Experimental Study of Effects of the Third Medium on the Maximum Friction Coefficient between Wheel and Rail for High-Speed Trains

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The changes of the friction coefficient between wheel and rail affect the wheel-rail adhesion characteristics of high-speed trains. The adhesion state in the wheel-rail contact area could be distinguished by the maximum friction coefficient between wheel and rail. Wheel-rail adhesion is of great significance for high-speed train traction. In order to study the influence of water, oil, fallen leaves, quartz sand, or their mixtures on the maximum friction coefficient between high-speed wheel and rail, a wheel-rail contact test bed is built to carry out the wheel-rail contact test and wheel-rail friction contact test. The comparative analysis of the test results shows that the axle load has little influence on the maximum friction coefficient between wheel and rail. Water, oil, and fallen leaves would reduce the maximum friction coefficient. Quartz sand could increase the maximum friction coefficient in a short time, while the excessive static friction coefficient would damage the wheel and rail. Besides, the maximum friction coefficient of water, oil, and fallen leaves mixing in pairs is lower than each of them existing alone. Both water and oil could increase the adhesion of quartz sand, and the effect of water is better. Therefore, when the sand still could not meet enough traction, it could be considered to add some water to increase the wheel-rail adhesion.

1. Introduction

With the rapid growth of the economy, the domestic demand for railway transportation is soaring. In recent years, China’s high-speed railway has made great strides from scratch to excellence. The Beijing-Tianjin intercity high-speed railway and the Wuhan-Guangzhou high-speed railway were put into operation in 2008 and 2009, respectively. By 2020, China’s high-speed railway operating mileage has exceeded 39,000 km, accounting for more than 70% of the global high-speed railway operating mileage. While the improvement of speed brings a lot of technical problems, one of which is the problem of high-speed wheel-rail adhesion. The wheel-rail sticking characteristics directly affect the traction performance, braking performance, and running quality of high-speed trains. The starting acceleration, deceleration, and stopping of high-speed emu are all directly related to the sticking characteristics [1].

There are two kinds of test bed, wheel-rail test bed and wheel-wheel rolling test bed. The former is closer to the actual working condition, but the equipment scale is larger and speed is limited. The latter is smaller, and the higher speed could be achieved, while there are some differences compared with the actual working conditions. On the one hand, Southwest Jiaotong University used a small-scale wheel-rail creep force test device of single wheelset to test the influence of wheelset motion position on the creep force of wheel-rail contact points [2]. On the other hand, Scholars have established wheel-wheel rolling test bed and studied the creep characteristics of the train [3, 4]. Liu et al. [5] has put forward a calculation method of friction coefficient based on the experimental platform designed by him. Gong and Zhou [6] have analyzed the influence of the single metallographic structure on the evolution law of the friction coefficient between wheel and rail and the influence of pearlite and martensite on the surface
characteristics of friction pair. Zhang et al. [7] have carried out the adhesion increasing test on the high-speed wheel-rail contact fatigue testing bed and given the best strategy of sanding amount and the sand diameter.

The existence of the third medium is one of the influencing factors for wheel-rail adhesion [8]. And, in practical operation, the existence of the third medium between wheel and rail is very common, such as rain, snow, lubricating oil, sand, and leaves.

Many experts and scholars at home and abroad have carried out numerous in-depth research studies on the influence of the third medium on wheel-rail adhesion. The studies have shown that different media have different effects on wheel-rail interaction. The surface roughness of wheel and rail with water media increases from 1 $\mu$m to 50 $\mu$m, and the adhesion coefficient increases by 126.5%. And, the surface roughness of wheel and rail with oil media increases from 5 $\mu$m to 20 $\mu$m, and the adhesion coefficient increases by 61.4%. The influence of the water medium on the wheel-rail adhesion coefficient is much greater than that of the oil medium, so oil pollution should be avoided in high-speed railway [9–12]. After the rail is added with water, the adhesion coefficient between the wheel and rail decreases. The amount of water spraying, the surface roughness of wheel-rail contact, and the running speed have a great influence on the adhesion coefficient of the wheel and rail under the condition of the water medium, while the temperature of spraying water and the axle load have a smaller influence. With the increase of velocity, the adhesion coefficient gradually decreases [13–16]. Some scholars have analyzed the effect of leaves on reducing adhesion and made some hypotheses on the mechanism [17, 18]. Chen et al. [19] used a twin-disc rolling contact machine to study the effect of water temperatures and surface roughness to the maximum traction coefficient. Gallardo-Hernandez et al. [20] used the twin-disc technique to study the influence of oil and water to the wheel/rail traction coefficients.

