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FRICTION MODIFICATION WITHIN WHEEL-RAIL CONTACT

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Dedicated to the memory of my girlfriend's dad Miroslav, an amazing person, who inspired me in many ways in my life.
We miss you…

STATEMENT

I hereby declare that I have written the PhD thesis *Friction Modification within Wheel-Rail Contact* on my own according to advice of my supervisor prof. Ing. Martin Hartl, Ph.D., and using the sources listed in references.

Brno, _____________

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Radovan Galas

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ABSTRACT

This dissertation thesis deals with an experimental study of top-of-rail products, specifically top-of-rail lubricants and friction modifiers, which are applied into the wheel-rail contact to optimize adhesion and reduce noise. The main goal of this thesis was to clarify the effect of the applied quantity and chemical composition of top-of-rail products on adhesion. The main attention was paid to low adhesion issues, associated with the application of these products, because low adhesion can result in traction and braking difficulties. This experimental study was conducted in both the laboratory and real conditions where a light rail system was utilized. In the case of laboratory investigations, a commercial tribometer and a twin-disc machine, enabling to achieve typical curve conditions, were employed. Apart from adhesion, wear and noise were analysed during the experiments. The obtained results showed that top-of-rail lubricants are able to provide a beneficial friction behaviour but their performance is strongly affected by the applied quantity. When the contact was overdosed with a top-of-rail lubricant, then a critically low adhesion resulting in a significant extension of braking distance was observed. In the case of friction modifiers, it was revealed that evaporation of base medium considerably changed a friction behaviour of these substances. Besides this, it was investigated that a high content of particles for friction modification can cause low adhesion issues. In general, it was observed that both types of top-of-rail products are able to significantly reduce wear and surface damage, while it seems to be difficult to achieve a significant reduction of noise without the impact on traction and braking capabilities. At the end of the present thesis, some future research steps in this area are recommended.

KEYWORDS

Wheel-rail tribology, top-of-rail lubricant, friction modifier, adhesion, traction, braking, wear

ABSTRAKT

Předložená disertační práce se zabývá experimentálním studiem modifikátorů tření a maziv pro temeno kolejnice, které jsou aplikovány do kontaktu kola a kolejnice za účelem optimalizace adheze a redukce hluku. Hlavním cílem práce bylo objasnit vliv aplikovaného množství a složení těchto látek na adhezi v kontaktu. Hlavní pozornost byla věnována zejména potencionálním hrozbám souvisejících s kriticky nízkou adhezí, která může nastat po aplikaci těchto látek. Experimentální studium probíhalo v laboratorních i reálných podmínkách, konkrétně v tramvajovém provozu. V případě laboratorních experimentů byl využit komerční tribometr a dvoudiskové zařízení umožňující simulovat průjezd vozidla traťovým obloukem. Kromě samotné adheze bylo při experimentech sledováno také opotřebení a míra hluku. Výsledky ukázaly, že maziva pro temeno kolejnice jsou schopna poskytovat požadované třecí vlastnosti, nicméně jejich chování je silně závislé na aplikovaném množství. V případě předávkování kontaktu dochází ke kriticky nízkým hodnotám adheze, které vedou k výraznému prodloužení brzdné dráhy. V případě modifikátorů tření bylo ukázáno, že chování těchto látek je výrazně ovlivněno odpařováním základního média. Výsledky také ukázaly, že nadměrné množství částic pro modifikaci tření může způsobit kriticky nízké hodnoty adheze. U obou výše zmíněných typů produktů byl prokázán pozitivní vliv na míru opotřebení a míru poškození povrchu, zatímco významná redukce hluku byla dosažena pouze v případech, kdy došlo ke značnému poklesu adheze. V závěru této práce jsou uvedena doporučení pro další výzkumné aktivity v této oblasti.

KLÍČOVÁ SLOVA

Tribologie kontaktu kola a kolejnice, mazivo pro temeno kolejnice, modifikátor tření, adheze, trakce, brzdění, opotřebení

CONTENTS

1 INTRODUCTION

Rail transportation is one of the most reliable, safest and the most efficient way of transportation of passengers and goods. Since 1804, when the first steam locomotive was invented by Richard Trevithick, rail transportation has undergone a rapid progress. Today, trains are significantly more eco-friendly, safer, and, of course, faster. A current speed record for conventional trains is held by the French TGV bullet train which reached 574.8 km/h in 2007, and a common operating speed of high-speed trains is between 200 and 320 km/h. Besides trains, rail transportation has also become indispensable for public transport where subway and tram systems play an important role. In Brno (Czech Republic), trams annually carry nearly 200 million of passengers.

From the above lines, it is evident that rail transportation occupies a significant position in both intercity and public transport. However, there are some phenomena which considerably affect a success of rail transportation. A wheel-rail interface represents one of the key factors responsible for transfer of forces from the wheel to the rail. This transfer is usually expressed by a ratio between the normal and friction force acting in the contact. This ratio is usually called the adhesion or friction coefficient; a difference between these two coefficients is discussed in the following chapter. It should be emphasized that the actual value of friction coefficient is strongly weather-dependent because the wheel-rail contact is an open system. It means that acceleration and deceleration capabilities can be limited due to unfavourable environmental conditions and contaminants. One of the most critical scenarios occurs during the autumn when a combination of moisture and crushed leaves forms a layer providing a low adhesion. This layer limits traction and braking performances. Moreover, it can also lead to the difficulties with train detection due to its insulating effect. To overcome these difficulties, sand is applied into the wheel-rail contact; thus, a rapid increase in adhesion in the wheel tread–rail head contact is achieved. The second widely used approach for friction modification at the wheel-rail interface is a method of flange lubrication. This method becomes important for the vehicle running through a curve. In this case, a lubricant reduces friction to a minimum in the wheel-flange-gauge corner contact; thus, wear, energy, and material cost savings are reduced.

Besides the above mentioned traditional methods to control friction, substances for top-of-rail friction modification, the so-called TOR products, were developed in 1990s. These products can be applied to the wheel-rail contact to achieve the required adhesion level and shape of traction curve. It means that these products are able to control adhesion/friction at the specific value unlike sanding and wheel flange lubrication. Typical benefits of these TOR products are a reduction of wear, noise and rolling contact fatigue (RCF).

The aim of this doctoral thesis is to clarify the friction behaviour and impact of TOR products on friction in the wheel-rail contact while the main attention is paid to low adhesion issues associated with the application of these substances. So far, only little has been published about this potential risk.

2 STATE OF THE ART

2.1 Adhesion and friction in wheel-rail contact

Friction between the contact surfaces has attracted the attention of scientists for several centuries. The first laws of friction were given by Leonardo da Vinci at the end of 15th century; however, his friction theories were not published. According to his notebooks, da Vinci discovered that friction is independent of the size of contact area between the contact surfaces. Moreover, Da Vinci observed that the friction force between two solid sliding surfaces is proportional to the normal force pressing the surfaces together. These two basic laws of friction were later rediscovered by Amontons in 1699, and nowadays they are known as Amonton's laws of dry friction. Besides that, Da Vinci introduced the effect of surface irregularities on friction the between the surfaces. Afterwards, Amonton's laws were confirmed and extended by Coulomb who studied the effect of speed, temperature, humidity, and other parameters, on friction. A significant milestone occurred in 1950 when Bowden and Tabor published their theory that the friction force depends on the true contact area. They noted that there is a significant difference between the true contact area, which is formed by the asperities, and the apparent contact area. Although Bowden and Tabor provided a much more satisfactory theory of friction compared to the previous ones, a simple law of friction described by Amontons and Coulomb, which is called the second law of friction, is still widely used for estimation of the friction coefficient despite significant simplifications. In this case, friction is expressed by the friction coefficient f, which is considered as a ratio between the friction force F_t and the normal force F_n in the contact, see Eq. 2.1.

$$f = \frac{F_\mathrm{t}}{F_\mathrm{n}} \tag{2.1}$$

In the railway field, the ability to transfer the traction force from a wheel to a rail is usually expressed by the adhesion coefficient μ. For this case, Eq. 2.1 can be rewritten as follows:

$$\mu = \frac{F_\mathrm{T}}{F_\mathrm{n}} \leq f \tag{2.2}$$

where F_T is the tangential force. A difference between the friction coefficient and the adhesion coefficient can be illustrated by a theoretical traction curve (sometimes called a creep-force characteristic), which was introduced by Carter in 1926 [1]. In his theoretical work, Carter suggested that the contact path between a wheel and a rail could be divided into stick (without slip) and slip regions, which vary as a function of the slip. This hypothesis was subsequently verified using a photoelasticimetry method by Ollerton and Haines in 1963 [2]. The theoretical traction curve describes the relationship between the adhesion coefficient and the slip, see Fig. 2.1. It is evident that if the contact operates without the slip, then a pure rolling condition occurs as is illustrated by point *A* on the traction curve in Fig. 2.1. However, this is only a theoretical situation because the contact always operates at some value of slip, usually less than 3% of slip. In this case, the contact path is composed of both the slip and stick region; thus, the contact operates under the so-called rolling-sliding conditions, see point *B* and *C* in Fig. 2.1. When the adhesion coefficient reaches the point *D*, which is termed as a saturation point, the stick region completely disappears; thus, the contact operates under pure sliding conditions. At this moment, the adhesion coefficient is equal to the friction coefficient. It indicates that the value of the adhesion coefficient in the contact can vary from 0 to *f*, as is evident from Eq. 2.2.

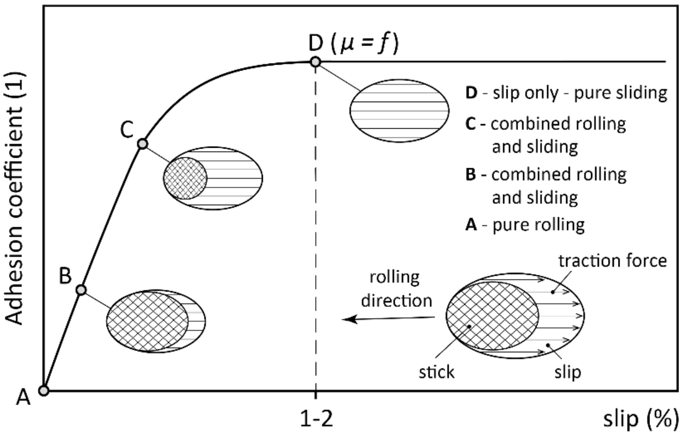


Fig. 2.1 Theoretical traction curve according to Carter.

With a further increase in slip, the adhesion coefficient remains theoretically constant. It means that the maximum level of traction force which can be transferred from a wheel to a rail is limited by the current value of the friction coefficient. However, it should be noted that the friction coefficient is strongly affected by the natural contaminants and environmental conditions. In real conditions, a saturation point usually occurs for the slip between 1 and 2%. The typical values of the coefficient of friction obtained using a hand-pushed tribometer for various contact conditions are presented in Tab. 2.1 [3].

Tab. 2.1 Examples of friction coefficients [3].

Condition	Coefficient of friction
Sunshine dry rail, 19 °C	0.6 – 0.7
Recent rail, 5 °C	0.2 – 0.3
With a lot of grease on rail, 8 °C	0.05 – 0.1
Damp leaf film on rail, 8 °C	0.05 – 0.1

A great deal of research focusing on wheel-rail adhesion was carried out in UK during the 1970s by Beagley et al. [4]-[7]. These studies dealt with the effect of typical contaminants, such as water, oil and wear debris, on adhesion in the wheel-rail contact. These observations showed that the adhesion coefficient is significantly influenced by an amount of oil, while the influence of chemical changes of oil is rather negligible compared to the effect of the amount used. If water was applied to the contact, the adhesion coefficient was reduced to 0.3 or less. It was also found that adhesion can be significantly affected by a mixture of wear debris, iron oxide, and fluid. A behaviour of these mixtures will be described in detail below.

