AN INVESTIGATION ON THE DESIRED PROPERTIES OF FRICITION MODIFIERS FOR SLIPPERY RAILS

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ABSTRACT

The adhesion level between wheel and rail has been since the beginning of railway a crucial parameter in the design and operation of rail vehicles. In the last decades, many railway organizations have suffered from low adhesion problems as consequence of the increased exploitation of the rail infrastructure. Leaves and water have been widely reported as major causes of low adhesion. Among the practical measures adopted, friction modification is one of the most popular used to enhance adhesion levels to the required minimum during traction and braking. In this paper, some results of investigations carried out with two friction modifiers are presented. Further, some of the desired properties of the friction modifiers to optimally overcome the slippery rails problem are discussed.

1. INTRODUCTION

The adhesion between wheel and rail is a crucial factor in the operation of the railway industry. In order to have an adequate braking and traction performance of the train, a minimum level of adhesion is required. On the other hand, very high friction may lead to other problems such as excessive wear and rolling contact fatigue. The adhesion required for braking and traction depends on the train type, the train composition, and the traction control and wheel slide protection systems (if available). In the last decades, there exists a more intensive exploitation of the railway networks that requires higher traction and braking efforts. Accordingly, the traction and braking capabilities of rail vehicles have been improved. On the other hand, the nature of steel-on-steel frictional contact between wheel and rail remain unchanged. Low adhesion problems have therefore been rising in the many railway networks around the globe. When low adhesion occurs, delays in the train service are the clearest consequence to the railway users. However, many other negative effects can arise, such as damages to wheels and rails, signals passed at danger, station platform overruns and, even, collisions. Therefore, not only the punctuality, but also the safety of the passengers may be threatened if low adhesion situations are encountered.

In order to fight low adhesion, some practical measures have already been applied in the affected countries, such as vegetation management, rail cleaning, and friction modification [1-2]. Sanding has been used on railway networks since the beginning of the railways to improve the adhesion of locomotives. Lately, some railway organizations have also fitted sanders in their electric multiple units (EMUs) to alleviate the low adhesion problems. In countries such as the United Kingdom and the Netherlands, friction modifiers (FMs) have been tested in field and used during the last years [2-3]. Despite all the practical measures, the low adhesion problem still persists.

In this paper, some of the results of laboratory investigations on two FMs are presented. Some of the desired properties of FMs to enhance the adhesion in wet and leaf contaminated contacts are discussed.

2. PAST RESEARCH IN WHEEL-RAIL ADHESION

The adhesion between wheel and rail depends on many factors, such as (micro-) slip between wheel and rail, contamination, vehicle speed, contact pressure and roughness of the wheel and rail surfaces (among others). The major cause of decreased wheel-rail adhesion is water and natural contamination. Rust, oil, and leaves have been identified as the main responsible contaminants [4-5]. Particularly, the combination of leaves and a small amount of water has been reported to bring the lowest adhesion levels [1].
Several studies on wheel–rail adhesion in leaf contaminated wheel-rail contacts have already been conducted both in laboratories and in field tests. A report on low adhesion published by the Rail Safety and Standards Board (RSSB) gives a good overview of the research and findings on leaf-related adhesion problems in the last decades [3]. Recently, full-scale tests were carried out in which the leaf layer properties were examined before and after the application of two buffer solutions of different PH values [6]. Previously, a study into the characteristics of the leaf layer contamination was carried out by AEA Technology Rail (DeltaRail Group) in UK [7]. Furthermore, laboratory tests to investigate the friction behavior in leaf contaminated contacts have also been carried out with pin-on-disk [8], ball-on-disk [9], and twin-disk [10] rigs.

3. TEST DESCRIPTION

In the Netherlands and the UK, an FM derivate of sand has been used in the last years, referred as FMB in this paper. It is a mixture of an inorganic gelling agent, stabilizer, water, sand grains and stainless steel particles. The gelling agent promotes the adherence of the mix to the wheel and rail surface, whereas the stabilizer provides a reasonable storage life. The stainless steel particles guarantee good electrical conductivity of the mix so that train detection by track circuit is not impaired. This paper presents and discusses some of the results of the laboratory investigations carried out with FMB in controlled dry, wet, and leaf contaminated contact conditions [11-12]. Another friction modifier, which is named FMA in this paper, was also tested because it was considered that a potential substitute of FMB may be derived from it. Fig. 1 displays the test disks when the FMs were applied on the rail disks. Furthermore, a baseline test was carried out to compare the performance of both FMs with the untreated conditions.

