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Analysis and Optimization Design of the effect of Tread Pattern Structure Parameters on Tire Performance

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Abstract **– In this paper, the tread pattern directly determines the tire grounding performance. With the help of ABAQUS software and orthogonal test method, the influence of pattern structure parameters on tire performance is analyzed. It is found that the change of groove wall angle has a significant influence on tire grip and wear performance, and it is easy to aggravate the inherent contradiction between the two properties. Further analysis shows that the problem is mainly caused by the change of longitudinal stiffness of blocks. In order to solve this problem, the arch structure design method was used to optimize the shape of the transverse groove wall of the tire pattern. The results show that the arch structure design of the transverse groove wall can increase the longitudinal rigidity of the pattern block, reduce the deformation of the tire pattern during sliding and the peak ground pressure at the front end of the ground contact to a certain extent, and alleviates the inherent contradiction between tire grip and wear performance, and improves the two performances synergistically.**

Keywords **– Tires, Pattern Parameters, Arch Design, Grounding Performance.**

I. INTRODUCTION

The tread pattern is the component of the tire crown that directly contacts the ground, and the adhesion between the tire and the ground is also affected by its parameters. In vehicle braking, starting and other driving conditions, the tire tread deformation caused by force is the main factor affecting the difference of tire grounding pressure distribution, which further interferes with the tire grounding performance. At the same time, many scholars at home and abroad have also studied the effect of tread pattern on tire grounding performance.

Sridharan et al. [1] established six different types of tread blocks and analyzed the stress-strain characteristics of the tread blocks at different contact surfaces and deformation. The results showed that the pressure distribution of tread patterns with different structures was quite different. Wu et al. [2] studied the friction characteristics under different loads and contact pavements through a self-developed new friction device, and found that the road surface has the most significant influence on the friction coefficient, and there are certain rules for the friction characteristics of different tread patterns. Carbon et al. [3] generalized and analyzed the rubber contact mechanics and friction theory. The results show that the friction coefficient has a significant relationship with the sliding direction, while the relationship between the grounding area and the sliding direction is weak. Mundl et al. [4] found that the tread pattern can directly affect the stiffness of the tread, and the grip characteristics of the tire can be improved by adjusting the tread pattern type and shape. Hofstetter et al. [5] established a contact model suitable for the contact between rubber and rough pavement, analyzed the influence of different groove numbers and angles on the deformation and wear of pattern blocks, and further improved the wear analysis through the friction iteration method. Fu Jing [6] used the finite element method to analyze the geometry of the tire tread pattern, and proposed the bionic design of the transverse tread groove, which realized the improvement of the tire's grip performance. It can be seen from the above research that the tread pattern deformation and stiffness have a significant impact on the tire grounding performance, and the tire grounding performance can be improved by changing the pattern shape and stiffness.

In this paper, the influence of tread pattern structure parameters on tire performance is explored by finite element method and orthogonal test method, and the arch structure design method is used to optimize the tire tread pattern transverse groove wall, in order to improve the tire grounding performance.

II. ESTABLISHMENT OF FINITE ELEMENT MODEL OF PATTERN BLOCK

A. *Constitutive Model of Rubber*

The tread block finite element model built in this paper uses 205/55r16 radial tire tread rubber. As the material composition of tire rubber is complex and has a variety of nonlinear mechanical characteristics [7], Yeoh material constitutive model with low requirements for the total amount of test data but good fitting accuracy is selected for simulation [8-9], and its strain energy density function is:

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \tag{1}$$

Where, W is the strain energy density of the material; C_{10}, C_{20} and C_{30} are deformation tensors; I_1 is the first fundamental invariant of the material.