Apart from water and oil, leaves represent one of the most common and most dangerous contaminant in the wheel-rail contact. Hence, the leaf issue is the centre of interest of many researches all over the world. As shown in Fig. 2.2, crushed leaves can form a highly durable solid film providing the adhesion between 0.02–0.06 [8],[9]. Sanding is a widely used approach to overcome a low adhesion due to leaf contamination. The effect of sanding on adhesion recovery has been studied by several authors [10]-[14] where the influence of feed rate [14] and particle size [12] were mainly investigated in terms of adhesion, wear, and electric insulation. It was concluded that adhesion recovery can be significantly faster when sand is used. Without sanding, the recovery time was approximately seven times slower [11]. An improvement in adhesion by sanding can be significantly affected by the appropriate size of sand particles. Smaller particles are more efficient compared to the larger ones because of better particle entrapment in the wheel-rail contact [11]. However, an almost opposite trend was found in laboratory conditions where the large particles led to the highest adhesion [12]. On the other hand, the larger particles increased the work-hardening effect and wear. It should be noted that the smaller particles as well as the higher feed rates can ensure an easier electric insulation [10]. Although sanding is beneficial in improving the adhesion in a leaf-contaminated wheel-rail contact, it is evident that inappropriate sanding parameters can cause risky situations, especially the electric insulation of a wheel and a rail leading to a collision of trains such as in Germany in 2008. Sanding is also widely applied in a tram transportation where sanding is required to overcome poor adhesion conditions, occurring as a consequence of high humidity or moisture, especially during traction/braking or during climbing a slope.

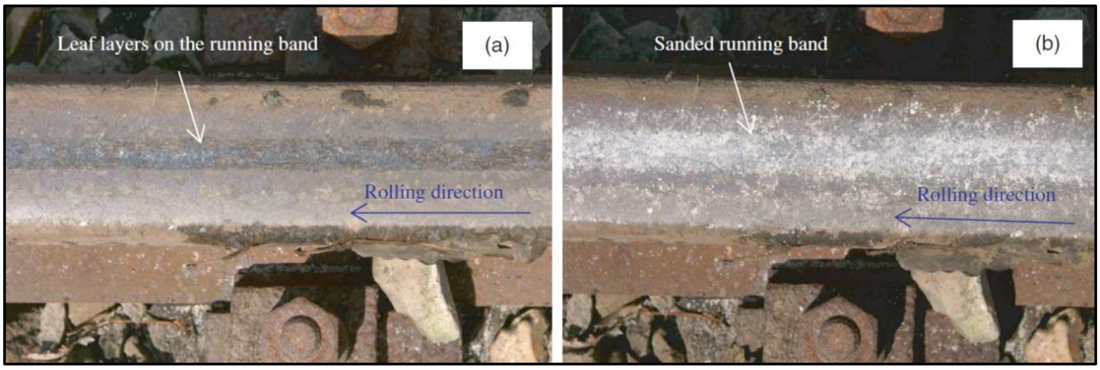


Fig. 2.2 Photographs of the top of the rail in leaf test before sanding (a) and after sanding (b) [11].

Besides the environmental effects, the impact of operating conditions such as speed, axle-load, slip, etc. on adhesion have been intensively studied under various environmental conditions [15]-[18]. Baek et al. investigated the effect of above-mentioned parameters under dry and wet conditions using a twin-disc machine [15]-[16]. The obtained results showed that the maximum adhesion coefficient decreases with increasing rolling speed for both dry and wet conditions. In contrast, a different relationship between the adhesion and the contact pressure was found for dry and wet conditions. Whereas the maximum adhesion coefficient remains almost unchanged under wet conditions, an increase in the contact pressure led to a growth of adhesion under dry conditions. A similar observation was previously reported by Zhang et al. [18] who employed a full-scale test rig; however, the opposite trend of the adhesion coefficient for various contact pressures was reported. It was found that the adhesion coefficient decreases with increasing axle-load for all tested speeds and contaminants. This trend was subsequently confirmed by Wang et al. [19]. All above-mentioned articles also showed that the adhesion coefficient increases with an increase in slip as was previously shown on the theoretical traction curve in Fig. 2.1. Based on this literature review, it can be concluded that the saturation point under dry conditions is usually reached at the slip of 1-3% leading to the adhesion coefficient in the range from 0.4 to 0.6. However, it should be noted that these values can differ regarding to the employed experimental device and the specific operating conditions as is shown in Fig. 2.3 [3].

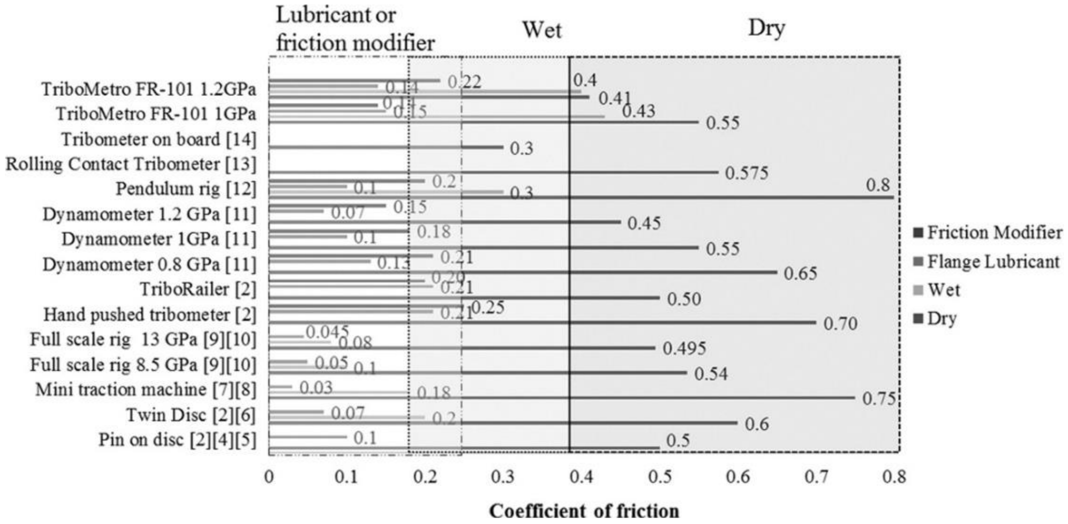


Fig. 2.3 Typical values of friction coefficient reported in literature using different methods [20].

2.2 Friction management

Friction management includes different approaches to the friction modification between the wheel and the rail. These approaches are widely used all over the word in order to achieve good transport efficiency, safety, noise reduction, and acceptable maintenance costs. According to the desired level of friction/adhesion, friction management can be divided into three categories [21].

- **Grease and lubricants** – typical representatives are grease and lubricants which are applied at the wheel-flange-gauge corner interface. These substances provide a friction coefficient lower than 0.1; thus, wear and noise are reduced. An application is mainly realized before a track and lubricant or grease are applied into the wheel flange-gauge corner contact of high rail as can be seen in Fig. 2.5. In some publications, these products are sometimes termed as *Low coefficient friction modifiers* (LCF).

- **High positive friction modifiers (HPF)** – these top-of-rail products (TOR products) maintain the friction coefficient at the intermediate level, which is usually the range from 0.2 to 0.4. Besides this, TOR products should provide a positive trend of the traction curve (positive friction characteristic), see Fig. 2.4. In this case, a substance is usually applied only into the wheel tread–rail head contact of the high rail as is shown in Fig. 2.5.
- **Friction enhancers** - a typical representative is sand which increases adhesion, especially during traction and braking under poor adhesion conditions. The application of sand should ensure the friction coefficient higher than 0.4. Sanding or the so-called *Very high positive friction modifiers* (VHPF) can be used on both the straight and curved sections of track.

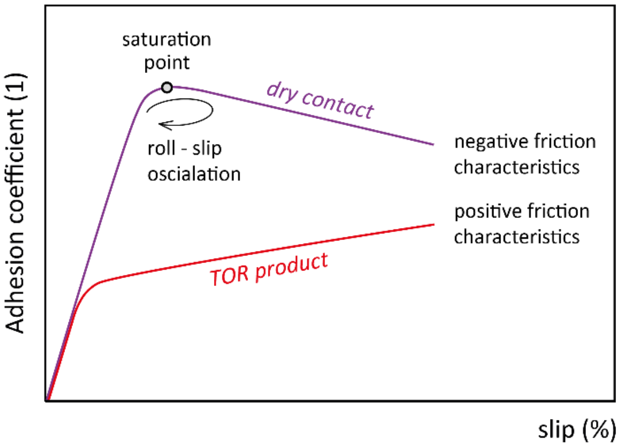


Fig. 2.4 Traction curve for dry contact and contact with TOR product.

In the past, many authors used the term *friction modifier* (FM) for both the water-based and oil-based substances despite significant differences in the behaviour of these substances. In order to avoid confusions, in this doctoral thesis, the term *friction modifier* is used only for the water-based products while the oil-based, grease-based, and hybrid products (the base medium is a mixture of oil and water) are called *TOR lubricants* in accordance with the recently published review articles [22],[23].

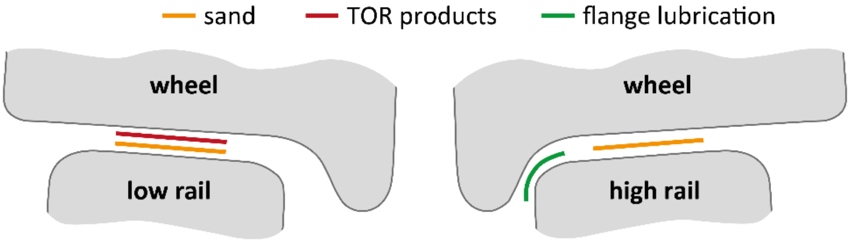


Fig. 2.5 Friction management in rail transportation.

2.3 Top-of-rail products

The first TOR product was developed as a solid stick in the early 1990s. This solid modifier was subsequently used in the Vancouver mass transit system [25] where rail corrugations were developed as a result of wear and a roll-slip oscillation within six months following its opening in 1986. The study showed that the solid modifier enables to change a trend of the traction curve from negative to positive; thus, a roll-slip oscillation can be completely suppressed. Although a solid stick modifier proved to be a suitable method for reduction of roll-slip oscillation, this method does not easily allow to precisely control a dosing process which is one of the most important factor for top-of-rail friction modification. A large amount of TOR products can have a negative impact on traction and braking performance. Therefore, these solid stick products are more often employed for the flange lubrication where the requirements for dosing are not so strict. With respect to these strict requirements for application of TOR products, a liquid FM (water-based) was developed in 1996.

FMs, sometimes also called drying products, are usually applied directly to the top-of-rail in the targeted section of track. As was mentioned above, FMs should mainly generate a positive traction curve and provide an intermediate level of friction. In addition, there are some other FM benefits such as reduction of lateral forces leading to fuel/energy savings, wear reduction, and also a control of noise. All these benefits are significantly affected by the presence of the third-body layer which is naturally formed on the contact surfaces. After the application of FM, water is evaporated; thereby dry FM particles interact with the third-body layer consisting of wear debris particles, oxides particles, contaminants, etc. It means that FMs should be designed with respect to the composition of the third body layer. However, it should be noted that this composition can significantly vary due to changing environmental conditions. It means that these water-based products should be beneficial in a wide range of both environmental and operating conditions. According to the patents [26]-[28], the following components contained in FMs exhibit a high positive friction characteristic (traction curve):

- **Base medium** – it is “only” a transport medium, which ensures a distribution of FM along the track or wheel circumference depending on the application method. The content of water is usually between 40 and 95 wt%.
- **Rheological control agent or binding agent** – this agent is a compound capable of absorbing base medium thereby a substance swells. This agent creates a continuous phase matrix which is able to bind solid particles such as lubricants, particles for friction modification and other compounds to a metallic surface of a rail or a wheel. Moreover, this agent has a function of a thickening agent, so it controls the flow properties and the viscosity of the composition. The typical representatives are e.g. clays such as sodium montmorillonite (bentonite), casein, starches, etc. The content of the rheological control agent is from about 1 to about 10 wt%.
- **Particles for friction modification (PFM)** – this compound is usually termed as a “friction modifier” as well as the whole substance. In order to avoid

confusions, this compound is called herein *particles for friction modification*. Particles for friction modification, if any, are usually mineral particles such as magnesium silicate (talc), silica, ground quartz, etc. Apart from mineral particles, some oxides can be used, e.g. zinc oxide, aluminium oxide, zinc oxide, antimony oxide, etc. These particles should ensure a desired level of adhesion and a positive friction characteristic. The size of PFM is usually in the range from 0.5 to 10 microns. In the case of HPF FM (hereinafter FM), a preferable size of PFM is in the range from 1 to 2 microns whereas VHPF FM has a desired PFM size about 10 microns.