The wheel-rail contact was simulated under closely controlled laboratory conditions with the SUROS (Sheffield University Rolling Sliding) roller rig, which is explained in detail in [13]. Fig. 2 shows the disks interface in the SUROS roller rig. In order to simulate wet wheel-rail contacts, one single drop of water was applied on top of the rail disk for each test. In the tests with leaf contamination, leaves were fed by hand to a chute and a suction system ensuring that they were entrained in the disks interface, as indicated in Fig. 2. It must be noted that wet and leafy tests were not combined in this work so that no water was applied during the leaf contamination feeding. Furthermore, the FMs were painted onto the rail surface in tests aiming at investigating its performance in dry and contaminated conditions. The FMs were painted prior to the application of contamination in the wet tests (preventive approach), while it was painted on the leaf layer covered disk in the leafy tests (reactive/corrective approach). More details can be found in [11-12].

![Fig. 1 Photographs of the tested FMs applied on the rail disk surfaces of the SUROS roller rig: (a) FMA and (b) FMB.](image)

![Fig. 2 Schematic representation of the disk interface and application of different contamination in the SUROS roller rig.](image)

4. CHARACTERISTICS OF LEAF LAYER

Leaf fall in autumn can lead to large amounts of leaves in the railroads. With every wheel passage, the leaves are crushed forming a black layer on the top of rail. The leaves are crushed forming a black layer on the top of rail. The transportation and logistics division of the Japan Society of Mechanical Engineers (JSME)
water content plays an essential role in the formation of the black layer as well as its characteristics. It has been reported that in dry conditions the black layer is hard, brittle and difficult to remove [1]. In combination with slight moisture the black layer swells, softens and can become very slippery. The shear strength of the leaf layer has been found to be inversely proportional to the moisture level [7]. On the other hand, large amounts of water during heavy rain may dissolve the black layer and wash it away. An additional advantage of heavy rain is that wet leaves are heavier and, therefore, less prone to be swept up onto the railheads. Fig. 3 depicts a characteristic adhesion test in dry wheel-rail contacts. Once the disks are put in touch, the adhesion coefficient initially increases sharply until the nominal slip (0.5% in this test) is reached. Further increase in the adhesion coefficient is due to the surface conditioning, also known as run-in, of the disks surfaces. Once the adhesion coefficient reached its steady state, leaves were fed at the disks interface. It can be seen in Fig. 3 that during the leaves feeding low values of adhesion were obtained. As a consequence of their entrapment during the rolling-sliding contact, leaves were compacted and sheared and, black leaf layers were formed on the disks surfaces, as shown in Fig. 4. Note that there was also remaining leaf mulch that did not transform into black leaf layer, as pointed out in Fig. 4.

Once leaf layers were formed, post-test analysis was carried out to examine two crucial parameters of the layers: hardness and thickness. These two parameters may play an essential role in the effective removal of the layer by the type of FMs which use the mechanical interaction between the contamination layer and the FMs for the enhancement of the adhesion, such as the two discussed in this paper. The hardness of the remaining layer after each test was measured by means of Vickers micro-indentation technique; average values between 47-68 HV10g were obtained depending on the degree of compaction of the layer [11]. These values are in line with those obtained in twin-disk tests published by other researchers [10]. Full-scale tests in the UK showed that the hardness of the leaf layer varied between 1 and 7 in the Mohs’s scale of hardness [7]. The variation was identified to be due to the degree of compaction of the layer, the water content and the constituents of contamination present in the mixture.

Furthermore, the thickness of the post-test leaf layers of our tests was measured with an optical 3D profiling system WykoNT3300 (Veeco Metrology Group, USA) [11]. The values of thickness ranged 3-13 µm. It must be noted that leaf mulch can be much thicker (around hundreds of microns) and if not removed may develop into black leaf layer. Measurements of leaf layers found on the Dutch network ranged from 20 to 30 µm. In full-scale testing carried out in the UK the thickness of the generated layers ranged from 10 to 100 µm [7]. Hence, the thickness of the leaf layer is larger than the surface roughness of wheels and rails in most of the cases. This implies that the metal surface asperities of wheel and rail may not be in touch with each other in the presence of a leaf layer.