Although there were a lot of experimental studies on the third medium, most of the test beds used was wheel-wheel rolling, ignoring the influence of the diameter of wheel and rail on the contact state. And, most of the above research studies are based on the wheel-rail adhesion theory, and the adhesion coefficient is used to characterize the contact state. At present, the research on the adhesion coefficient has been relatively mature, and some scholars have proposed some methods for calculating the adhesion coefficient [21], while under the starting condition, the interaction between the wheel and rail is closer to the static friction. It is more reasonable to use the maximum static friction coefficient as the reference.

In this paper, a wheel-rail contact test bench is built to simulate the starting conditions of high-speed trains by using the method of experimental research. The test bed retains the original profile of wheel and rail, which could more truly reflect the contact state between wheel and rail. The relationship between longitudinal load and vertical load in different media is studied, and the influence of the third medium on the maximum static friction coefficient between wheel and rail is analyzed. This study proposes a new research method for the wheel-rail adhesion coefficient, which could provide experimental reference for railway operation and maintenance.

2. Wheel-Rail Contact Test Bed

2.1. The Structure of Test Bed. In order to study the contact between high-speed train wheels and rail, a wheel-rail contact test bed is built. The test bed could simulate the contact between wheel and rail in a real sense. And, the wheel and rail are used instead of the test blocks, which could make up for the disadvantages of the existing test bed, such as large size, high cost, and large maintenance.

The basic structure of the test bed is shown in Figure 1, and the physical picture is shown in Figure 2. The wheel-rail test bed involves hydraulic station, control box, and wheel-rail contact module. The hydraulic station provides the vertical and longitudinal force by the hydraulic cylinder. The lateral force could be applied by rotating the screw directly. The sensors measure the value of the force in three directions. The rail test block is installed on the foundation platform and could move along the longitudinal direction. The wheel test block is installed under the vertical limit plate. The wheel test block, vertical limit plate, and linear bearing flange can move along the optical axis in the vertical direction.

The test bench is powered by pushing the start button on the control box. The output force of the hydraulic cylinder is controlled by adjusting the output flow of the hydraulic station. The value of the force could be recorded by the paperless recorder in the control box.

2.2. Test Materials. The test materials include test block of rail and high-speed train wheel, quartz sand, oil, and water.

2.2.1. Rail Test Block. The rail test block is obtained from the 60 kg/m track purchased and laid on-site, which is processed by line cutting technology. The longitudinal length of the rail test block is 140 mm and the vertical thickness is 30 mm (measured from the top of the rail down), which is shown in Figure 3. During the test, the rail cant is 1 : 40.

2.2.2. Wheel Test Block. The wheel test block is obtained from high-speed train wheelset with profile S1002, which is also processed by line cutting technology. The longitudinal width of the wheel test block is 50 mm, and the vertical thickness is 30 mm (measured from tread to upward), which is shown in Figure 4.

2.2.3. Quartz Sand. Quartz sand whose basis is silicon dioxide is taken from the sand box of CRH380 B train, and its shape is shown in Figure 5.

2.2.4. Fallen Leaves. In autumn and winter, fallen leaves are common, and there is inevitable accumulation of fallen leaves along the railway. The fallen leaves are a kind of common “third medium.” In this paper, the fallen leaves of Chinese parasol trees are selected for the experiment, which are shown in Figure 6.
2.2.5. Oil. The Qiangli No.46 lubricating oil is selected for the experiment. The temperature of the oil is 25°C.