- **Solid lubricant** – a compound reducing the friction coefficient between surfaces. In the case of top-of-rail FMs, the following solid lubricants are preferably employed: molybdenum disulphide (molyka), graphite and aluminium, or zinc stearate. If a solid lubricant is required, the content is in the range of unit of wt%.
- **Wetting agent** – this agent helps to reduce a surface tension of liquids. Furthermore, this agent ensures a better adhesion of FM on the rail surface. One of the most common wetting agents is nonyl phenoxypolyol, which is usually contained in the amount less than 2 wt% but a predominant amount is about 0.002 wt%.
- **Other additives** – antioxidant, antibacterial agent, retentivity agent for lifetime increase, etc.

Based on the patents [26]-[28], it is clearly evident that the main difference between HPF and VHP FMs is a size of PFM and a concentration of solid lubricant. In the case of VHPF FM, the size of PFM is significantly larger compared to (HPF) FM; moreover, VHPF FM does not contain a solid lubricant. Composition examples of VHPF and (HPF) FMs are listed in Tab. 2.2. A detailed description of the effect of FM on adhesion, wear, fatigue, etc. is given in the following subchapters.

Tab. 2.2 Examples of very high and high positive FMs [26].

Constituent	**(HPF) FM**		**VHPF FM**	
	Constituent	CONCN (%)	Constituent	CONCN (%)
Base medium	Water	80.193	Water	85.254
Rheological agent	Bentonite	8.9	Bentonite	9.45
PFM	Talc	4.93	Alum. silicate	5.2
Solid lubricant	Molyka	4.93	Molyka	-
Wetting agent	NP	0.002	NP	0.002
Other additives	–	1.045	–	0.094

Besides the above-described FMs, TOR lubricants represent another possibility of friction management with similar benefits as those of FMs [23]. In this case, friction behaviour is much more affected by the applied amount than in the case of FMs. Representative constituents of TOR lubricants are base oil (usually plant oil), thickener (e.g. calcium or lithium soap), PFM (e.g. metal and oxides), solid lubricant (e.g. molyka or graphite) and other additives such as antioxidant or extreme pressure additives.

2.4 Lubrication regimes

Fig. 2.6 shows a Stribeck curve describing the relationship between the adhesion coefficient and the Hersey number or the parameter of lubrication *Lambda*, which is a ratio of a film thickness to a combined surface roughness. Four following regimes of lubrication can be distinguished on the Stribeck curve:

- **Boundary Lubrication** – film thickness is too thin to separate the contact surfaces; therefore, the contact between the opposing asperities occurs. These asperities are covered with adsorbed molecules of the lubricant and oxide layer.
- **Mixed Lubrication** – loading is carried out by a combination of the contact pressure between the surface asperities and hydrodynamic pressure of lubricant, created as a consequence of higher speed. This lubrication regime is sometimes referred to as partial elastohydrodynamic lubrication.
- **Elastohydrodynamic and Hydrodynamic Lubrication** – if the speed is sufficiently high, then the hydrodynamic pressure of lubricant increases and the film thickness becomes sufficiently strong and thick to completely separate the contact surfaces. It means that the film thickness is larger compared to the combined surface roughness.

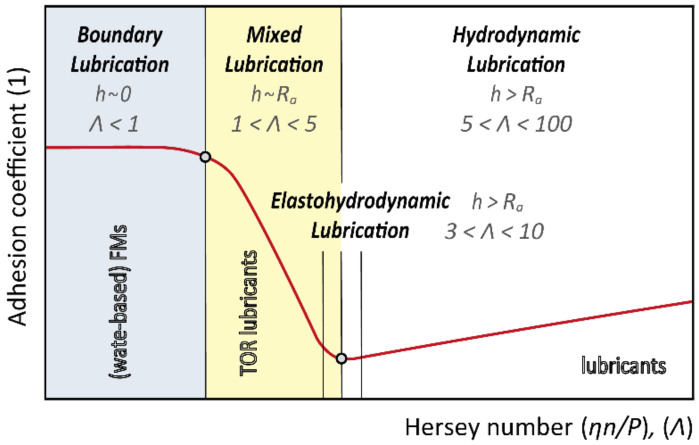


Fig. 2.6 Stribeck curves showing different lubrication regimes.

Under dry conditions, the adhesion coefficient in the wheel-rail contact is given by the third-body layer, which is naturally formed on the contact surfaces. If the rail is wet, then the contact usually operates in the boundary or mixed lubrication regime. The elastohydrodynamic or hydrodynamic regime can occur when the contact is contaminated with oil or grease. In the case of TOR products, a boundary regime of lubrication is expected for FMs (drying materials), while TOR lubricants (non-drying materials) usually lead to the boundary or mixed lubrication [22], [23], see Fig. 2.6.

2.5 Field research of TOR products

2.5.1 Effect of TOR products on corrugation

In the railway field, six different types of corrugations are distinguished in accordance with [24]. These corrugation types differ in wavelength, damage mechanisms, typical frequency, locations, etc. In this doctoral thesis, the term *corrugation* is mainly considered as the so-called *short pitch corrugation* or *rutting*, which is characterized by a uniform wavelength with the amplitude of tenths of a millimetre. The frequency of the pertinent wavelength-fixing mechanism is between 250–400 Hz; it corresponds to the corrugation wavelength of 45–100 mm for the vehicle speed at 40 km/h. This type of corrugation generally occurs on a low rail of curves as a result of roll-slip oscillation. One of the possibilities of how to mitigate or avoid a formation of this corrugation is an application of TOR products.

As was mentioned above, the first contribution of the solid TOR product to reduce the corrugations have been reported by Kalousek and Johnson [25]. In this case, 85% of the track of Vancouver Skytrain was corrugated six months after its opening in 1986. The authors identified three factors which were assessed in terms of development of corrugation. The identified factors were as follows: (a) poor alignment of wheelsets in the trucks, (b) generation of a stick-slip oscillation, which is often referred to as a roll-slip oscillation, (c) development of close conformity between the wheel tread and the rail. It was revealed that development of corrugation can be suppressed by tightening the tolerance of arc misalignment to ±10 minutes. However, this solution was effective only in the case of severely corrugated wheels but ineffective in the case of rail corrugation and mildly corrugated wheels. These two remaining problems were solved by avoiding of a tight conformity of wheel-rail profiles and by application of a solid TOR product. In the case of tight conformity, the relative position of the rail head was specifically changed in the four tangent track sections as is depicted in Fig. 2.7. This ensured the wheel tread profile to be differently changed by the action of wear; thus, a close conformity was avoided. Suppression of the rail corrugation formation was achieved by the application of solid TOR product, which provided a positive traction curve; thus, development of corrugation was suppressed.

Development of short pitch corrugations was intensively studied from 2002 to 2008 [29]-[32]. One of the first papers dealing with the effect of a liquid version of FM was published by Eadie in 2002 [29]. In this study, the initiations of short pitch corrugations were introduced in the theoretical part of this article. Two following initiation mechanisms of formation of short pitch corrugation were mentioned: (a) wheel-rail surface irregularities and (b) a trend of traction curve after the saturation point. While the former mechanism is mainly associated with newly manufactured rails and wheels, the latter occurs as a result of the roll-slip oscillation due to the negative friction behind the saturation point, see Fig. 2.4. A roll-slip oscillation causes small patches to be formed on both contact surfaces. These patches, which are formed in the slip region of roll-slip oscillation, can be easily observed with the naked-eye on rails and wheels, see Fig. 2.8. Subsequently, these shiny patches grow together forming the corrugation valleys. The evolution of this short pitch corrugation is associated with a significant increase in corrugation noise, wheel squeal, and wear.

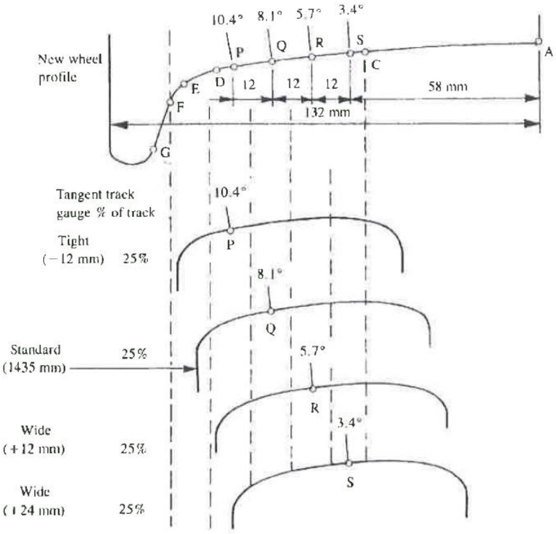


Fig. 2.7 Result of gauge widening and rail profile inclination for four sections of tangent track [25].

A theoretical description of evolution of corrugations was subsequently supported by two practical examples from field experiments. In both cases, FM was used in order to alleviate the corrugation formation. In the first case, the elevated light rail system in Asia was employed because of the rapid formation of short pitch corrugation. In some areas, grinding was carried out even every week. It was found that if FM was applied through 25% of the wheel set, the required frequency of rail grinding was reduced from one week to six months. However, it should be noted that, apart from the application of FM, other changes were made. Despite the changes in the wheel profile, rail profile, etc., it can be reasonably expected that FM had a significant impact on the alleviation of corrugation formation. The ability of FM to reduce the evolution of corrugation was proven by the second example where two lines of American light rail system were studied. It was shown that Line 1 (no FM) was significantly more corrugated after 4 years of operation than Line 2 (FM) after 10 years of operation.

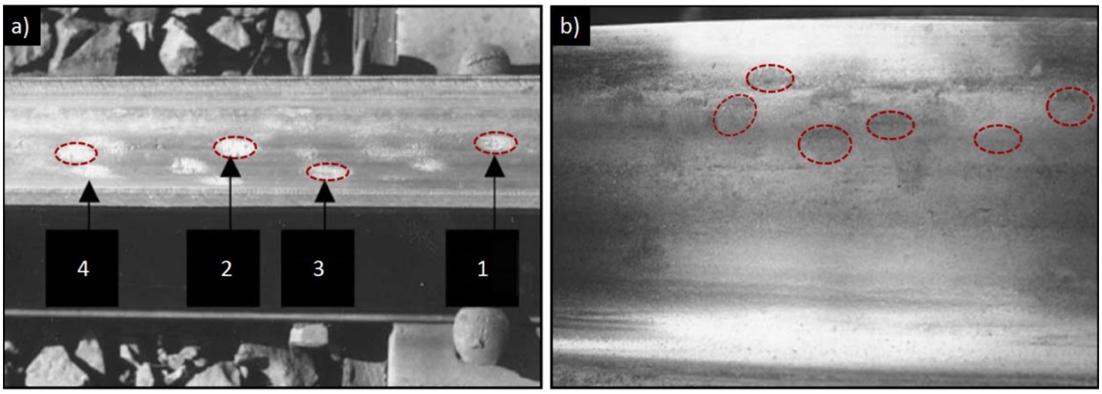


Fig. 2.8 Patches on rail (a) and wheel (b) represent the slip regions of roll-slip oscillation [29].

Egana et al. investigated the evolution of corrugation amplitudes and wavelengths at Metro Bilbao [30]. The length of the tested curve was 250 m and the profile measurements were carried out every 20 m to evaluate the corrugation. A liquid FM was applied via a trackside application system. As is clear from Fig. 2.9a, the rail was ground before the beginning of experiments. The results showed that almost no increase in the corrugation amplitude was observed during the first 19 months when the liquid FM was applied. After 19 months, the application of FM was stopped and the immediate and linear growth of the corrugation amplitude was detected while the wavelength did not change without FM. For both tested conditions (with and without FM), two predominant wavelengths were found in the range from 100 to 200 mm, see Fig. 2.9b. These investigations clarified the hypothesis that a liquid FM is able to delay or completely avoid the corrugation formation.

