0.016mm². Through the pressure image scanning software, the film color can be automatically converted to the pressure value and displayed in the software window for data analysis. Therefore, the pressure film method can conveniently and visually check the pressure distribution and uniformity, get extremely detailed pressure distribution on the pressure distribution diagram, even the pressure distribution of designated point area or specified area. The advantages are that the measurement process is simple and fast, and the measurement results are accurate, intuitive and clear. Besides, no special equipment or device are needed. In the study of the contact characteristics between tire and paved-surface under static load, using the pressure film measuring technique will provide more accurate analysis.

According to the measurement data and the contact area, the error limit within effective range of the pressure film measurement data can be controlled within plus or minus 3%, and the error limit of film pressure measurement system can be controlled within plus or minus 5%.

In the study of contact characteristic between tire and paved-surface, the pressure film can be well reflected in the contact area and pressure distribution characteristics, and the pressure film technology has overcome the shortcomings of the traditional method. Not only high precision and slight error, but also the larger detection area (6000mm ×270mm above), convenient to cut, and the operation of the test is simple and the result is intuitive.

D. Test Procedure

Figure 4. The two ranges film color contrast: (a) LLLW film; (b) LLW film.

The flatness of track board is 2.36mm measured by horizontal ruler method; the texture depth (TD) is 0.91mm and the friction coefficient is 84.2BPN measured by sand patch method and pendulum instrument method. Using jack to control static loading and unloading process of the tire; using pressure sensor to measure the load of the tire; using pressure tester to adjust the change of tire pressure condition.

The standard ground pressure of tire is 0.7 MPa, considering the ground stress concentration effects and stress diffusion effect caused by superposition of multiple different range films. This study mainly used small-range LLLW type film ([0.2,0.60] MPa) and large-range LLW type film ([0.5, 2.5] MPa) by primary tests, the pressure exceeding the effective range will still be fully responsive in the form of the maximum range value in the film pressure image, as shown in figure 4. Effective contact area in this paper refers to all the pressure response area include yellow, red and green area, which is the actual pattern area between tire and paved-surface, do not contain the blank area without interstitial area or pressure. Average pressure is the average value of all pressure response areas; and impression outline area is the envelope area of stress area of pressure-sensitive film.
TABLE III. LLLW TYPE FILM GROUNDED IMPRESSION PICTURE UNDER SAME WORKING CONDITION

<table>
<thead>
<tr>
<th>Working Condition</th>
<th>600kPa</th>
<th>500kPa</th>
<th>400kPa</th>
<th>300kPa</th>
<th>250kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.57kN</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>7.04kN</td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>5.21kN</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 5. AC-16 and the tire contact impression rectangular rates k1, k2 variation diagram: (a) Impression rectangular rates k1; (b) Effective contact rectangular rates k2.
III. RESULTS AND ANALYSES

Real contact area between tire and paved-surface varies with different tire types, patterns, tire pressure and loads. For the same tire, the ground area increases progressively as the load increases under the same tire pressure. For the same tire, the ground area increases progressively as the tire pressure increases [10]. However, the degree of change is different due to the fact that the actual contact state is not completely scattered granular local contact. In literature [11-13], the stress distribution of the real paved-surface is studied by using the light plate instead of the real paved-surface. It is shown that the stress distribution is highly correlated with tire load and tire pressure. The smallest correlation coefficient is 0.92 and the average value is 0.98. Because of ignoring the real contact state, the contact between tire and rough paved-surface cannot be effectively explained.

A. Grounded Impression Outline Shape Analysis

Select the Small-range film to study the influence of different working conditions on the impression outline shape. Measure the grounded impression image of LLLW film under three loads and five kinds of tire pressure, as shown in table 3.

It is visually from table 3 that with the increase of the single-wheel load and the decrease of the tire pressure, the grounded impression of the tire is gradually changed from the ellipse to the rectangle, and is in the geometrical morphology between the ellipse and the rectangle. According to a lot of experiments, when the grounded impression of tire is closer to the rectangle, the contact between tire and paved-surface becomes more accurate. In order to describe the contact degree between tire and paved-surface, define the tire and paved-surface contact impression rectangular rates (k1) and effective contact rectangular rates (k2) for quantitative analysis and engineering applications to describe the full extent of contact between tire and paved-surface under different working conditions. The mathematical description is shown in equation (1).

\[
\left\{ \begin{array}{l}
k_1 = \frac{A'}{A_s} \\
k_2 = \frac{A}{A_s}
\end{array} \right. \quad (1)
\]

In equation (1), k1 is the impression rectangular rates and k2 is the effective contact rectangular rates; A' is the impression outline area, mm²; A is the effective contact area, mm²; AS is the circumscribed standard rectangle area, mm².