In order to obtain the corresponding parameters of Yeoh model, uniaxial tensile test was carried out on the tread to obtain the material data. The test equipment is gotech ai-7000m electronic tensile testing machine. The test is carried out by referring to the national standard gb/t 528-2009 [10]. The test ambient temperature is standard room temperature, the tensile rate is 1%/s, and the strain magnitude is 100%. In order to ensure the reliability of the tensile data, each rubber sample to be tested shall be subject to repeated tests for many times, and the average tensile value shall be taken. The tensile specimen adopts the national standard I dumbbell type, and its shape and specific dimensions are shown in Figure 1.

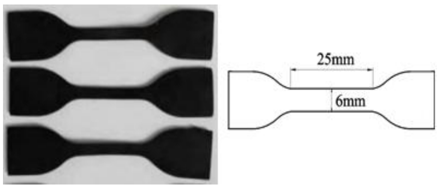


Fig. 1. Rubber tensile samples and dimensions.

Through the fitting toolbox of ABAQUS, the mechanical data obtained from the test are fitted, and the relevant parameters of Yeoh model are obtained. The fitting curve is shown in Figure 2. The compound parameters C10, C20 and C30 are 0.7110, -0.1659 and 0.0533 respectively.

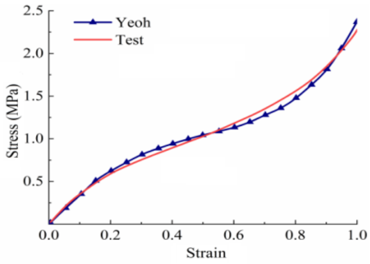


Fig. 2. Fitting curve of Yeoh model.

B. *Finite Element Model of Single Pattern Block*

Considering the efficiency of building a complete tire model simulation [11], this paper establishes a pattern block element model in the grounding area to analyze the mechanical properties of the pattern block. The pattern block of 205/55r16 radial tire is modeled by ABAQUS. The model is shown in Figure 3. The groove depth, longitudinal groove wall angle and transverse groove wall angle of the original design pattern block are 5.5 mm and 12 ° respectively.

Mesh the pattern block after modeling. In order to improve the accuracy of pattern simulation, the mesh near the ground end of the pattern block is refined. The model is shown in Figure 4. The pavement in the figure is rigid, and the number of pattern block elements and nodes are 1535 and 2007 respectively. In the simulation software, the load is applied to the pattern block and the degree of freedom at the bottom of the pattern block is constrained. Apply radial displacement to the rigid pavement to ensure the contact force between the pavement and the pattern block, and further set the upward concentrated force on the pavement to realize the application of load on the pattern block. The load size is set to 120 n. The sliding state of the pattern block on the road surface is simulated by horizontally pumping the rigid road surface, and the relative speed in the horizontal direction is set as 5 mm/s.

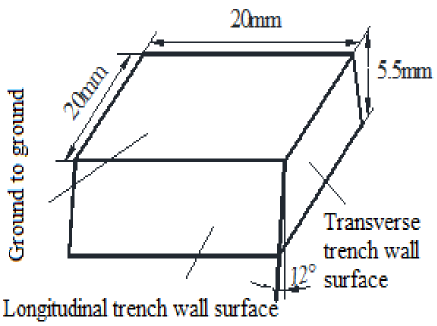


Fig. 3. Block solid model.

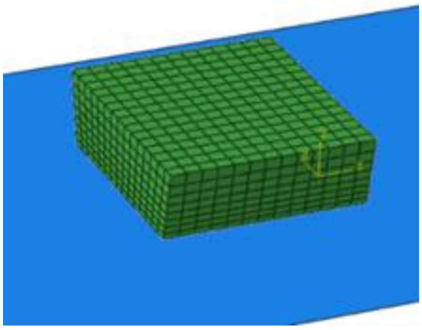


Fig. 4. Finite element model of pattern block.

III. ORTHOGONAL TEST ANALYSIS

A. *Orthogonal Experimental Design*

Orthogonal test is the most common and efficient test method, which can carry out reasonable parameter sampling from numerous test data and complete scheme combination [12]. In order to analyze the influence of the structural parameters of the pattern on the mechanical properties of the pattern block, the orthogonal experimental design of the pattern block parameters is carried out in this paper.