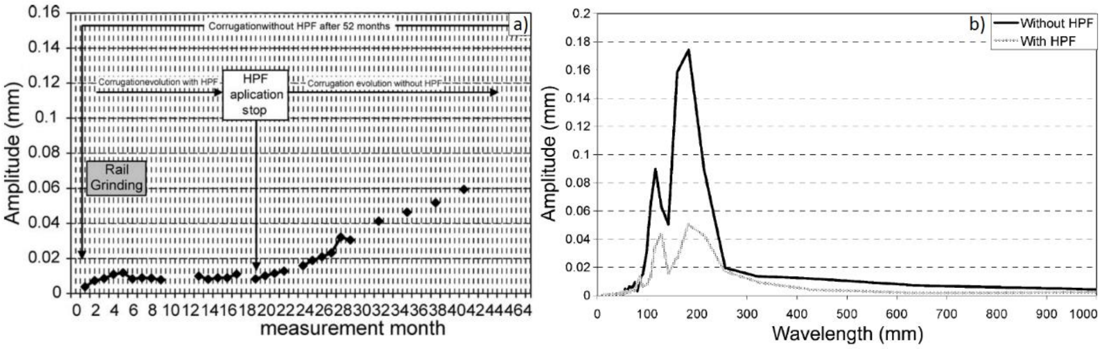


Fig. 2.9 Evolution of rail corrugation amplitude (a) and wavelength spectrum comparison (b) [30].

The study [30] was later followed by Eadie et al. [31]-[32] where the effect of FM on the development of corrugations was analysed for several different wheel-rail systems such as European metro (system A), European commuter rail system (system B), and Japanese metro (system C). These systems are characterized by different vehicle and track characteristics, e.g. radius of curve varied from 40 to 227 m, speed was between 30 and 50 kph, axle load was in the range from 6.6 to 16 tons, traffic reached the values between 1 500 and 6 720 axles per day, etc. The employed FM was Keltrack™ which was applied using a wayside top of rail applicator on both rails. The results in Fig. 2.10 gave the evidence that

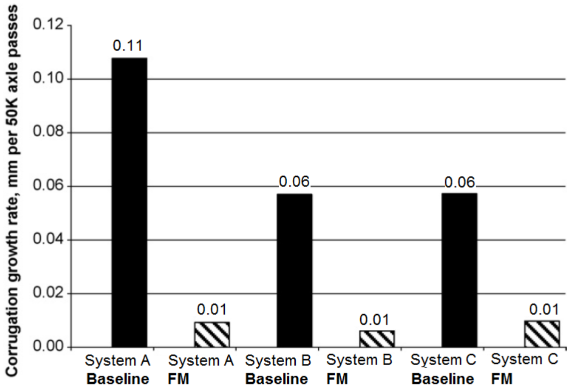


Fig. 2.10 Comparison of corrugation growth rates for different wheel-rail systems [31].

the application of FM can mitigate or completely avoid the formation of short pitch corrugations for a wide range of wheel-rail systems. The most significant reduction in the corrugation growth rate was found for the European metro (system A) where this rate was reduced even by 11 times. In the remaining two cases, corrugation growth rates were reduced by 6 times.

2.5.2 Effect of TOR products on noise

A railway noise represents one of the most important minuses of rail transportation, especially in urban areas. There are several sources of noise: rolling noise, traction noise, aerodynamic noise, etc. [33]. The relevance of the individual sources of noise depends on the vehicle speed, track characteristics, vehicle, etc. In the case of curve noise, two significant sources of noise can be identified. The first one is a wheel squeal (a pure tonal squeal) and the second one is a flanging noise (a broad band metal-on-metal rubbing noise). It is believed that the former is mainly affected by the lateral creep (slip) leading to the vibration of wheels, while the latter occurs as a consequence of sliding at a wheel flange–gauge face contact [34]. Both these noises are mitigated through the friction management. In the case of noise from the wheel flange–gauge face contact, the gauge face lubrication of the outer rail is usually employed in order to decrease the flanging noise and wear of contact bodies, see Fig. 2.5. The second approach is represented by TOR products which are applied on the top of the low rail only to achieve an intermediate level of friction and to reduce the squeal noise. An overview of railway noise and frequency is listed in Tab. 2.3 [35].

Tab. 2.3 Frequency ranges for different types of railway noise [35].

Noise type	Frequency range (Hz)
Rolling	30 – 5 000
Flat spots	50 – 250 (speed dependent)
Ground borne vibrations	4 – 80
Structure – borne noise	30 – 200
Top of rail squeal	1 000 – 5 000
Flanging noise	5 000 – 10 000

The effect of FM on railway noise has been intensively studied by Eadie et al. where the liquid FM known as Keltrack™ was utilized [29],[31],[35],[36]. At first, changes in sound and vibration spectral distributions in curves were investigated for baseline (dry) and FM conditions [35]. For this purpose, several different wheel-rail systems were used in order to investigate the performance of FM, which was applied on the both rails, for a wide range of operating conditions, see Tab. 2.4. It was observed that FM reduced the average sound level, across all considered systems, in the range from 7.3 to 15.5 dB. It means that the average noise reduction was nearly 11 dB.

Tab. 2.4 Characteristics of employed wheel-rail systems [35].

	S1*	S2	S3	S4	S5	S6	S7
Parameter	*Tram*	*Tram*	*Tram*	*Metro*	*Metro*	*HVF***	*HVF*
Curve radius (m)	19	19	35	97	90	291	200
Speed (kph)	16	16	16	8	32	32	32
Axle per car	8	8	6	4	4	4	4
Cars per train	1	1	1	10	10	100	60
Application of FM	Manual (both rails)				Trackside applic. (both rails)		
Gauge face lubrication	No	Yes	No	Yes	Yes	No	Yes
Avg. L_{Leq} baseline (dB)	83.3	92.4	83.3	101.5	105.9	90.6	102.4
Avg. L_{Leq} FM (dB)	71.2	80.6	72.5	91.9	98.6	81.8	86.9

**S1 – System 1 **HVF – Heavy haul freight*

Changes in sound spectral distributions for four wheel-rail systems are shown Fig. 2.11. It is obvious that the application of FM significantly reduced both the squeal and flanging noise but the efficiency of FM for HVF (S6) is lower compared to the others due to higher lateral and flanging forces, especially in curves.

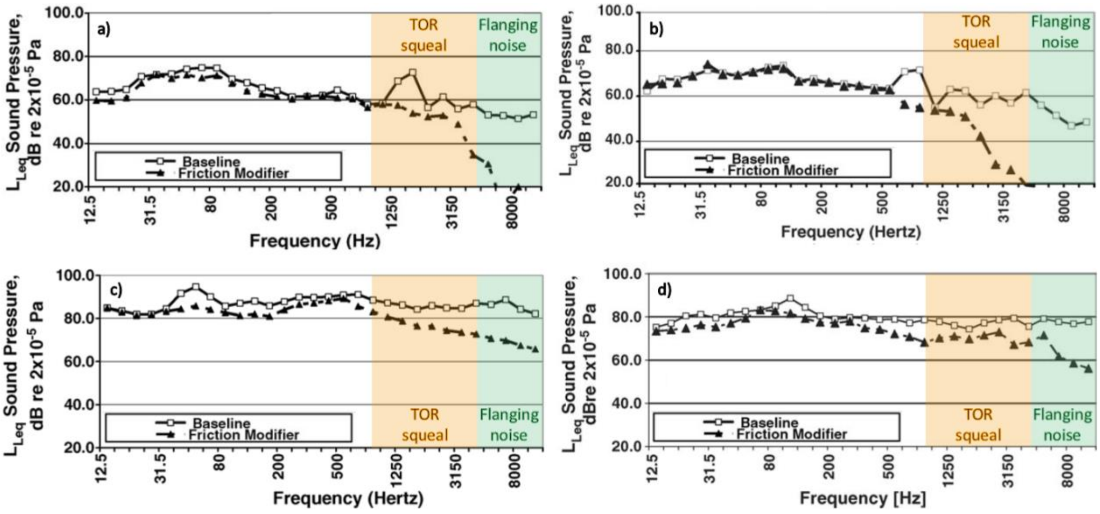


Fig. 2.11 Sound spectrum: system S1 (a), S3 (b), S5 (c), and S6 (d) [35].

Besides the change in sound distribution, the influence of FM on vibration was studied for S4 under baseline and FM conditions; see Fig. 2.12a. These measurements showed that there is only a small positive impact of FM on the vibration level in the frequency range from 30–60 Hz and also at the frequencies higher than 1 500 Hz where the roll-slip oscillations usually occur. The last set of experiments was targeted on the comparison of three following contact conditions: baseline (dry), FM–low rail only, and FM–both rails, see Fig. 2.12b. These experiments showed that a decrease in the sound level occurred at the frequencies between 1 000 and 3 000 Hz when FM was applied only to a low rail. If FM was applied to both rails, a further decrease in the sound level was observed. Apart from this, FM on both rails was effective in a wider range of frequencies, up to 8 000 Hz. According to Tab. 2.3 and Fig. 2.12b, the authors concluded that the lubrication of both rails reduced both the squeal and flanging noise.

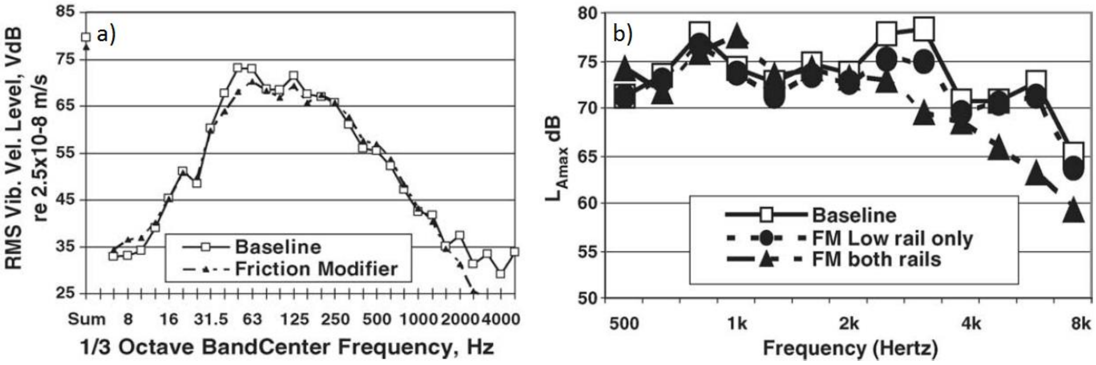


Fig. 2.12 Vibration spectrum: S4 (a), comparison of different FM applications [35].

The follow-up article [31] confirmed the above-mentioned results. As in the previous study [35], a significant reduction in the curve noise was observed under FM conditions (both rails) where five various wheel-rail systems with similar vehicle and track characteristics were utilized. All employed systems were also equipped with gauge face lubrication. An average reduction in A-weighted noise level under FM conditions varied in the range from 6.3 to 22.8 dB for all tested systems; approximately, an average noise reduction of 12 dB was achieved. However, it should be noted that the gauge face lubrication was ineffective for the noise control in curves. As in the previous study, the change in the spectral distribution was mainly associated with the top-of-rail squeal but the effect of FM on the mitigation of flanging noise was not so substantial, see Fig. 2.13. The lowest noise reduction was observed for HVF corrugated system.

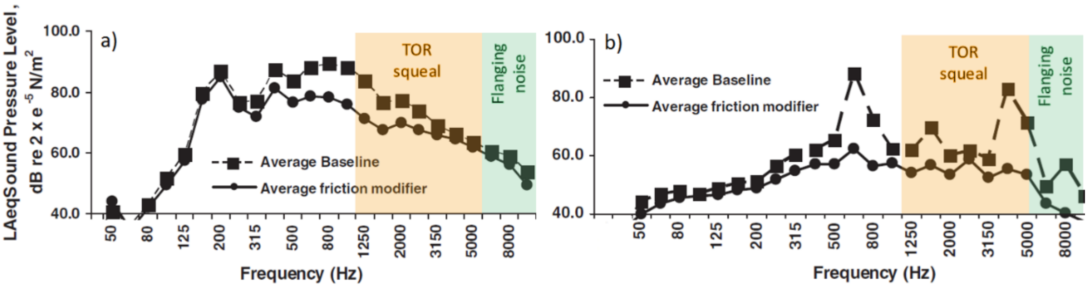


Fig. 2.13 Sound spectrum: Metro system in Spain (a), Tram system in United Kingdom (b) [31].