5. INVESTIGATING THE PROPERTIES OF FRICTION MODIFIERS FOR SLIPPERY RAILS

The friction available and exploited between wheel and rail during braking and traction is known in the railway terminology as adhesion. Traction and braking require high friction level. But high friction is usually accompanied by wear, rolling contact fatigue (RCF), noise and rolling resistance. Surface initiated RCF is particularly a major problem [14]. Because the maximal shear stress at rolling contact will shift from sub-surface to surface when the coefficient of friction (COF) exceed 0.3, the COF should not be higher than 0.3 from RCF prevention point of view. Fig. 5 depicts a typical adhesion curve in dry clean wheel-rail contacts obtained with the SUROS roller rig [12]. It can be seen that the peak in the adhesion coefficient, i.e. COF = 0.6, is reached at around 2% slip for the conditions used in this study. Note that ideal laboratory clean conditions may
hardly be reached on the actual track, thus lower COF is usually present. Values around 0.3 in apparently clean dry rails have been reported to be typical in field [1]. Moreover, it must be noted that the adhesion requirements of the rolling-stock vary for braking and traction, with adhesion coefficients as high as 0.3 in traction and 0.15 in braking for EMUs.

![Fig. 5 An adhesion curve in clean wheel-rail contact on SUROS.](image)

When applying an FM to achieve a desired friction level, the minimum number of axle passages with which the FM can maintain the desired level needs to be known. In this way, railway organizations can estimate the frequency of the FM applications. It is obvious that ideally an FM should have a lasting effect as long as possible. Suitable adherence to the rail is a desired property to ensure long lasting effect. Some FMs may contain polymeric components that enhance the bonding to the railhead [12]. In Fig. 6 the lasting effect at 1% slip of the two FMs tested is shown. It can be seen that FMA seems to have longer lasting effect as the adhesion coefficient increases continuously with the test cycles. FMA shows a less strong bond to the steel surfaces, in such a way that after about 1000 cycles the increase of the adhesion level is already flattened.

![Fig. 6 Adhesion coefficient in clean wheel-rail contacts at 1% slip with baseline (no FMs), FMA and FMB [12].](image)

Since most of the low adhesion incidents are water related, suitable adhesion behavior of an FM in wet contacts is desired. One of the most important characteristics is the recovery time, which is defined as the number of cycles required to recover the adhesion coefficient to the level prior to the water application after a drop of water is applied to the contact. Fig. 7 depicts an adhesion recovery test at 1% slip once water has been applied at the disks interface [12]. It can be seen that the recovery time of both FMs is better than the baseline, but FMA has a remarkably shorter recovery time.

![Fig. 7 Adhesion tests with one drop of water at 1% slip, without leaf contamination [12].](image)

The adhesion recovery enhancement with FMs under leaf contaminated conditions, i.e. with a black leaf layer on the disks surfaces, was investigated. Fig. 8 shows the results of the tests carried out at 1% slip [11]. Note that a Baseline-dry is given that represents the uncontaminated dry conditions, while the Baseline is leaf-contaminated, but without FM being applied. It can be seen that the best adhesion recovery is obtained with FMB because the adhesion coefficient increases quickly, and after 2000 cycles the influence of the leaf contamination is almost removed. On the other hand, FMA did not yield better results than the baseline as it seemed to mix up with the leaf layers into a coating that sheared, yielding an adhesion coefficient of around 0.15. After 1500 cycles, the coating started to break up and the adhesion coefficient increased accordingly. If one considers the adhesion requirements for braking and traction, it can be concluded that the minimum number of wheel passages (i.e. cycles) for the adhesion recovery is much larger with the baseline and FMA than with FMB.

![Fig. 8 Adhesion tests in leaf contaminated tests at 1% slip [11].](image)

The size of the solid particles included in an FM plays a
very important role in the performance against leaf contamination layers. Ideally, the particles should be larger than the thickness of the layers so that they prevail in the contact. Otherwise, the particles may be submerged in the layer and have negligible (if any) effect. Therefore, it is indispensable to decide on the solid particles size based on the contamination to be removed. Fig. 9 gives the particle size distribution of the two FMs used in the testing, which was obtained with a laser particle analyzer. It can be seen that FMA has a relatively small size that may complicate the removal of leaf layers as these can have a thickness of up to 100 µm. This could explain the less effective results in adhesion recovery achieved with FMA (see Fig. 8). Moreover, it must be noted that the initial size of the solid particles are not necessarily the size of the particles traversing the wheel-rail interface because the particles may be crushed as they get entrained in the contact [11]. Particle strength analysis may need to be performed to obtain an understanding of the size reduction that the particles may experience.