There are many geometric design parameters in the tire pattern design. Considering that the design parameters of the deformation stiffness of the pattern block mainly include groove depth and groove wall angle [13], this paper selects the groove depth and groove wall angle of the pattern as the research object. In the design of radial tire tread groove with section width of 205 mm, the groove depth is generally 0~8.5 mm [14], the value range of transverse groove wall angle is generally less than 10°, and the design of longitudinal groove wall angle is generally not less than transverse groove [15]. Therefore, the design factors of the orthogonal test are the groove depth a, the longitudinal groove wall angle B and the transverse groove wall angle c, and the level number of each factor is 3. L9 (34) orthogonal table combination test is selected to obtain 9 groups of test data, and the fac-

-tor level is shown in Table 1.

Table 1. Factor level table.

Factor	**Level**		
	1	**2**	**3**
A/mm	4.5	5.5	6.5
B/°	8	12	16
C/°	0	4	8

B. *Result analysis*

a. *Analysis of Tire Mechanical Properties*

The grounding characteristics studied in this paper are the traction performance and wear performance of tyres. Among them, the evaluation index of the grip performance and wear performance of the pattern block is the longitudinal grip between the pattern block and the pavement and the uniformity of the distribution of the grounding pressure. Among them, the uniformity of the grounding pressure distribution is calculated through the post-processing of the grounding pressure deflection value. The grounding pressure deflection value is inversely proportional to the wear uniformity of the pattern block [16], and the calculation formula is:

$$\alpha = \sqrt{\frac{1}{n-1}\sum\left(p_i - \bar{p}\right)^2} \tag{2}$$

Where, p_i is the pressure value at the i-th point in the contact surface; $\bar{p}$ is the average value of the pressure in the contact surface.

The test results are shown in Table 2. According to the data in the table, scheme 6 has the maximum grip, but at the same time, the corresponding ground pressure deflection value of this scheme is also the maximum, so there is a contradiction between grip and wear performance. The influence degree of design factors on target performance can be analyzed by analyzing the extreme value result R. if the value of R is larger, the influence of corresponding factors on target performance will be more obvious. The range analysis results are shown in Table 3. It can be seen that the horizontal groove wall angle has the most significant impact on the grip and grounding pressure deflection value of the pattern block, followed by the groove depth and the longitudinal groove wall angle. Figure 5 shows the main effect diagram of the three design factors. It can be seen from the figure that the increase of the groove depth in a small range has little impact on the grip. With the further increase of the depth, the grip is significantly improved. The grip has an approximately linear positive proportional relationship with the longitudinal groove wall angle, but the trend is opposite with the transverse groove wall angle; When the trench depth is large, the value of grounding pressure deflection decreases obviously, and has weak correlation with the value of longitudinal trench wall angle, but decreases significantly with the increase of transverse trench wall angle. From the range analysis results, it can be seen that the influence weight of the transverse groove wall angle on the grip and wear performance of the pattern block is greater than that of the groove depth and the longitudinal groove wall angle, and there is an obvious restrictive relationship between the two sexes. In order to analyze the mechanism of the influence of the angle of the transverse groove wall on the grounding performance of the checkered block, the change of its stiffness is analyzed.

Table 2. L 9$^{(34)}$ orthogonal table.

Plan	Factor			Traction /N	Grounding Pressure Deviation Value /MPa
	A/mm	B/°	C/°		
1	4.5	8	0	89.02	0.201
2	4.5	12	4	88.56	0.188
3	4.5	16	8	87.13	0.162
4	5.5	8	4	86.89	0.185
5	5.5	12	8	85.48	0.163
6	5.5	16	0	91.82	0.206
7	6.5	8	8	86.47	0.158
8	6.5	12	0	90.54	0.189
9	6.5	16	4	90.73	0.171

Table 3. Results of range analysis.