Curley et al. investigated the influence of FM, TOR lubricant, and gauge face lubricant on the noise generated in curves [37]. The experiments were conducted for the curve with a radius of 290 m, which is primarily occupied by freight trains. FMs and gauge face lubricant were applied either on the high/low rail only or on both rails. In general, it was found that both these approaches to friction management are suitable for the noise reduction. Both the FM and TOR lubricant resulted in a similar noise reduction under freight traffic but the TOR lubricant seems to be more effective for passenger trains. However, some of the results are in conflict with the findings of other researches. The authors reported that the gauge face lubrication showed a better performance for squeal reduction than the FM or TOR lubricant. Moreover, the findings showed that if the FM or TOR lubricant was applied only to the low rail, there was no benefit.

2.5.3 *Effect of TOR products on contact forces*

The initial study, which was focused on the measurement of lateral and vertical forces acting in the wheel-rail contact, was conducted by Suda et al. [38]. The authors introduced an on-board friction control system allowing for spraying of FM on the top of the low rail at the specific track section, especially curves. This unit was employed to evaluate the contact forces in metro in Japan where a tight curve with a radius of 147 m was studied. The data from the wheelset measurements showed that the application of FM on the top of the low rail only caused a decrease in the lateral force and its fluctuations; see Fig. 2.14, particularly a 59% reduction for the low wheel and a 42% reduction for the high wheel. The ability of FM to reduce the L/V ratio (a ratio between the lateral and vertical forces) was subsequently approved by Oldknow et al. [39] for dry and wet conditions where FM (Keltrack™) was tested in heavy haul railways. A significant impact of FM on the contact forces was also described by Egana et al. [30] in the metro system. It was found that the presence of FM on the rail led to a substantial reduction in lateral and vertical accelerations.

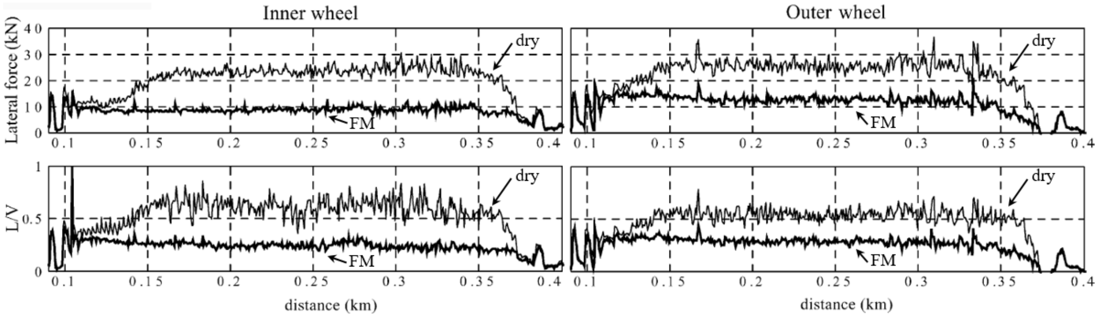


Fig. 2.14 L/V ratio and lateral force of low and high rail under dry and FM conditions [38].

Besides the measurement dealing with the effect of FM on lateral forces, the influence of FM on the friction coefficient was investigated [29],[40]. Eadie et al [29] studied the changes in the friction coefficient through the progression of sequential train laps. In this study, the authors compared the performance of FM and the commonly used lubricant, see Fig. 2.15. The results showed that the application of the common lubricant is inappropriate for a top-of-rail friction modification because this lubricant resulted in a low friction for the high rail, and in a very high friction for the low rail, see Fig 2.15b. In contrast, the application of FM led to a rapid convergence of friction on both rails to the stable friction of 0.35, see Fig 2.15a. This value is often considered as an optimal value for the wheel tread–rail head contact.

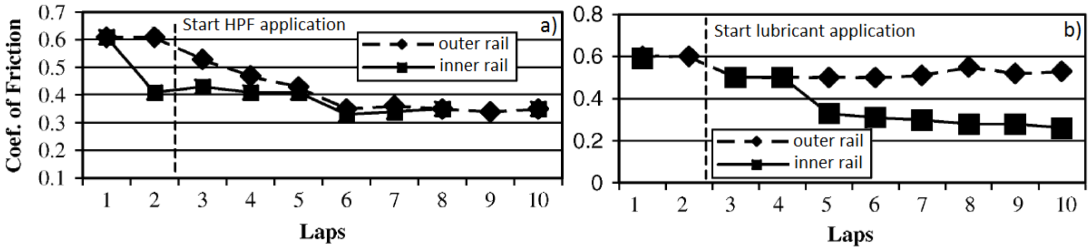


Fig. 2.15 Performance of FM (a) and lubricant (b) [29].

Tomeoka et al. [40] measured the friction coefficient in two tight curves under dry and FM conditions. FM was sprayed on the low rail from the last bogie of the passing train; thus, a FM layer was created on the rail for the next train. The results showed a decrease in the friction coefficient by 58% and 70% for the curve 1 and the curve 2, respectively. Subsequently, Ishida et al. [41] investigated the effect of the grease lubricant on the coefficient of friction in the curve with a radius of 160 m. For this purpose, a hand tribometer was employed. The grease lubricant was applied either on the top of the low rail or on the gauge face of the high rail. A summary of the results is listed in Tab. 2.5. On the one hand, the grease lubricant reduced the friction coefficient for both methods of application; on the other hand, an increase in the friction coefficient was found at the gauge face of the high rail despite the fact that the grease lubricant was applied on the top of the low rail. This behaviour was explained by the change in the atmospheric conditions and in the third-body layer. The same reason was also expected for the reduction of the friction coefficient on the top of the low rail when the lubricant was applied on the gauge face of the outer rail only.

Tab. 2.5 The influence of FM and gauge face lubricant on the friction coefficient [41]

Conditions	**Coefficient of friction**	
	Top of low rail	**Gauge face of high rail**
No lubrication (baseline)	0.55	0.47
Top of low rail lubrication	0.20	0.60
Gauge face of high rail lubrication	0.43	0.15

Recently, two articles focusing on the effect of TOR products on adhesion in the wheel-rail contact have been published [20],[42]. In both cases, a real track and a hand-pushed tribometer were employed. In the case of reference [20] the performance of two TOR products was evaluated. Note the type of TOR products was not specified in the article but from the figures, it can be reasonably expected that one or both these products were TOR lubricants (oil-based or hybrid products). The measurements revealed that the tested TOR lubricants reduce the friction coefficient to the values between 0.13 and 0.22. The friction behaviour of hybrid TOR lubricant was later tested by Lundberg et al. [42]. Investigations showed that this product caused an unacceptably low adhesion (0.13–0.16) when the product was overdosed. It was concluded that adhesion is low as a consequence of a thick TOR lubricant layer. These results were subsequently clarified using a locomotive allowing for evaluation of the friction coefficient. The authors mentioned that more research into the optimal amount of TOR products is needed for different types of TOR products.

2.6 Laboratory research of third body and TOR products

2.6.1 Third-body layer

Although the concept of the third body was introduced in 1984 by Godet [43], Beagley et al. intensively studied the effect of common railhead contaminants under wet and oily conditions in the 1970s [4]-[7]. In the reference [6], the authors dealt with the influence of railhead contaminants such as rail debris, rust, six types of powders and oily fluid. Solid particles were mixed with oily fluid (naphthenic acid) for various oil-debris ratios. The results obtained by a rolling disc tribometer showed that a relatively high amount of fluid is needed to provide a low friction coefficient, approximately 23–41 wt% of oil in dependence on the type of solid particles, see Fig. 2.16. The higher is the surface area of particles, the higher is the amount of oil needed to induce a low friction. In practice, railhead debris on the rail track do not usually contain more than 2 wt% of oil; therefore, it was concluded that the presence of railhead debris is able to maintain adhesion at an acceptable level even under oily fluids contamination. In the case of oil-free state, the effect of all tested solid particles, except for Fe_3O_4 and alumina, was rather negligible because these particles were removed from surfaces by the action of slip. Alumina led to a higher friction because of its higher hardness, but an increase in surface damage was observed due to abrasion. In contrast, Fe_3O_4 particles provided a lower friction compared to other particles, see Fig. 2.17.

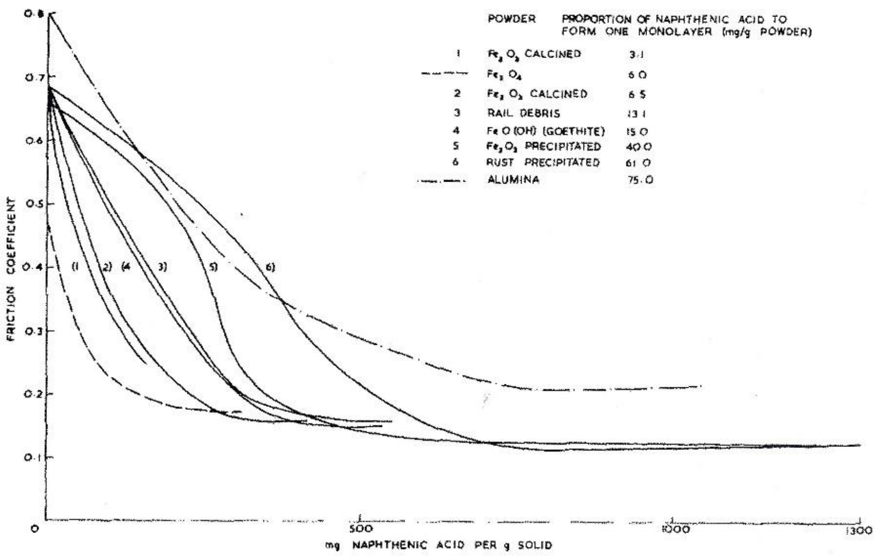


Fig. 2.16 The effect of railhead debris mixed with naphthenic acid on friction [6].

A different situation occurs when the contact with debris is influenced by air humidity. Experiments using the Amsler machine (disc-on-disc), where humidity was changed in the range from 10 to 100%, showed a decrease in the friction coefficient from 0.55 (10% humidity) and 0.3 (100% humidity). In a fully saturated air, the value of friction coefficient depends on the water/solid ratio; a further reduction in friction can be expected. Unlike the above-described case, when contact was contaminated with debris and oily fluids, the amount of water in the contact can be sufficiently high for friction reduction. From this point of view, the effect of humidity on adhesion seems to be more important compared to the effect of oily fluids (in the case of small amounts). Moreover, another study of these authors showed that the above conclusions are valid for a wide range of oils because chemical changes in oil have a negligible effect in comparison with the change in the amount of oil [4]. It was reported that a typical amount of oil, which varies in the range from 0.15 x 10^{-6} to 1.5 x 10^{-6} g/cm^2, on the wear band of rails can cause significant changes in friction.

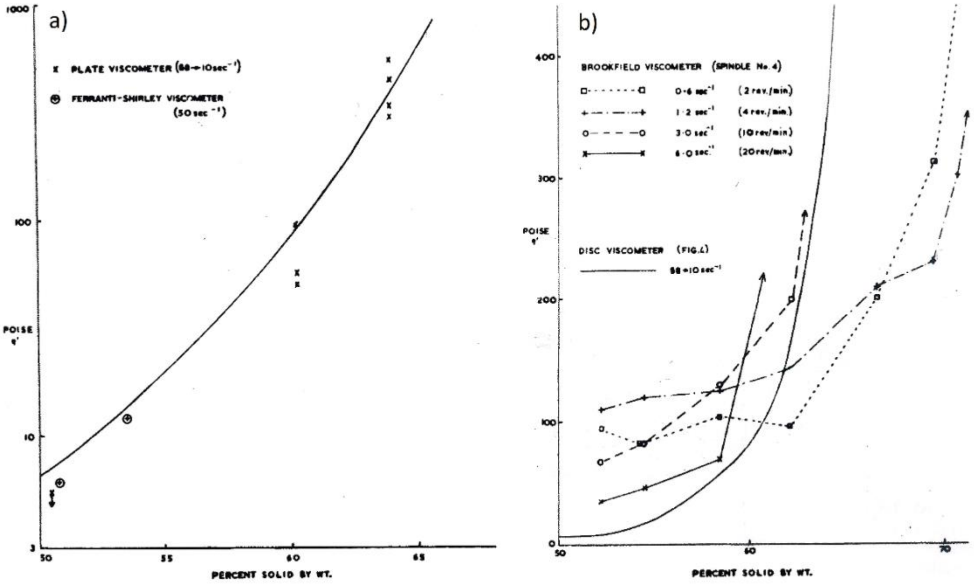


Fig. 2.17 Viscosity of Fe_2O_3/water mixtures (a) and the effect of shear rate on viscosity (b) [7].