The hardness of the solid particles of an FM determines the capacity of cutting through the leaf layer so that the bond between layer and rail is broken and adhesion may be recovered. The hardness of the leaf layer mainly depends on the degree of compaction (given by the contact load and wheel slip) and the water content [11]. It was shown in previous laboratory tests that dry leaf layers are harder than wet ones [10]. In fact, the softening effect of water can help in the removal of the leaf layer, as already mentioned in the literature [3, 7]. In this work, the hardness of the remaining leaf layer has been found to be 47-68 HV10g on average. The hardness of the solid particles of the tested FMs was also measured. The stainless steel particles of FMB gave an average 320 HV10g, while an average of 1500 HV10g was obtained for the sand particles. Despite many attempts, the hardness measurements of the particles contained in FMA were not successful due to their small size. Hence, the solid particles of FMB were much harder than the leaf layer. Accordingly, the solid particles could effectively cut through the leaf layer, leading to a fast recovery in adhesion as was shown in Fig. 8. Conversely, they caused indentations on the surface of both wheel and rail disks. FMA did not show as effective break-up of the leaf layer as FMB; however, no indentations were observed in the tests with FMA.

6. DISCUSSIONS

In the presence of leaf layers the adhesion coefficient dropped to values around 0.02 that are far below the minimum requirements for braking and traction. Therefore, effectiveness in the removal of the contamination layers is a major concern for railway operation. The tests results have shown that FMB was much more effective in improving the adhesion in leaf contaminated wheel-rail contacts. Hence, when using FMB in practice the number of wheel passages needed to restore adhesion to an adequate level for traction could largely be reduced. On the other hand, the moderate adhesion characteristics of FMA brought about slower recoveries in adhesion compared to the baseline.

When compared to the thickness and hardness of the leaf layer, the size and hardness of the solid particles contained in the FM will primarily determine the capacity to break up the leaf layer and restore the adhesion back to acceptable levels. In our laboratory tests, the thickness of the post-test leaf layer ranged 3-13 µm. The solid particles of FMB could prevail over the leaf layer due to its large size, leading to an effective removal. On the other hand, the particle size of FMA is in the same range as the leaf layer thickness. This fact seemed to be responsible for the formation of a coating of mixed FMA and leaf layers. Moreover, it has been shown that the solid particles of FMB are harder than the leaf layers; consequently, the solid particles could effectively cut through the leaf layer, leading to a fast recovery in adhesion. Nevertheless, they caused indentations on the surface of both wheel and rail disks. FMA did not show as effective break-up of the leaf layer as FMB, but no indentations were observed. Hence, it may be concluded that the hardness of the solid particles of an FM should be optimized to a compromise between effective leaf layer removal and minimized surface damage to wheel and rail.

In the presence of water the recovery time is one of the most important factors to consider, as it will determine the number of wheel passages in which the negative influence of water on adhesion will disappear. In this paper it has been shown that FMA has the shortest recovery times compared with FMB and the baseline. Since water is present in most of the low adhesion problems, an FM should reduce recovery time as much as possible.

Since water will cause reduced adhesion level, as shown in fig. 7, it would be advantageous to have such an FM

![Fig. 9 Particle size distribution of FMA and FMB.](image-url)
that it can be applied beforehand (the preventive approach) when low adhesion is foreseen, and the FM can not only prevent the low adhesion effect of the contamination, but also reduce the water related adhesion decrease as much as possible, so that an almost constant adhesion level can be maintained.

Finally, it has been shown that FMA has the longest lasting effect, which could be attributed to the strong matrix that is formed between the solid particles and the polymeric components. On the contrary, it seems that the solid particles in FMB tend to be removed from the disks surface once they are crushed due to the weak bond between particles and gelling agent. Since the lasting effect of an FM will determine the frequency in which the FM has to be applied, it is a crucial parameter to take into account during the development stage of an FM because of its economical impact on the costs of the railway network operators.

7. CONCLUSIONS

Some of the results of laboratory investigations with two FMs have been presented in this paper. Some of the desired properties of FMs have also been discussed. This work leads to the following conclusions:

a) Leaf layers reduce the adhesion coefficient to unacceptable levels for braking and traction of proper railway operation.

b) The hardness and particle size of FMs should be designed in accordance to the hardness and thickness of the contamination layer to be removed so that optimum removal can be achieved without causing excessive surface damage of wheels and rails.

c) Since water is present in most of the low adhesion incidents, FMs should incorporate elements in their formulation that enhance short recovery times and avoid large drop in the adhesion coefficient.

d) The lasting effect of an FM should be reasonable so that the railway operators do not have to face large costs to maintain the optimum adhesion levels.

REFERENCES