Extreme Result	Traction /N				Grounding Pressure Deviation Value /MPa		
	A	B	C		A	B	C
K1	88.24	87.46	90.46		0.184	0.181	0.199
K2	88.06	88.19	88.73		0.185	0.180	0.181
K3	89.25	89.89	86.36		0.173	0.179	0.161
R	1.19	2.43	4.10		0.012	0.002	0.038

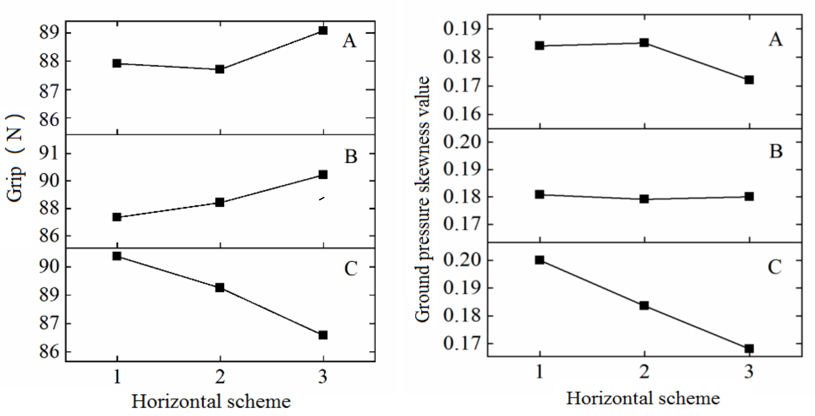


Fig. 5. Main effect diagram of each factor.

b. *Stiffness Analysis*

Figure 6 shows the influence curve of the angle of the transverse groove wall on the load displacement in each direction of the pattern block. Under the same load condition, the greater the displacement of the pattern block in different directions, the smaller the stiffness. It can be seen from the figure that with the increase of the angle of the transverse groove wall, the longitudinal, transverse and radial stiffness of the pattern block are improved, and the influence of the angle of the transverse groove wall on the longitudinal stiffness is the most significant.

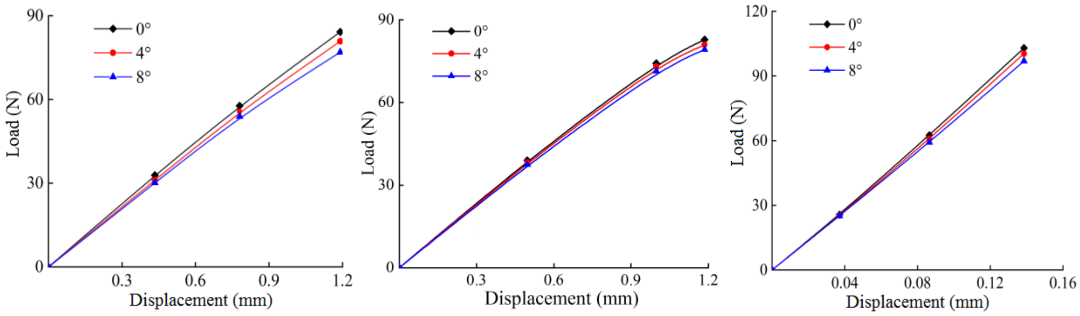


Fig. 6. Load-displacement curves of blocks with different transverse groove wall angles.

It can be seen from the curve in Figure 6 that the change of the angle of the transverse groove wall of the tread pattern has the greatest impact on the longitudinal stiffness of the tread pattern block. The change of the longitudinal stiffness makes the tread pattern block deform in varying degrees during the sliding process, resulting in obvious differences in the distribution of tire grounding pressure. The greater the longitudinal stiffness of the pattern block, the stronger the resistance to deformation during braking, with better wear performance, but the grip performance will be reduced. Therefore, the angle of the transverse groove wall of the tread pattern needs to be comprehensively selected, so that the tread pattern block can obtain the ideal longitudinal stiffness characteristics when braking and sliding, and reduce the grounding pressure deflection value while improving the tire grip, so as to achieve the purpose of alleviating the inherent contradiction between the tire grip and wear performance.