In the following studies [5],[7], the authors investigated rheological properties of mixture of water and common track contaminants and also their effect on adhesion in a wheel-rail contact. In the reference [7], rheological properties (mainly yield stress and viscosity) of the oxide/water mixtures were analysed. The authors reported that three different theoretical models can be used for the description of wheel-rail adhesion. A widely known boundary lubrication model cannot be used for this purpose because the third-body layer contains solid particles. It was found that two other models can be considered for the description of wheel-rail adhesion depending on the content of solid particles in the third-body layer, the so-called "solid" and "viscous" models. The former can lead to a reasonable value of friction because of high shear strength of particles. However, a stable layer formation is not affected only by yield strength (yield shear stress) but an important role is also played by material pliability. Both these properties are necessary for formation of the solid friction layer. This is the reason why the iron oxide particles are usually thrown out of the contact despite high shear strength. On the contrary, a "viscous" model is applied if the third-body layer includes more than 10 wt% of water; then a viscous behaviour prevails and a lower friction coefficient can be expected due to the lower shear strength of the third-body layer. The authors mentioned that if the mixture is sufficiently viscous, even the hydrodynamic lubrication can occur with respect to other conditions (especially roughness and speed). Based on this, it was concluded that for mixtures exhibiting a viscous behaviour, a key role is played especially by viscosity. As is evident from Fig. 2.17a, a logarithmic dependence of viscosity on water/debris content was revealed. Besides the viscosity dependence, it was found that mixtures of water and debris exhibit a non-Newtonian behaviour, see Fig. 2.17b. At first, a mixture exhibits a pseudoplastic behaviour (viscosity decreasing with a shear rate) but then there is a transition to a dilatant behaviour (viscosity increasing with a shear rate) with the increasing content of solid particles. The authors expected that this change in the behaviour can ensure that more solid particles remain in the contact.

With respect to the previous publications [4],[6], the authors discussed a transition between the boundary lubrication model and the rheological lubrication model including the above-mentioned solid and viscous behaviour. In the former, a small amounts of rail debris can improve adhesion because debris are able to absorb oil. In the latter, debris can form a viscous layer resulting in low adhesion. The authors mentioned that slightly wet conditions can lead to a reduction in friction as a consequence of partial rheological lubrication. It means that the adhesion coefficient under these conditions is mainly given by the strength of debris or by the viscosity of the mixture. Once the debris/mixtures become more and more sparse, a “classical” boundary lubrication occurs; thus, the adhesion coefficient mainly depends on the oil molecules, water, oxides, etc.

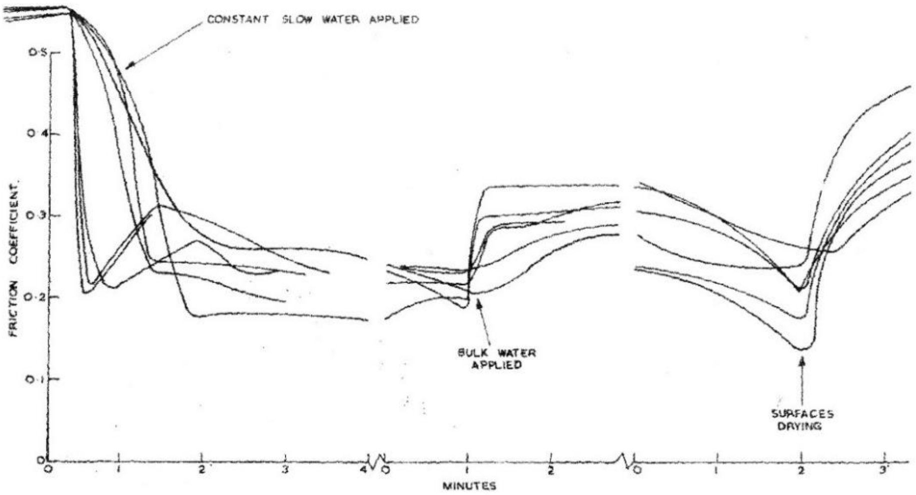


Fig. 2.18 Effect of water and debris formed during rolling/sliding on friction curve [5].

The fourth article by these authors was more closely focused on the effect of water and mixtures of water, and railhead debris [5]. Apart from this, the article summarized the effects of water and oil in terms of previous publications. At first, the effect of water on friction was studied using the Amsler machine at 3.3% of slip, see Fig. 2.18. From this figure, it is evident that an application of small amount of water together with debris led to the formation of viscous paste reducing the friction coefficient to approximately 0.2. Then, the bulk water was applied; it resulted in the friction coefficient about 0.3 which corresponds to friction under wet conditions without debris particles. This behaviour was explained as an inability of solid debris to enter the contact because debris and a larger amount of water formed a slurry, which was built up in the meniscus on either side of the contact area between the discs; therefore, friction corresponds to wet conditions. After drying of surfaces, the friction coefficient continuously grew up to a dry level of friction. These measurements showed that the water and debris are able to form an enough viscous paste separating the contact bodies and providing a critically low adhesion (0.05).

The second type of experiment was conducted in order to demonstrate how the surface debris layer influences friction. It was observed that the absence of debris avoided a drop in friction occurring after the stable part of friction curve, see Fig. 2.19. No drop of friction was also found for water and stainless-steel specimens. In contrast, coating containing Fe_2O_3 and water caused a similar friction behaviour as rail steel, especially in terms of minimum friction. The last measurement was conducted with slightly wet rusted discs, where a critical adhesion (lower than 0.1) was observed for approx. 6 minutes. It means that, besides debris, also the rust particles can cause a low and stable adhesion.

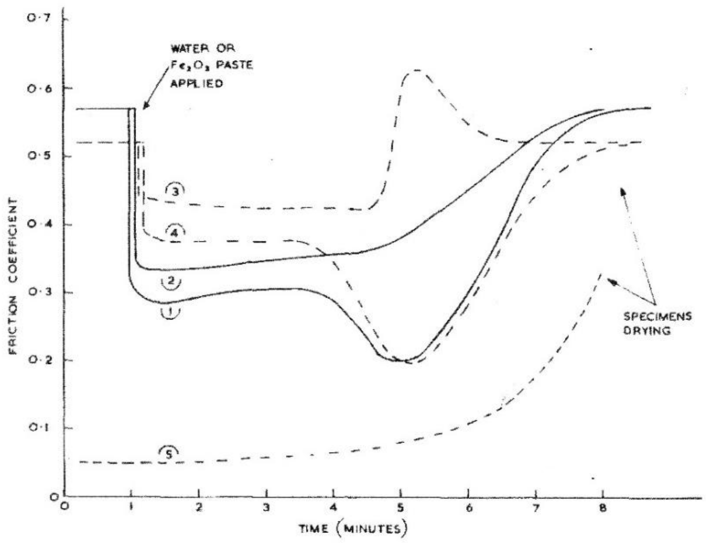


Fig. 2.19 Effect of debris and materials on friction: (1) rail steel sprayed with water; (2) as (1) but with surfaces wire brushed; (3) stainless steel sprayed with water; (4) stainless steel coated with Fe_2O_3/water paste; (5) slightly wet rusted discs [5].

An important study on rheology of solid layer in rolling contact was published by Hou et al. in 1997 [44]. In this study, the authors firstly described a process of interfacial layer formation. Then, they suggested a rheological model of the interfacial layer which gives the evidence that friction in wheel-rail contact can be controlled by the artificial interfacial layer. The layer formation is explained as a result of shear stress acting on the contact asperities; thus, free particles and their oxides are continuously created. Some of these particles are pushed out of the contact while others are agglomerated on the surfaces. With respect to the thickness of this layer, contact surfaces can be partially or completely separated by this layer. It means that this very thin layer (the authors refer to a thickness of about 20 μm) carries the normal load and accommodates the shear force between contact surfaces. After reaching of critical thickness, stiffness of the layer becomes too low to withstand these forces; therefore, some portions of the layer are detached from the rest of the layer. Based on the experiments conducted using the Amsler machine, three possible types of interfacial layers were identified: negative (clay), neutral (magnetite and molybdenum sulphide), and positive (sand) interfacial layer, see Fig. 2.20. The following shear stress model of the interfacial layer was proposed:

$$\tau = G \cdot \gamma \qquad \tau \leq \tau_c \tag{2.3}$$

$$\tau = \tau_c + k \cdot (\gamma - \gamma_c) \qquad \tau > \tau_c \tag{2.4}$$

where three key properties of the interfacial layer were identified, namely: the shear elastic modulus G influencing the initial period of slip; the critical shear stress τ_c influencing a level of friction; the shear plastic modulus k representing the slope of friction curve beyond the critical shear stress. These parameters were subsequently used by Meierhofer et al. [45] who developed and verified, using a twin-disc machine, a model of the third body layer and its effect on adhesion. Moreover, the influence of three above-mentioned key parameters on adhesion was introduced in the Meierhofer's study. The analyses showed that the adhesion coefficient decreases if one of the following parameters is reduced: the critical shear stress τ_c, or the elastic shear modulus G, or the plastic shear modulus k. On the contrary, a decrease in the thickness of the third body layer results in an increase in the adhesion coefficient.

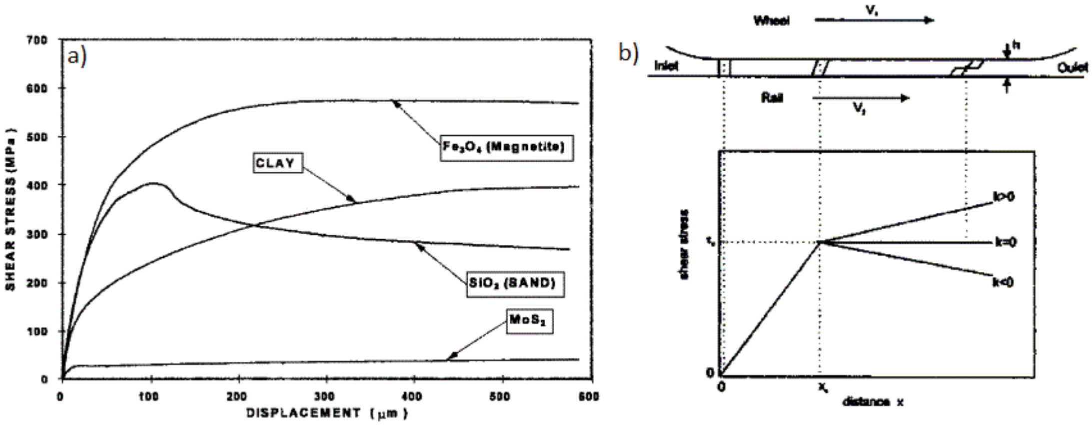


Fig. 2.20 Shear stress curves for tested components (a) and shear stress model of the layer [44].

Afterwards, Berthier et al. [46] distinguished the so-called “natural” and “artificial” third body. The former contains particles from the contact bodies formed during a rolling/sliding motion while the latter is formed by contaminants such as leaves, water, dust, etc. It can be important to be aware of these differences because the thickness as well as the friction behaviour of these two third bodies can be significantly varied. In the case of natural third body, thickness can be varied in the range from a few microns to tens of microns. The authors mentioned that significant differences in friction values can be expected because the rheological properties of the third body can be substantially changed due to contaminants.

The presence of the third body layer can also reduce the risks associated with cracks and the presence of the third body can ensure a higher reliability and a longer lifetime of contact bodies.