3. Experimental Study

3.1. Test Plan. The method of controlling variables is used in this paper. The problem of multiple factors could be changed into a problem of multiple single factors, and only one factor could be changed, so as to study the influence of this factor on things, respectively. Finally, a comprehensive solution is made.

Firstly, the test block with the same profile has been utilized and the wheel-rail is dry. The axle weight varies in the range of 12t, 13t, 14t, 15t, and 16t to explore the influence of axle weight on the maximum friction coefficient between wheel and rail in high-speed railway.

Secondly, to explore the influence of the third medium on the maximum friction coefficient between the high-speed wheel and rail, the test block with the same profile is used, and the axle weight is 14t. The third media include oil, water, quartz sand, oil-water mixture, oil-sand mixture, water-sand mixture, and oil-water-sand mixture.

Each experiment was repeated three times for analysis to exclude accidental factors. At last, the influence of axle load and third medium on the wheel-rail contact state is studied.
3.2. The Experimental Procedures

3.2.1. Explore the Influence of Axle Weight on the Maximum Friction Coefficient

(a) Install the test block and adjust the position of the test block to ensure that the test block is installed firmly
(b) Open the vertical cylinder switch, open the oil valve, adjust the pressure regulating valve, and carry out the axle load
(c) Open the longitudinal cylinder switch, open the oil valve, adjust the pressure regulating valve, and gradually increase the longitudinal load until the relative movement between the wheel and rail occurs
(d) Close the oil valve, remove the test block, and record the data
(e) Repeat the above steps twice
(f) Change the axle load and repeat the above procedures

3.2.2. Explore the Influence of Different Media on the Maximum Friction Coefficient

(a) A third medium is evenly applied to the surface of the rail test block
(b) Install the test block and adjust the position of the test block to ensure that the test block is installed firmly
(c) Open the vertical cylinder switch, open the oil valve, adjust the pressure regulating valve, and load the axle load of 14 t
(d) Open the longitudinal cylinder switch, open the oil valve, adjust the pressure regulating valve, and gradually increase the longitudinal load until the wheel and rail have relative movement
(e) Close the oil valve, remove the test block, and record the data
(f) Repeat the above steps twice
(g) Change other third medium again, and repeat the above steps

When the experiments are all finished, the test bench should be cleared up.

4. Reliability Analysis of Test Bed

To verify the reliability and accuracy of the test bed, the wheel-rail contact patch in the center position got from the experiment is compared with the simulation results. The center position is that the wheel-rail relative lateral displacement is 0 mm. The axle load is 14 t. In the process of the experiment, pigment is used to show the contact patch.

4.1. Experimental Results Analysis. The wheel-rail contact patch in the center position is shown in Figure 7. Its shape is similar to ellipse. The lateral length of the contact patch is 10 mm, and the longitudinal length is 18 mm. But the center point of the longitudinal axis is not the same with that of the lateral axis.

4.2. Finite Element Model Established. The finite element analysis of the wheel-rail relationship at the center position is carried out. The profile measuring instrument is used to measure the profiles of wheel and rail test blocks. Figure 8 shows the measured wheel tread profile of high-speed train and rail profile.

The three-dimensional finite element model of wheel and rail is established by software ABAQUS with the measured profiles of the blocks, which is shown in Figure 9. For reducing the calculation time under the premise of ensuring the calculation accuracy, the wheel and rail models are divided into contact area and noncontact area, respectively. The mesh of the contact area is hexahedron with side length of 1 mm. The mesh size of the noncontact area increases gradually. The wheel-rail models have 92297 nodes and 119198 elements in total.

The stress-strain curve of wheelset and rail is shown in Figure 10. Young’s modulus of wheel is 206 GPa, Poisson’s ratio is 0.3, and yield limit is 627.8 MPa. Young’s modulus of rail is 210 GPa, Poisson’s ratio is 0.3, and yield limit is 565.3 MPa. Penalty friction is used to simulate the contact relationship between wheel and rail, and the friction coefficient is determined by the test results. The axle load is applied at the axle box position, and a force couple is applied at both ends of the wheelset. The value is determined by the longitudinal load curve obtained by the paperless recorder during the test. The translation of x-axis and rotation around y-axis and z-axis of wheelset are constrained, and full constraint is applied at the bottom of rail.