IV. SLIP GROUNDING ANALYSIS AND ARCH DESIGN OF CHECKERED BLOCK

The deformation of the pattern block during sliding is shown in Figure 7. Due to the tangential force in the driving direction, the pattern block grounding is prone to curl deformation, and is separated from the ground at the rear end of the grounding, resulting in insufficient adhesion to the ground at the deformed position of the pattern block, which reduces the effective grounding area of the tire, intensifies the uneven pressure distribution on the ground, and reduces the service life of the tire [17].

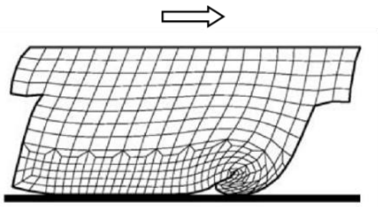


Fig. 7. Block grounding slip.

When the tire braking and the road surface slip relatively, the irregular deformation of the pattern block is mainly due to the large impact at the front end of the grounding, the rubber stiffness is not enough to withstand the rapid increase of pressure, and the curling deformation at the front end of the pattern block occurs under the combined action of the vertical load and the inertia in the slip direction. The main reason for the deformation of the rear end of the pattern block is that during the relative sliding process, the center of mass of the pattern block tilts forward, but the central area of the pattern block that does not directly contact the ground does not have obvious displacement. In order to balance the stress, the rear end of the grounding is warped.

Based on the above reasons, this paper designs from the structural dimensions of the pattern block. It plans to improve the longitudinal stiffness of the grounding front end of the pattern block, reduce the overall irregular deformation of the pattern block when the tire slips, increase the grounding area of the pattern block and reduce the grounding pressure deflection value at the same time, so as to achieve the purpose of improving the grip and wear performance of the pattern block.

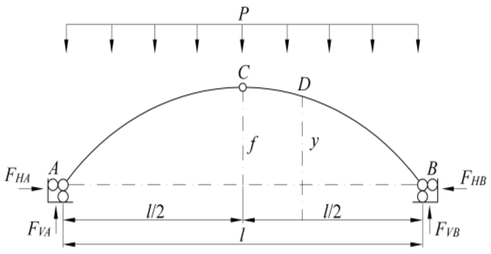
A. *Rational Curve Equation of Three Hinged Arch*

In structural mechanics, arch structure is a very typical and commonly used structure, which can be used for reference in all aspects of social construction [18]. Arch structure is also called thrust structure, which can decompose the vertical force into vertical reaction force and outward divergent thrust. This structure has strong deformation resistance. Therefore, this paper explores the application of arch structure to the design of tread block parameters, in order to improve the longitudinal stiffness of tread block, and analyze its impact on tire grip and wear performance.

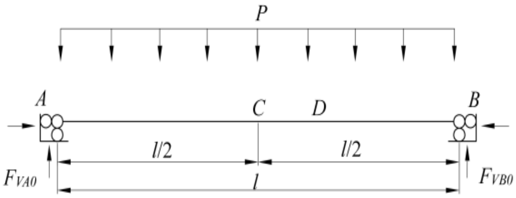
Among the arch structures, the three hinged arch is the most typical, which is a statically fixed arch structure. It is widely used in many aspects, such as bridge structure and infrastructure construction. In this paper, the edge structure of the transverse groove of the pattern block is redesigned based on the reasonable curve equation of the three hinged arch, and the mechanical properties and grounding state of the pattern block are analyzed.