Niccolini et al. [47] described a rheological behaviour of the third body as the part of the so-called tribological triplet, see Fig. 2.21. This triplet includes: the base bodies S_1 and S_5 (wheel and rail), the screens S_2 and S_4, and the third body S_3. At first, three different rheological behaviours of the third body, which can be activated at different slips in wheel-rail contact, were introduced. In the case of low slip (approx. 1%), the so-called screens layers (yellow traces) can be identified on the surfaces as a result of the action of asperities, see Fig. 2.22a. At higher slip values, small third body particles are created. These particles form, together with screens layers, a solid film of third body, see the local black strips in Fig. 2.22b. The last type of behaviour of the third body is associated with the formation of large particles (approx. 200 µm^2) within the solid film, see Fig. 2.22c. After this description, the authors studied, using a roller machine (the roller is loaded against the rail), the influence of the third body on adhesion. When the natural third body covered both the roller and the rail, it was revealed that the presence of this third body enables to increase the maximum adhesion in the contact depending on the shear strength of this third body. The higher is the shear strength, the higher is the level of adhesion which can be achieved. Then, the roller third body was removed by grinding while the rail third body remained untouched. The results showed that the absence of the roller third body limits the maximum value of adhesion in the contact.

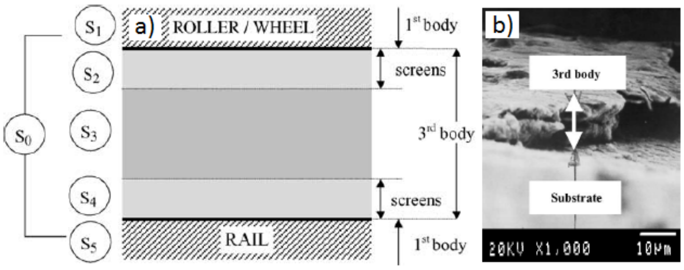


Fig. 2.21 Tribological triplet (a) and section of natural third body (b) [47].

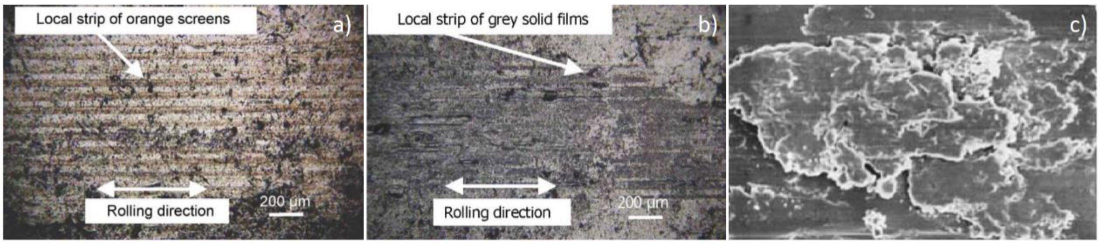


Fig. 2.22 Screens layers (a), solid third body layer (b), and large particles of third body (c) [47].

Subsequently, Nakahara et al. [48] investigated the changes in the composition of the surface oxide layer and their impact on adhesion depending on the sliding distance. All friction measurements were conducted using a twin-disc machine which was previously employed by Baek [15],[16]. Chemical analyses were carried out using auger Electron Spectroscopy, laser Raman scattering spectroscopy and

Fourier transform infrared spectroscopy. It was found, for both dry and wet conditions, that the presence of hard α-Fe_2O_3 (hematite) in the layer causes a sudden increase in the traction coefficient while a decrease in adhesion was observed when the oxide layer consisted of soft Fe_3O_4 (magnetite), see Fig. 2.23. The atomic concentration of oxygen close to the disc surface (sputter depth 10 nm) was changed from almost 0% (A) to 60% (D) for dry conditions and from 10% (a) to 50% (d) for wet conditions. The concentration of iron had an inverse relationship to the concentration of oxygen. The thickness of the layer at the end of the experiment reached 680 nm for dry conditions and 100 nm for wet conditions.

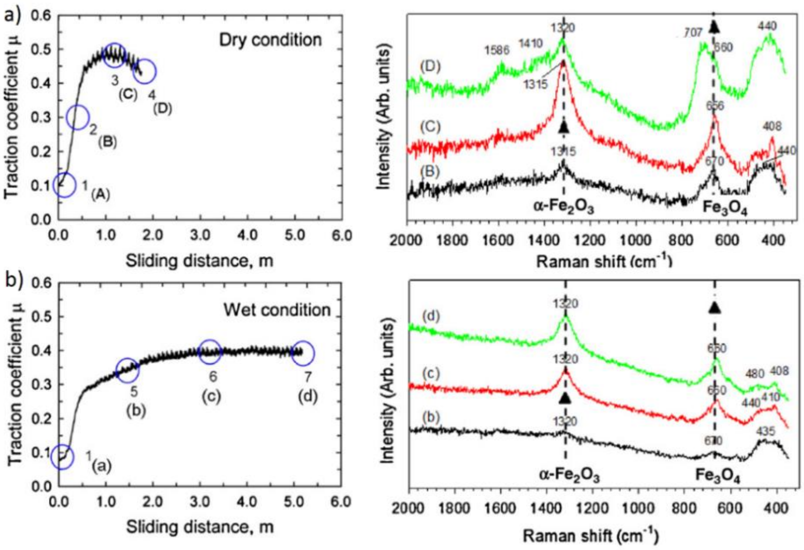


Fig. 2.23 Trend of traction coefficient and Raman spectra of discs for worn surfaces from stage (B) to (D) for dry conditions (a) and for wet conditions (b) [48].

A great deal of research into the effects of environmental conditions, third body layer, and iron oxides was recently performed by Zhu et al. [49]-[51]. In the articles [49] and [51], a pin-on-disc tribometer with a climate chamber was used in order to set various temperatures and relative humidity (RH); thus, different oxides can be formed on the contact surfaces. The authors referred to three types of iron oxides which can be found at the wheel-rail interface, specifically: wustite (FeO), magnetite (Fe_3O_4) known as “black oxide”, and hematite (Fe_2O_3) known as “red oxide”. The authors also revealed that the presence of hematite together with humidity influences the shape of friction curve, while magnetite is formed in a damp environment and creates a friction layer protecting the contact surface against severe wear. The effect of wustite was not considered in these articles because this oxide is usually formed at high temperatures (500 °C) which did not occur in the contact under used experimental conditions. The results showed that hematite strongly affected the friction coefficient in the case of the boundary lubrication regime. It was observed that if the contact surfaces are covered with hematite, it prevents a significant reduction in the friction coefficient by e.g. water, see Fig. 2.24a. This figure gives the evidence that hematite is able to weaken the effect of water molecules (boundary lubrication); thus, a further decrease in friction is avoided. These articles also showed that the friction coefficient significantly decreases with increasing RH especially when RH is low, see Fig. 2.24b.

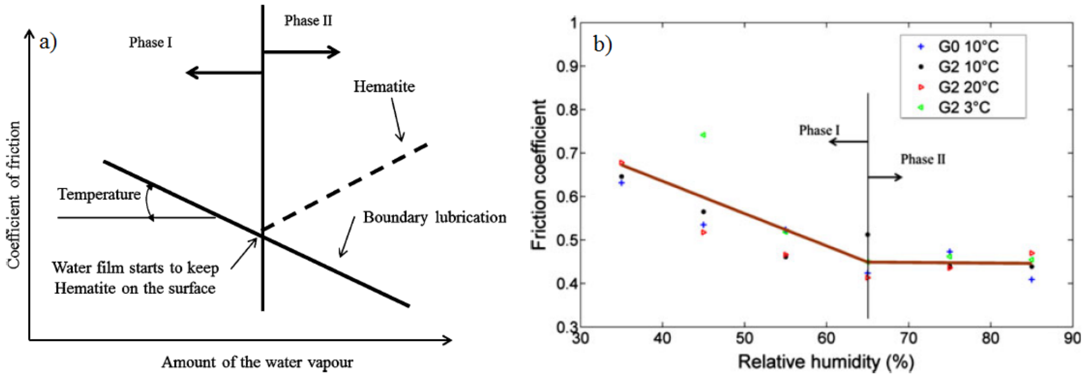


Fig. 2.24 Diagram showing the effect of hematite and water vapour on friction (a), and the effect of RH on friction (b) [49].

Besides environmental conditions, Zhu et al. [50] dealt with the effect of surface roughness and thickness of the oxide layer on the adhesion coefficient. For this purpose, a twin-disc machine was employed where the discs with different roughness (rail disc) and thickness of the oxide layer (wheel disc) were run. As is depicted in Fig. 2.25a, the adhesion coefficient reached almost 0.4 for a clean pair of discs (baseline conditions). It is evident that the highest adhesion provides a pair of rough rail disc and a wheel disc with a thick oxide layer while the adhesion closest to baseline conditions was found for a smooth rail disc and a wheel disc with a thick oxide layer, see Fig. 2.25a. It means that there is no clear dependence of adhesion on the oxide layer for smooth surfaces but both the oxide layer and surface roughness had a substantial effect on the adhesion coefficient. In contrast, an almost negligible effect of these parameters was observed under wet conditions, see Fig. 2.25b. Wear tests showed that a rough surface with a thick layer caused a sharp increase in the wear rate for both dry and wet conditions. The lowest wear rate, lower than that for a clean pair, was found for smooth surface with a thin layer; it indicates that a thin oxide layer is able to protect contact surfaces. This pair of discs also provided the lowest surface roughness after experiments.

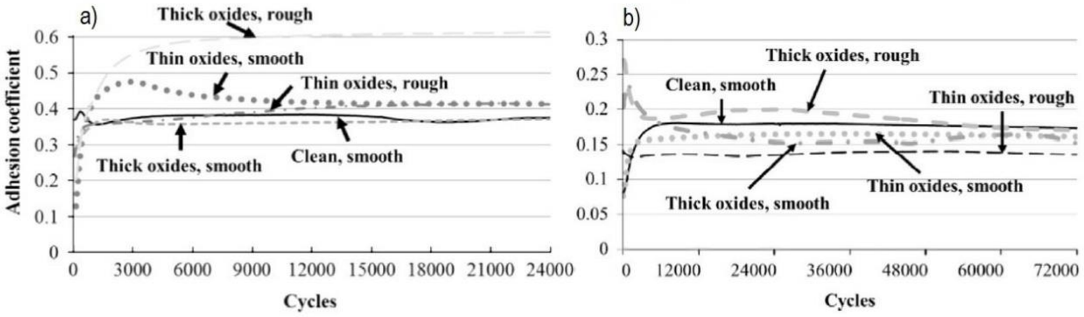


Fig. 2.25 Effect of oxides and roughness on adhesion under dry (a) and wet (b) conditions [50].

2.6.2

2.6.2 Effect of TOR products on adhesion

A performance of TOR products in laboratory conditions has been intensively investigated since 2002 when Matsumoto et al. [52] described, using a scaled roller stand (scale 1/5), how a liquid FM influences a shape of longitudinal and lateral traction curves. The results showed that the tested liquid FM is able to avoid a negative trend of longitudinal and lateral traction curves which was observed under dry conditions, see Fig. 2.26. However, the effect of FM on the level of adhesion was not discussed in this paper. Afterwards, the same authors employed a 1/10-scaled model vehicle in order to describe how FM affects adhesion in the contact during several consecutive passes of vehicle through the tight curve (3.3 m radius) [53]. The tested FM was again Keltrack™, which was sprayed only on the top of the low rail using a nozzle. As is clearly evident from Fig. 2.27a, the adhesion coefficient is dramatically reduced (to approx. 0.15) immediately after the application (the 21st test) and then, a gradual increase in adhesion up to the dry level was observed. The same trend was found after re-application of FM. To find a balance between the supply and consumption of FM, other experiments were carried out using a twin-disc machine. For this purpose, a set of experiments was conducted with various values of spraying time (0.2, 0.4, and 1.0 sec) and various values of slip (0–2%). A summary of these experiments is shown in Fig. 2.27b.