4.3. Comparison between the Experimental and the Simulation Results. Figure 11 shows the contact patch of the simulation result in the center position. The shape of the contact patch is also similar to the ellipse. The lateral length of the contact patch is 8.513 mm, and the longitudinal length is 16.106 mm.

The results of finite element calculation are slightly less than the experimental results because the pigment used in the experiment is liquid and there is a layer of oil film on the surface of liquid. The oil film breaks and diffuses in the extrusion process, which has a certain influence on the experimental results. From the viewpoint of contact patch, simulation and experiment have verified each other. The test bed could be used to calculate the friction coefficient between wheel and rail.

5. Results and Analysis

5.1. The Influence of Axle Load on the Maximum Friction Coefficient. When the longitudinal force increases to make the wheel and rail slide relatively, the static friction changes into sliding friction. The maximum longitudinal force is related to the maximum friction coefficient, so only the error line is given at the maximum longitudinal force.
Figure 12 shows the change of longitudinal load of wheel and rail in dry condition under the action of different axle loads. Under the action of a certain axle load, the vertical force on the rail is constant, and the longitudinal force is gradually increased. The trend of longitudinal force with time is observed.

Figure 12 shows that, with the change of axle load, the longitudinal load have similar changing rules with the increase of time. The longitudinal load shows linear growth in the early stage and tends to be stable after reaching a specific value.

In the early stage, the wheel and rail are relatively static. When the longitudinal load is greater than the maximum static friction force between wheel and rail, the wheel would slide on the rail, and the longitudinal load tends to be stable.

The maximum friction coefficient between wheel and rail under different axle loads is calculated and listed in Table 1.

From the data in Table 1, under dry conditions, the maximum friction coefficient between wheel and rail is between 0.42 and 0.48. With the increase of axle load, the maximum friction coefficient between rail and wheel does not change obviously.

Figure 13 shows the state of the wheel test block after the test in the dry state. When the wheel and rail are dry, the relative sliding between them would cause slight wear of tread.

\[ \mu = \frac{F}{P} \]  

where \( \mu \) is the maximum friction coefficient, \( F \) is the maximum longitudinal load, and \( P \) is the vertical load.

The calculation formula of the maximum friction coefficient is

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Figure 13 shows the state of the wheel test block after the test in the dry state. When the wheel and rail are dry, the relative sliding between them would cause slight wear of tread.
5.2. The Influence of the Third Medium on the Maximum Friction Coefficient. Nothing, water, oil, sand, or fallen leaves exists alone between the wheel and rail, and the maximum friction coefficient is shown in Figure 14.

When there is water between wheel and rail, the maximum friction coefficient is 0.32, which decreases by 27.27% compared to the dry state. When oil exists alone between wheel and rail, the maximum friction coefficient is 0.3, which decreases by 31.82% compared to the dry state. And, when quartz sand exists between wheel and rail, the maximum friction coefficient is 0.98, which increases by 122.73% compared to the dry state. When leaves exists alone, the

| Axle load | 12 t | 13 t | 14 t | 15 t |
|-----------|------|------|------|------|
| Maximum friction coefficient | 0.42 | 0.43 | 0.46 | 0.48 |
maximum friction coefficient is 0.24, which decreases by 45.45% compared to the dry state.

Water, oil, and fallen leaves would reduce the maximum friction coefficient between wheel and rail, while quartz sand would significantly increase the maximum friction coefficient. This is because a small amount of water mixed with oxides between wheel and rail would result in low adhesion [22]. After the oil is extruded, a layer of oil film is formed between the wheel and rail, which results in the decrease of the maximum friction coefficient. So, water and oil should be avoided as much as possible during the operation of high-speed trains.