The equation (1) shows that the closer the rectangular rate is to 1, the tire makes more contact with the paved-surface, and vice versa. Factors affecting the rectangular rate mainly includes the tire load, tire pressure, and the roughness of the paved-surface. As shown in figure 5, it can be found that the impression rectangular rates are higher than the effective contact rectangular rates, which is mainly related to the tread-markings spacing and paved-surface structure.

With the decrease of tire pressure, contact impression of tire and paved-surface is closer to the standard rectangle. The larger the rectangle rate is, the increase of the tire pressure shows the trend of the decreasing of the rectangular rate. Under the same tire pressure, with the increase of the single-wheel load, the more the tire and the paved-surface contact, the larger the impression rectangular rate is. This indicates that with the increase of single-wheel load and the decrease of tire pressure, the grounded impression outline shows the trend of outward expansion.

The rule of effective contact rectangular rate is the opposite. Reason is that with the increase of tire pressure and the single-wheel load, the tighter the tire rubber and the paved-surface occludes, the deeper the depth of the coarse aggregate on the paved-surface, leading to the increasing concentration of grounded impression. That is, the contact density increased in the unit impression area.

B. Influence Factor Analysis of Contact Interface Pressure Distribution

In general, the stiffness of the pneumatic tire is mainly controlled by inflation pressure and tire size (mainly tread width and external diameter). Under standard operating pressure, the tire structure itself only accounts for 10% to 15% of the tire bearing capacity. The deformation of the tire itself causes the deflection under the tire load and tire pressure to achieve the contact interface area of the paved-surface.

The definition of tire hardness coefficient can be expressed by equation (2):

\[
H = \frac{F}{A \times P}
\]  

(2)

In equation (2), H is the tire hardness coefficient; F is the single-wheel load, N; A is the effective contact area, mm²; P is the tire inflation pressure, N/mm².

The larger hardness coefficient can be understood as the low tire pressure, which causes the large deformation of tire during rolling compression and a large loss of energy of the rubber, leading to high rolling resistance.

The equation of the average pressure of tire contact area is as follows:

\[
p = \frac{N}{A}
\]  

(3)

In equation (3), F is the single-wheel load, N; A is the total effective contact area of small-range film, mm².
Considering the deflection of the tire is more helpful to analyze the pressure distribution of the tire and paved-surface, so that the anti-slip performance of the contact area based on the friction mechanism can be analyzed. The equation of the tire deflection is as follows:

\[ d = \frac{L}{K_z} \]  

In equation (4), \( d \) is the deflection, mm; \( L \) is the load, kg; \( K_z \) is the shear stiffness, kg/mm.

### B1. Effects of Mechanical Parameters of the Tire

According to the metrical data of pressure film (including effective contact area from LLLW type small-range pressure film), and mechanical parameters calculated as above. The relationship between the tire hardness coefficient, the deflection and the effective contact area is shown in Figure 6. It can be seen from the asphalt paved-surface structure of AC-16 specimen that no matter how tire pressure and load changes, there is a good linear relationship between the deflection of the tire and the effective contact area, and the effective contact area increases with the increase of the deflection.

The tire deflection is taken as independent variable \( x \) and the effective contact area is taken as dependent variable \( y \), linear regression with the formula \( y=ax+b \). It can be concluded that the correlation coefficient between the two is 0.846, shown in the same contact area of paved-surface, the deflection of the tire and the effective contact area has good linear relationship. It can be seen from the figure that with the increase of the deflection, when the tire deflection is less than 20mm the variation trend of the effective contact area increases more rapidly than when the tire deflection is more than 20mm.

\[ y = 378.8x + 4921 \]

\( R^2 = 0.846 \)

### B2. Effects of Tire Pressure

Draw the relationship between tire pressure, effective contact area and average pressure, as shown in figure 7 and figure 8. The tire pressure is taken as independent variable \( x \) and the effective contact area is taken as dependent variable \( y \), linear regression with the formula \( y=a_1x+b_1 \) and regression parameters \( a_1 \) and \( b_1 \) are calculated. It can be concluded that the smallest correlation coefficient between the two is 0.87741, showing the tire pressure and the effective contact area has good linear relationship. Similarly, tire pressure is taken as independent variable \( x \) and the average pressure is taken as dependent variable \( y \), linear regression with the formula \( y=a_2x+b_2 \) and regression parameters \( a_2 \) and \( b_2 \) are calculated. It shows the tire pressure and the average pressure basically present linear relationship, linear correlation between tire pressure, effective contact area and average pressure is consistent. It can be seen from the chart that when the load is constant, the tire pressure has a good linear relation with the effective contact area and average pressure.