Figure 8 (a) shows the stress diagram of three hinged arch. In the figure, AC and CB are arch curved bars, C is the connection point, and a and B are bottom hinged supports. Four forces will be generated under the action of vertical load P, the supporting force of point a F_{VA}, thrust F_{HA} and supporting force of point B F_{VB}, thrust F_{HB}. When the three hinged arch is in the balanced stress state, the stress characteristics are similar to those of the flat arch, which is often compared with the simply supported beam with the same mechanical characteristics, as shown in Figure 8 (b). The equation of reasonable arch axis of three hinged arch is:

$$y = -\frac{4f}{l^2}x^2 + \frac{4f}{l}x \tag{3}$$



(a) Three hinged arch.



(b) Simply supported beam.

Fig. 8. Stress diagram of three-hinged arch and simply supported beam.

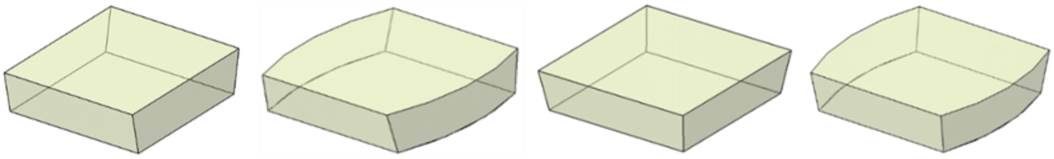
B. *Design and Analysis of Arch Shape of Cross Groove Wall with Pattern*

a. *Arch Design of Cross Groove Wall with Pattern*

According to formula (3), the shape of the reasonable arch axis has nothing to do with the magnitude of the load it bears. The equation curve is a parabola, and the shape of the curve is mainly affected by the value of F and L. therefore, this paper uses the reasonable arch axis curve equation of the three hinged arch to construct and design the shape of the cross groove wall.

Before drawing the curve, the scale relationship between f and l should be defined. The common value of the scale relationship between f and l is 1/10~1/2. The size of the grounding outer edge of the pattern block model is 20 mm, i.e. the value of l. Considering the value of sea land ratio of relatively fixed tire and the service performance requirements of transverse groove, the ratio of f/l in formula (3) is defined as 1/10, and then f is calculated as 2 mm.

In order to study the influence of the design of the arched structure of the patterned transverse groove wall on its mechanical properties and grounding state, this paper designs four model schemes for analysis. Scheme 1 is the original scheme, the angle of the transverse groove wall is 0°, scheme 2 designs the arched structure of the transverse groove wall on the basis of the original scheme, scheme 3 sets the transverse groove wall as 8°, and the other variables are consistent with the original scheme. Scheme 4 also designs the arched structure of the transverse groove wall on the basis of scheme 3. After calculation of each scheme, it is ensured that the grounding area of the pattern block is consistent with the original scheme. The models of the four design schemes are shown in Figure 9.

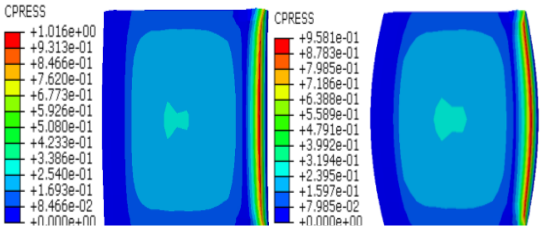


(a) Model 1 (b) Model 2 (c) Model 3 (d) Model 4

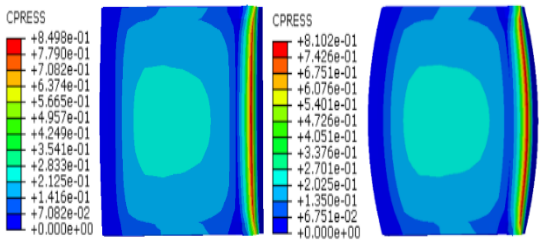
Fig. 9. Different design scheme models.