Figure 15(a) shows the state of the quartz. After the quartz sand is extruded, it forms into the powder and gets attached to the wheel and rail, which greatly increases the surface roughness, resulting in a significant increase in the maximum friction coefficient. The use of quartz sand could rapidly increase the maximum friction coefficient in a short time, thus ensuring sufficient traction of the train.

Figure 15(b) shows the wheel test block after the test when quartz sand is used. It could be seen that there is an obvious scratch on the surface of the wheel test block. Quartz sand could increase the friction coefficient between wheel and rail, but it would damage the wheel at the same time, so it should be used carefully in the process of operation.

5.3. The Influence of the Mixture of the Third Medium on the Maximum Friction Coefficient. In practice, there might be a mixture of two or even three media between wheel and rail. Figure 16 shows the maximum friction coefficient when different media are mixed.

When the mixture of water and leaves exist between wheel and rail, the friction coefficient is 0.18. It is 43.75% lower than that of water alone and 25% lower than that of the leaves alone. It shows that the wet fallen leaves between the wheel and rail would do great harm to the train traction. More attention should be paid to the cleaning of fallen leaves on the rail surface after raining.

Figure 17(a) shows the state of leaves and water after the experiment. Because the leaves become much softer after being soaked in water, they will not break like dry leaves during the test. But the more complete leaf covering on the rail would greatly reduce the wheel-rail adhesion coefficient. Therefore, there are fallen leaves between wheel and rail in rainy days being easy to cause insufficient traction.

When oil and leaves act at the same time, the maximum friction coefficient between wheel and rail is 0.23. The maximum friction coefficient of the mixture is 23.33% lower than that of the oil alone and 4.17% lower than that of the leaves alone.

The maximum friction coefficient between wheel and rail is 0.56 when the mixture is the fallen leaves and quartz sand. It increases by 1.33 times compared with that of leaves alone, while decreases by 42.86% compared with that of quartz sand alone.

Figure 17(c) shows the state of leaves and quartz sand. It could be seen that when the fallen leaves and quartz sand are crushed, there are some quartz sand particles on the surface of the leaves which could improve the adhesion reduction caused by the leaves piling up.

Above all, the friction coefficient of water, oil, and fallen leaves mixing in pairs is lower than each of them existing alone. All of them have different degrees of function of adhesion reduction. The adhesion reduction caused by leaves is the most obvious.

The maximum friction coefficient is 1.59 when there is water and quartz sand between wheel and rail. Compared with the water medium alone, the maximum friction coefficient increased by 4 times. In rainy days, the insufficient traction caused by wet surface of rail could be alleviated by sanding operation. The maximum friction coefficient increases by 62.24% compared with that of quartz sand. Therefore, the water medium has a certain adhesion increasing effect on quartz sand.

Figure 18(a) shows the state of the water and quartz sand after the test. Quartz sand and water are mixed and then extruded to form a paste. Compared with quartz sand alone, there is no compact caking after extrusion. Therefore, adding water to quartz sand could increase the adhesion.

When oil and quartz sand act at the same time, the maximum friction coefficient between wheel and rail is 1.45. It increases by 3.8 times compared with that of oil alone and increases by 47.96% compared with that of quartz sand alone.

Figure 18(b) shows the state of oil and quartz sand after test. The mixture forms loose caking after being rolled, which is different from the substance formed when quartz sand acts alone. Due to the oil mixing, the massive substance does not form a tight surface layer.

When water, oil, and sand act simultaneously, the maximum friction coefficient between wheel and rail is 1.63. It is 4.1 times higher than that of the water alone, 4.43 times higher than that of the oil alone, and 66.33% higher than that of the quartz sand alone.

Above all, it shows that quartz sand could improve the traction shortage caused by water and oil. Both water and oil could increase the adhesion of quartz sand, and the effect of water is better. Water and oil acting simultaneously has the largest impact on the adhesion of quartz sand.

6. Discussion

In order to study the influence of the third medium on the maximum friction coefficient between the wheel and rail in high-speed railway, a wheel-rail contact test bed is designed to simulate the train starting condition. Water, oil, quartz sand, deciduous leaves, or their mixture are added between the wheel and rail, respectively. The maximum friction coefficient between wheel and rail is determined by
Figure 15: The state of wheel and rail when quartz sand exists alone. (a) Rail. (b) Wheel.