When the load is 75% of rated load, rated load, overrated load 40%, the tire pressure has a good linear relation with the effective contact area. The tire pressure has a good linear relation with the effective contact area and average pressure under the same load. When the load is 9.57kN, correlation coefficient between tire pressure and effective contact area is as high as 0.95936, and correlation coefficient between tire pressure and average pressure is as high as 0.97232, and the linear relationship is the most significant. This fully shows that when the load is higher, the greater the deflection of tire is. The closer to the full contact state, the greater linear relationship between tire pressure, effective contact area and average pressure. In addition, it can be seen from
the figure that although the slope of each line is roughly similar and load 7.04kN has the highest slope, indicating that with the increase of tire pressure, tire stiffness increases, the more the effective contact area between tire and paved-surface decreases, the more obvious the change of average pressure is under rated load. It can be seen from the analysis of the shape of impression on pressure film that when the load is 5.21kN, the tire impression basically presents the elliptical scatter distribution. With the decrease of the tire pressure, the shape of the ellipse gradually disappears, and then a rectangular impression appears. The linear correlation coefficient between tire pressure, effective contact area and average pressure decreases too at low load, fully demonstrated that in the contact of the tire and paved-surface, not only two independent variables including tire pressure and load influenced the contact between tire and paved-surface, but also the influence of the rough paved-surface on the contact characteristics of tire/ paved-surface cannot be ignored due to the complex structure and the interaction between the tire and the paved-surface.

**TABLE IV. REGRESSION PARAMETER TABLE**

<table>
<thead>
<tr>
<th>Load(kN)</th>
<th>a1</th>
<th>b1</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>12241</td>
<td>-7.1922</td>
<td>0.82697</td>
</tr>
<tr>
<td>7.0</td>
<td>17350.25</td>
<td>-12.5508</td>
<td>0.8404</td>
</tr>
<tr>
<td>9.5</td>
<td>19345.5</td>
<td>-9.87878</td>
<td>0.95936</td>
</tr>
</tbody>
</table>

**B3. Effects of Load**

For the contact area between tire and paved-surface, the load has a good linear relation with the effective contact area when the tire pressure is constant, as shown in figure 9 and figure 10. The load is taken as independent variable x and the effective contact area is taken as dependent variable y, linear regression with the formula y = a1x+b1 and regression parameters a1 and b1 are calculated. It can be concluded that the correlation coefficient between the two is 0.87741, shows the load and the effective contact area has good linear relationship. Take the load as independent variable x and the average pressure as dependent variable y, linear regression with the formula y = ax+b. It shows that the load and average pressure basically present linear relationship, but the linear correlation between load and average pressure is less significant than that between effective contact area. It can also be seen from the chart that the slope of each line is approximately similar under different loads of five different tire pressure, but the linear correlation between load and effective contact area or the linear correlation between load and average pressure under high tire pressure is generally higher than that under low pressure.

The paved-surface construction has some influence on the incomplete contact. Besides, the deflection of tire directly affects the contact extent of interface, and the deflection of the tire is the ratio of load and stiffness, stiffness is in proportion to the tire pressure. So when the load is constant, as the tire pressure changes, the tire stiffness changes correspondingly, which directly affects the deformation of the tire, the incomplete contact degree
between tire pattern blocks and rough paved-surface changes accordingly, so the load and the effective contact area or the load and the average pressure has good linear relationship. When the tire pressure is constant, as the load changes, the tire deflection as the ratio of load to stiffness changes correspondingly, the load and the effective contact area has good linear relationship. The average pressure is the ratio of load to effective contact area, the correlation coefficient between the load and average pressure is low due to the offset between the change of load itself and the change of effective contact area.