b. *Result Analysis*

The slip simulation is carried out for the pattern block designed in the above model scheme, and the grounding pressure distribution of the pattern block is obtained, as shown in Figure 10. Through the comparison of the grounding mechanical characteristics of each scheme, it can be seen that the arched structure design of the transverse groove wall reduces the peak grounding pressure at the front end of the pattern block, alleviates the stress concentration at the front end of the pattern block, and at the same time, the grounding pressure of the area of the grounding center is significantly increased, the grounding adhesion is enhanced, and the change of the angle of the transverse groove wall also follows the above law. Figure 11 shows the longitudinal stiffness curve of the checkered blocks of different schemes. It can be seen from the figure that the longitudinal stiffness of the transverse groove wall of the pattern block with the arch structure design is greater than that of the original scheme. When there is a sliding condition, the pattern block structure has stronger deformation resistance, which can improve the problems of the front end curling and the rear end cocking when the pattern block slips, and realize the stable contact between the pattern block and the ground.



(a) Option 1. (b) Option 2.



(c) Option 3. (d) Option 4.

Fig. 10. Ground pressure distribution in different design schemes.

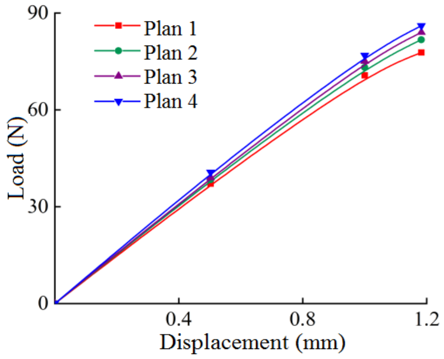


Fig. 11. Longitudinal stiffness curves of blocks with different schemes.

Table 4 shows the simulation data when the pattern block slips. When the transverse groove wall angle of the pattern is 0°, the grip and grounding area of the pattern block are increased by 2.04% and 8.19% respectively, the peak grounding pressure at the front end of the pattern block is reduced by 5.70%, and the grounding pressure deviation is reduced by 2.49%. When the transverse groove wall angle of the pattern block is 8°, the grip and grounding area of the arched design pattern block are also increased by 2.95% and 4.18% respectively, the peak grounding pressure at the front end of the pattern block is reduced by 4.71%, and the grounding pressure deviation is reduced by 1.81%. The above simulation results show that the grounding performance of the cross ditch wall patterned block with arch structure is improved in varying degrees.

Table 4. Simulation analysis results of different schemes.

Programme	**Grip/ N**	**Peak Grounding Pressure / MPa**	**Grounding Pressure Deviation Value / MPa**	**Grounding Area / mm2**
Option 1	90.12	1.016	0.201	316.71
Option 2	91.96	0.958	0.196	342.65
Difference	2.04%	-5.70%	-2.49%	8.19%
Option 3	85.87	0.850	0.166	341.39

Programme	Grip/ N	Peak Grounding Pressure / MPa	Grounding Pressure Deviation Value / MPa	Grounding Area / mm2
Option 4	88.40	0.810	0.163	355.65
Difference	2.95%	-4.71%	-1.81%	4.18%

V. CONCLUSION

In this paper, with the help of ABAQUS software and orthogonal test method, the influence of the structural design of the tread block on the tire grip and wear performance is analyzed, and the arch structure of the transverse groove wall of the tread block is designed. The analysis results show that:

1. The angle of the horizontal groove wall has the greatest influence on the grip and ground pressure deflection of the pattern block, followed by the depth of the groove and the angle of the longitudinal groove wall.
2. The change of the angle of the transverse groove wall mainly affects the longitudinal stiffness of the pattern block. The greater the longitudinal stiffness, the smaller the deformation of the pattern block during sliding, the better the wear performance of the pattern, but at the same time, it will lead to the reduction of the grip performance. The tire grounding performance can be improved through the reasonable design of the cross groove wall of the tread pattern.
3. The arch structure design of the transverse groove wall of the tread block can reduce the grounding pressure deflection value of the tread block in the grounding area, improve the grip and increase the grounding area, improve the irregular deformation of the tread block when sliding, and alleviate the inherent contradiction between the tire grip and wear performance.

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