Figure 16: Maximum friction coefficient when different media are mixed.

Figure 17: Continued.
calculating the ratio of the maximum longitudinal force and the vertical force. It suggests that the axle load has little effect on the maximum friction coefficient between wheel and rail under dry condition. Water, oil, and leaves could greatly reduce the maximum friction coefficient, and quartz sand could increase the maximum friction coefficient. When quartz sand is mixed with the third medium above, respectively, the maximum friction coefficient could be increased.

When the high-speed train is running, there is rain, snow, sanding, lubricating oil, and other third media on the track inevitably. These third media could affect the adhesion state between the wheel and rail. When the adhesion is insufficient, the wheel would idle and the wheel and rail would be easy to damage. By calculating the maximum friction coefficient under different third media, some suggestions are put forward. When there is water, oil, and other third media on the rail, it should be cleaned in time to avoid the reduction of wheel-rail adhesion. Quartz sand should be used reasonably to increase the adhesion. Besides, when the adhesion increased by quartz sand is insufficient, it could be considered to add some water between wheel and rail.

This paper only studies four common third media, water, oil, fallen leaves, quartz sand, or their mixture between wheel and rail, but there are also many other kinds of media in the actual operation process. In the following research, the type of third medium should be increased. The maximum friction coefficient corresponding to each third medium should be analyzed by the experiment. The results would be made into a table for reference to better put forward the operation and maintenance suggestions for the railway transportation.

7. Conclusion

In this paper, a wheel-rail contact test bed has been built to simulate the starting condition of high-speed train. The influence of water, oil, fallen leaves, quartz sand, and their mixture on the maximum static friction coefficient between wheel and rail has been studied by utilizing the test bed. The following conclusions are drawn:
(1) Under the dry condition, the maximum friction coefficient between wheel and rail is between 0.42 and 0.48, and the influence of axle load is very small.

(2) Under the action of water, oil, and fallen leaves, the maximum friction coefficient between wheel and rail changes from 0.24 to 0.32, which is 27.27%–45.45% lower than that between dry wheel and rail. Under the action of quartz sand, the friction coefficient is 0.98, which is 122% higher than that between dry wheels and rails. That is, when the third medium acts alone, water, oil, and fallen leaves have the function of reducing adhesion, while quartz sand has the opposite function.

(3) The friction coefficient of water, oil, and fallen leaves mixing in pairs is lower than each of them existing alone. All of them have different degrees of function of adhesion reduction. The adhesion reduction caused by leaves is the most obvious. Both water and oil could increase the adhesion of quartz sand, and the effect of water is better. Water and oil acting simultaneously has the largest impact on the adhesion of quartz sand.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that they do not have any conflicts of interest.