![Figure 9. Relationship between load and effective contact area](image9.png)

![Figure 10. Relationship between load and average pressure](image10.png)

### TABLE V. REGRESSION PARAMETER TABLE

<table>
<thead>
<tr>
<th>Tire inflation pressure (kPa)</th>
<th>a1</th>
<th>b1</th>
<th>correlation coefficient</th>
<th>Tire inflation pressure (kPa)</th>
<th>a2</th>
<th>b2</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>893.829</td>
<td>1352.256</td>
<td>0.99039</td>
<td>600</td>
<td>0.551</td>
<td>0.015</td>
<td>0.93956</td>
</tr>
<tr>
<td>500</td>
<td>1429.087</td>
<td>1320.290</td>
<td>0.99646</td>
<td>500</td>
<td>0.560</td>
<td>0.013</td>
<td>0.60606</td>
</tr>
<tr>
<td>400</td>
<td>1334.392</td>
<td>1443.392</td>
<td>0.99994</td>
<td>400</td>
<td>0.543</td>
<td>0.009</td>
<td>0.98296</td>
</tr>
<tr>
<td>300</td>
<td>2968.915</td>
<td>1462.156</td>
<td>0.87741</td>
<td>300</td>
<td>0.405</td>
<td>0.014</td>
<td>0.85253</td>
</tr>
<tr>
<td>250</td>
<td>4018.317</td>
<td>1376.125</td>
<td>0.94084</td>
<td>250</td>
<td>0.358</td>
<td>0.021</td>
<td>0.79044</td>
</tr>
</tbody>
</table>

### C. Stress Concentration Analysis of Contact Interface Pressure Distribution

In the study of the interface friction characteristics and anti-slide performance between tire and paved-surface, the interface friction force mainly comes from the adhesive force between pattern of the tire and micro-bulge on the paved-surface. The cohesion and crosslinking between tire and stone of paved-surface within the scope of microstructure are mainly determined by interfacial shear strength τi and contact area Ai. In general, the more complex the microstructure of the stone and the larger the superficial area of the exposed surface, the larger the effective contact area and the higher shear strength of the contact interface. The magnitude of shear strength τ is closely related to the number and shape of "micro-bulge" on the paved-surface. By Coulomb theory, the more curved the edges and corners of the aggregate micro-texture and the better the abrasion resistance, the larger the internal friction angle and higher the shear strength is. When the tire is in contact with the paved-surface, from the symmetrical distribution of positive stress at the micro-bulge in the static state to the asymmetrical distribution of shear stress in the motion state, it can be qualitative judged that when the paved-surface structure remains the same, higher the positive stress value in the static state is, higher the shear strength in the motion state and the friction between tire and paved-surface, and better the effectiveness of landslide control.

Therefore, apart from integral analyzing the pressure distribution of grounded impression, this paper also focuses on distribution of stress concentration to provide experimental foundation and data analysis for judging the contact friction of interface. Overall and partial two aspects are selected to analyze the stress concentration.
C1. Analysis of Stress Concentration

From the contact mechanism between tire and paved-surface, the first concern is the tire deformation to balance the vehicle load, namely the grounded area. The larger the total effective contact area, the better the tire safety performance. Secondly, the partially wrapped and embedded deformation of the tire on the coarse aggregate convex particles leads to the stress concentration at the contact interface. However, stress concentration is caused not only by the roughness of the paved-surface, but also by the flat plate, as shown in figure 11.

![Figure 11. Pressure distribution plan of contact interface between tire and steel plate](image)

According to the analysis of pressure distribution obtained by large-range LLW type pressure film, the research found that the stress concentration mainly occurs at the edge of tire pattern blocks of the grounded impression, especially at the toe of tire pattern. This is because the existence of tire pattern results in uneven hardness of all parts of the tire tread, and the hardness of toe of tire pattern is larger than that of the heel. This contact pressure is not an ideal smooth contact state simplified by previous researchers, but it truly reflects the pressure distribution at the contact interface.

C2. Analysis of Stress Concentration in Overall Contact Area

Select the pressure interval area of [0MPa, 0.6MPa] in small-range LLLW type film and pressure interval area of [0.6MPa, 3.06MPa] in large-range LLW type film for joint analysis. Different contact pressure values are divided into intervals for statistics, calculated at equal intervals. Draw the effective contact area ratio (percentage of effective contact area to impression outline area) of pressure interval, as shown in figure12. As can be seen from figure12, the cumulative percentage of contact area in different pressure interval under 16 working conditions shows similar curve characteristics, and a more obvious inflection point of curvature generally appears at the position where the pressure value is about 1.25MPa. Curvature changes on the left side of p<1.25 show an increasing trend in all working conditions, while the curvature changes on p>1.25 shows a moderate increasing trend.

![Figure 12. Effective contact area ratio in pressure interval area](image)

C3. Change Regulation of Extreme Pressure Value

Since it is difficult for people to obtain the exact distribution of extreme value, empirical data are usually used to fit the distribution of extreme value and study the asymptotic distribution of extreme value. The theoretical research results show that: Extreme Value Distribution can describe the maximum (minimum) value distribution very well, that is to say Frechet, Gumbel, Weibull distribution can be used to fit such random variables. By means of nonlinear least squares method or maximum likelihood estimation method, using the weighted sum of two normal distribution functions and the cumulative distribution function of the bimodal distribution of the actual contact interface compressive stress can be fitted. The 95% fraction of the maximum value distribution of the tire/ paved-surface contact stress can be used as the maximum pressure point. Based on this, the change regulation of tire pressure and load is analyzed, and then the stress concentration of tire / paved-surface interface contact under different working conditions is explained, as shown in figure 13 and figure 14.

As can be seen from figure 13, the change of tire pressure has little effect on the point of maximum stress, and the amplitude of variation is very small. Taking the fixed load as an example, the variation rate of maximum and minimum tire pressure is 58%, but the maximum stress difference between the maximum tire pressure and the minimum tire pressure is only 0.2 MPa, only accounts for 10% of the maximum tire pressure. From figure 14, the change of load has great influence on the point of maximum stress, and the amplitude of variation is obvious. Taking 600KPa fixed tire pressure as an example, the variation rate...
of maximum and minimum load is 65%, but the maximum stress difference between the maximum load and the minimum load is 0.99MPa, accounts for 37% of the maximum load. It can be seen from the figure that the tire pressure and load have a good correlation with the point of maximum stress, but the load is more correlated with it than the tire pressure.

![Figure 13. Relationship between tire pressure and maximum stress](image)

It can be concluded that under the same load, the change of tire pressure has little effect on the contact stress peak value. With the increase of load, the maximum value of tire/paved-surface contact pressure increases significantly. The effect of single wheel load on stress concentration is greater than that of tire pressure.

IV. CONCLUSIONS

In our research reported in this paper we used pressure film measurement technology to study the contact characteristics between tire and paved-surface under the real contact state. Different loads and tire pressures were selected as influencing factors; effective contact area, average pressure and stress concentration effect were used as evaluation indexes. The following research results were obtained:

Pressure film measurement technology has a good effect in reflecting the real contact characteristics between tire and paved-surface, and a complete set of test methods was initially formed. LLLW film and LLW film were used to jointly analyze the effective contact area and stress concentration effect.

In order to describe the contact degree between tire and paved-surface, we defined the tire and paved-surface contact impression rectangular rates and effective contact rectangular rates for quantitative analysis and engineering applications. The study found that: the smaller the tire pressure and higher the single-wheel load, the higher the tire and paved-surface contact impression rectangular rates is, and the more the tire and the paved-surface contact. The higher the tire pressure and the single-wheel load, the richer the coarse aggregate structure on the paved-surface, the higher the effective contact rectangular rates is, indicating that the higher the effective contact degree of the impression is.

The partially wrapped and embedded deformation of the tire on the coarse aggregate convex particles lead to stress concentration at the contact interface. The research found that stress concentration mainly occurs at the edge of tire pattern blocks of the grounded impression, especially at the toe of tire pattern.

The 95% fraction of the maximum value distribution of the tire/paved-surface contact stress can be used as the maximum pressure point. Based on this, the change regulation of tire pressure and load is analyzed, and then the stress concentration of tire/paved-surface interface contact under different working conditions is explained. Under the same load, the change of tire pressure has little effect on the contact stress peak value. With the increase of load, the maximum value of tire/paved-surface contact pressure increases significantly. The effect of single wheel load on stress concentration is greater than that of tire pressure.

**Author Contributions:** Nie Wen, Bo Chen, Li Wei-Xiong, Zhang Xiao-Ning, and Zhou Pei designed and conceived this study. Nie Wen and Bo Chen performed the experiments. Bo Chen wrote the paper. All authors approved this manuscript.

**Funding:** This research was supported by the “Fundamental Research Funds for the Central Universities” (2015ZZ074), the Guangdong Science and Technology Department plan project (2014B010105005), and the Guangzhou Science and Technology plan project (1563000255).

**Conflicts of Interest:** The authors declare no conflict of interest.
REFERENCES