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References
[1] H. Hu and G. T. Yang, “Research status and innovative development planning of high-speed rail relations in China,” China Railway, vol. 56, no. 11, pp. 1–9, 2017.
[2] C. Y. Zhou, J. B. Wang, and C. Y. Chang, "Establishment and verification of simulation model for high speed wheel rail relationship test bed," Railway Locomotive Cars, vol. 37, no. 1, pp. 61–64, 2017.
[3] L. Shi, Q. Li, and J. Guo, "Adhesion-creep curve characteristics of wheel/rail under various conditions," Journal of Mechanical Engineering, vol. 55, no. 10, pp. 151–157, 2019.
[4] Y. T. Hu, S. H. Zhang, and X. M. Yao, "Adhesion test of wheel/rail based on lateral creep characteristics," Lubrication Engineering, vol. 45, no. 9, pp. 78–82+112, 2020.
[5] H. L. Liu, X. H. Wang, and X. P. Xie, "A measuring method of friction coefficient based on wheel-rail friction testing device," Lubrication Engineering, vol. 41, no. 12, pp. 107–111, 2016.
[6] Y. F. Gong and Y. S. Zhou, "Experimental research on friction wear of wheel-rail material under single metallographic structure," Journal of Shandong Agricultural University (Natural Science Edition), vol. 50, no. 3, pp. 520–523, 2019.
[7] Z. X. Zhang, J. Tan, and S. C. Huang, “Test on the best sanding and viscosity increasing strategy of high speed wheel/rail under complex operation environment,” Acta Railway Sinica, vol. 41, no. 2, pp. 123–130, 2020.
[8] W. J. Wang, H. F. Zhang, and Q. Y. Liu, “Progress and simulation test of high-speed wheeling and rail adhesion mechanism,” Lubrication Engineering, vol. 36, no. 11, pp. 105–108, 2011.
[9] B. Wu, Z. F. Wen, H. Y. Wang et al., "Research on influencing factors of high-speed wheel-rail adhesion," Acta Railway Sinica, vol. 35, no. 7, pp. 18–22, 2013.
[10] W. J. Wang, H. Wang, J. Guo et al., "Effect of surface roughness on wheel and rail adhesion," Journal of China University of Mining and Technology, vol. 43, no. 1, pp. 107–112, 2014.
[11] B. Wu, Z. F. Wen, H. Y. Wang et al., "Three-dimensional numerical analysis of the adhesion characteristics of wheel rail oil pollution," Acta Railway Sinica, vol. 35, no. 7, pp. 26–31, 2013.
[12] P. Shen, H. F. Zhang, Q. F. Zeng et al., "Study on wheel-rail adhesion characteristics under oil pollution conditions," Lubrication Engineering, vol. 37, no. 3, pp. 25–28, 2012.
[13] J. H. Song, P. Shen, W. J. Wang et al., "Experimental study on the adhesion characteristics of wheel and rail under water medium," China Railway Science, vol. 31, no. 3, pp. 52–56, 2010.
[14] C. Y. Chang, B. Chen, Y. W. Cai et al., "Experimental study on adhesion characteristics of high-speed wheel-rail under water-medium condition based on full-size test bed," China Railway Science, vol. 40, no. 2, pp. 25–32, 2019.
[15] C. Chang, B. Chen, Y. Cai, and J. Wang, "An experimental study of high speed wheel-rail adhesion characteristics in wet condition on full scale roller rig," Wear, vol. 440-441, Article ID 203092, 2019.
[16] L. E. Buckley-Johnstone, G. Trummer, P. Voltr et al., "Assessing the impact of small amounts of water and iron oxides on adhesion in the wheel/rail interface using High Pressure Torsion testing," Tribology International, vol. 135, pp. 55–64, 2019.
[17] K. Ishizaka, S. R. Lewis, and R. Lewis, "The low adhesion problem due to leaf contamination in the wheel/rail contact: bonding and low adhesion mechanisms," Wear, vol. 378-379, pp. 183–197, 2017.
[18] H. Chen, T. Furuya, S. Fukagai et al., "Wheel slip/slide and low adhesion caused by fallen leaves," Wear, vol. 446-447, Article ID 203187, 2020.
[19] H. Chen, T. Ban, M. Ishida, and T. Nakahara, "Experimental investigation of influential factors on adhesion between wheel and rail under wet conditions," Wear, vol. 265, no. 9-10, pp. 1504–1511, 2008.
[20] R. Gallardo-Hernandez, E. A. Gallardo-Hernandez, T. Hilton, and T. Armitage, "Effect of oil and water mixtures on adhesion in the wheel/rail contact," Proceedings of the Institution of Mechanical Engineers—Part F: Journal of Rail and Rapid Transit, vol. 223, no. 3, pp. 275–283, 2009.
[21] Q. Y. Huang, "Adhesion coefficient of railway wheel and rail," Railway Locomotive Cars, vol. 30, no. 5, pp. 17–25+33, 2010.
[22] L. E. Buckley-Johnstone, G. Trummer, P. Voltr, K. Six, and R. Lewis, "Full-scale testing of low adhesion effects with small amounts of water in the wheel/rail interface," Tribology International, vol. 141, Article ID 105907, 2020.