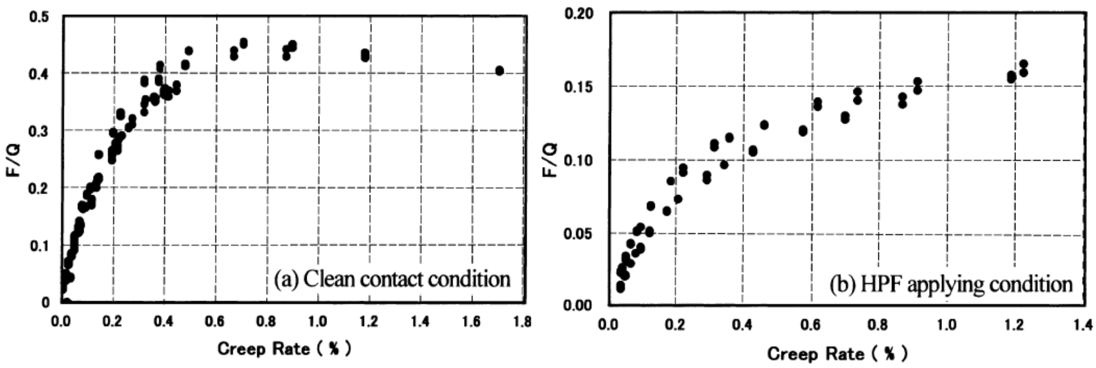


Fig. 2.26 Longitudinal traction curve under dry (a) and FM conditions (b) [52].

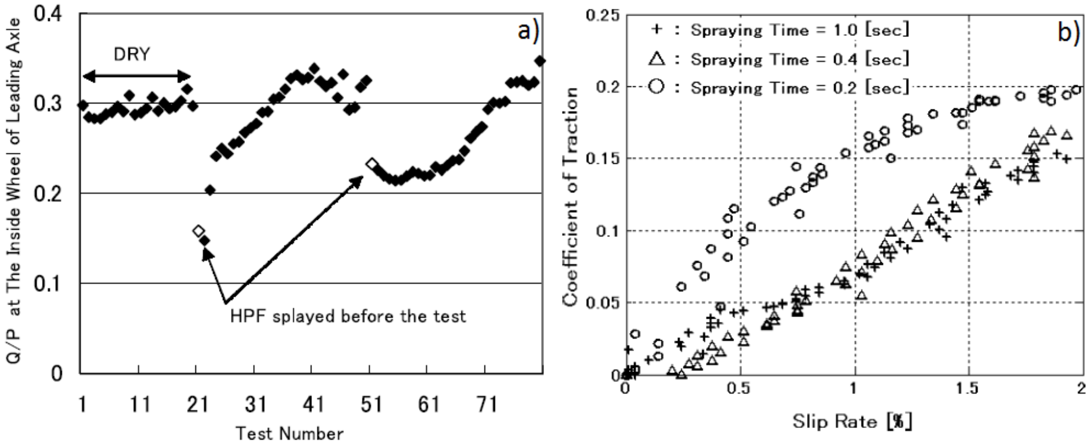


Fig. 2.27 Effect of vehicle passes on adhesion (a) and traction curve for various spraying time [53].

Although there was no significant difference between the spraying time of 0.4 sec and 1.0 sec, the spraying time of 0.2 sec provided an intermediate positive characteristic. Based on this, the authors concluded that the trend of traction curve can be controlled through the FM amount. Moreover, these experiments also showed that the duration of FM is significantly affected by the actual value of slip. The higher is the slip value, the shorter is the FM duration in the contact.

In 2005, Lu et al. published the article [54] dealing with the interaction of FM (Keltrack™) with iron oxides (Fe_2O_3) and the interaction of FM with calcium-based grease for rail gauge face lubrication. A pin-on-disc rheometer (pure sliding conditions) was utilized to evaluate a relationship between the shear stress and displacement (shear strain) of FM-Fe_2O_3 and FM-grease composites. Friction properties of these composites were studied using a twin-disc machine at 3% of slip. The obtained results showed that if the friction film contains only iron oxides, then this film enables to accommodate a very high shear stress (approx. 460 MPa), see Fig. 2.28a. When FM was applied on the iron-coated steel surface, it was established that the shear stress, as well as the adhesion coefficient, decreases with the increasing content of FM in the friction film, see Fig. 2.28. These results give the evidence that the tested FM is able to control friction in the contact over a wide range of iron oxides concentration (0–80%). Moreover, it is clear that these results correspond to the EW (equal wear) model. According to this model, the adhesion coefficient is mainly influenced by the particles with a higher wear-resistance. It explains why the effect of FM particles prevails over the effect of iron oxide particles despite higher concentration of iron oxide particles.

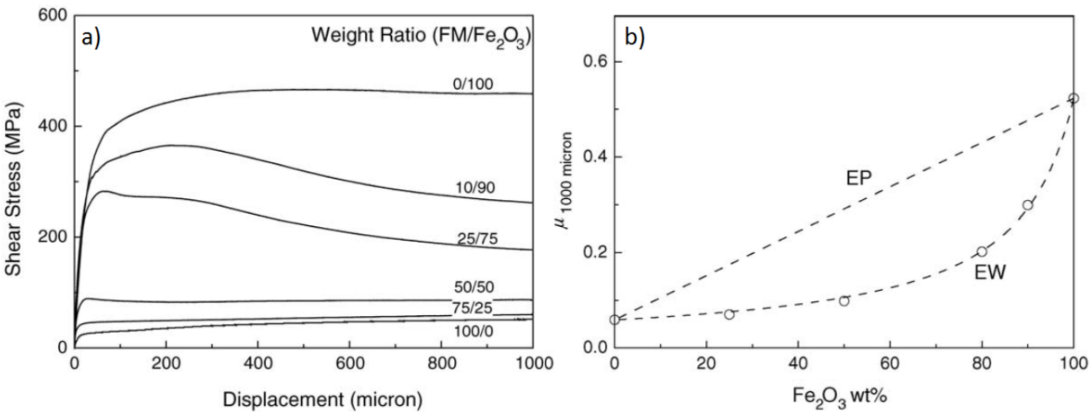


Fig. 2.28 Shear stress vs displacement for FM-Fe_2O_3 composites (a) and effect of Fe_2O_3 concentration on adhesion (b) [54].

In the case of friction measurements with FM-grease composites, the upper disc was coated with a thin FM film (2–3 mg), while the contact zone of the lower disc was partially covered with grease of weight ranging 0 to 60 mg. Based on the results in Fig. 2.29, it was suggested that some of FM-grease composites exhibit the so-called "N"-shape behaviour. In these cases, a friction curve can be divided into three following parts: (1) a rapid increase of adhesion (running-in), (2) a relatively stable adhesion, and (3) a second rapid increase of adhesion accompanied by a steel-steel contact. This behaviour is advantageous for a lasting effect of FM. This lasting effect is usually considered as the time period between the FM application and the moment when adhesion is recovered to a dry level. The results in Fig. 2.29 showed that an increase in grease content led mainly to the extension of the second part. In the extreme case (60 mg of grease), a friction curve was almost identical to that of grease only.

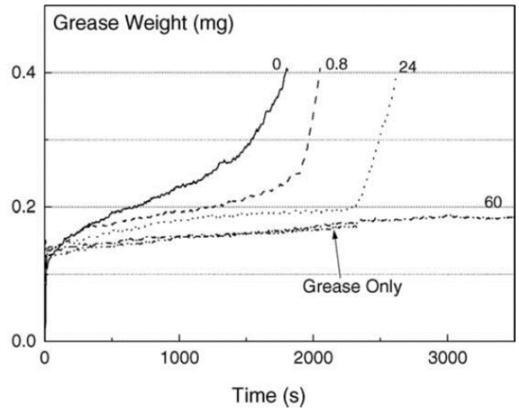


Fig. 2.29 Effect of grease concentration in FM-grease composites on adhesion [54].

In the following study, Cuevas et al. [55] investigated the performance of FMs (identified as FMA and FMB) using a twin-disc machine (SUROS) under dry and wet conditions. Laser particle analyses showed that FMA and FMB contain solid particles (PFM) with a predominant size of 100 and 420 µm, respectively. Furthermore, there are other differences in compositions of both FMs, e.g. FMA contains polymeric components leading to a better adherence to the contact surfaces. Another difference is that FMB contains, besides mineral particles, also steel particles which guarantee suitable electrical properties of FMB. Both tested FMs provided a positive trend of the traction curve; however, significant differences in the behaviour of tested FMs were found under dry conditions, see Fig 2.30a. While FMA was able to form a durable friction layer providing an intermediate level of adhesion for all tested slips (0.5–3%), FMB caused a rapid increase of adhesion immediately after its application; thus, the lasting effect of this FM was rather limited and a higher wear rate and more serious damage of contact surfaces can be expected (the effect of both FMs on wear is discussed in the following subchapter). The ability of FMB to provide a higher adhesion coefficient was beneficial during experiments under

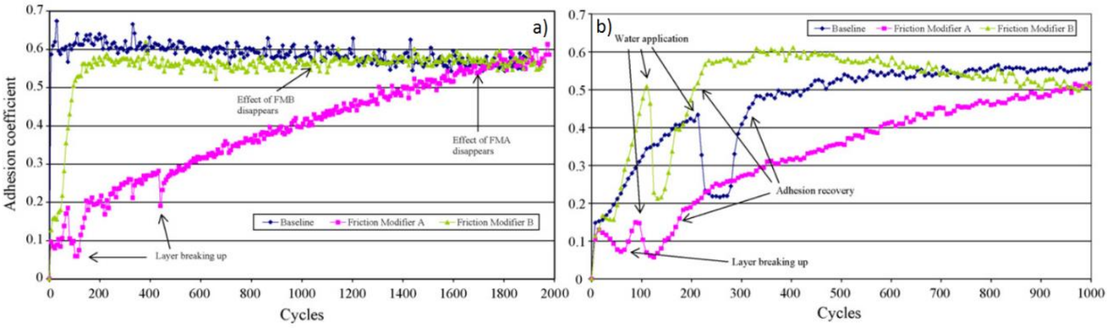


Fig. 2.30 Friction test at 2% slip under dry conditions (a) and under wet conditions (b) [55].

wet conditions. Whereas FMA, FM with smaller solid particles, caused a drop in adhesion below 0.1, which is insufficient for traction and braking, FMB maintained adhesion close to 0.2 after the application of water, see Fig 2.30b. Based on these experiments, it was concluded that the size of PFM which are contained in FM, plays a crucial role in friction behaviour. FM with smaller particles (FMA) provides a longer lasting effect and an intermediate level of adhesion. However, this FM can lead to traction and braking difficulties under wet conditions.

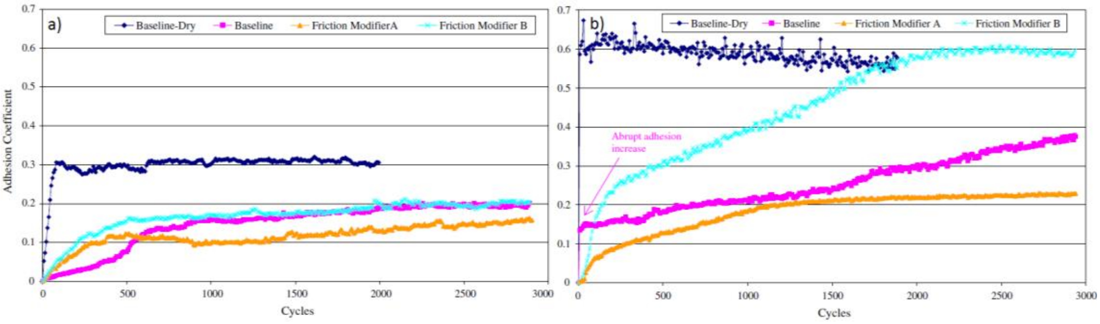


Fig. 2.31 Leaf contaminated tests at 0.5% slip (a) and at 2% slip [56].

The same authors studied an interaction between the above-mentioned FMs and leaf layers (Dutch sycamore leaves) [56]. For this purpose, the same conditions and the same experimental apparatus were employed. These finding showed that leaves (baseline) can reduced adhesion below 0.05, especially at low slip values, see Fig. 2.31a. As in the previous publication [55], large and hard solid particles of FMB are able to break up the leaf layer; thus, an abrupt increase in adhesion occurs, see Fig. 2.31b. In contrast, FMA provided a rather intermediate and stable adhesion, which is advantageous for wear, but with some risks, especially immediately after the application, associated with poor adhesion conditions. This paper gives the evidence that the size and hardness of PFM play the main role in adhesion recovery. The authors mentioned that these two parameters should be chosen with respect to the hardness and thickness of the leaf layer because the excessive hardness and size of PFM can have a negative impact on wear and (RCF).

Afterwards, Lewis et al. employed a pin-on-disc apparatus to investigate how RH (40–90%), temperature (10 and 20°C), and railhead contaminants (red and black iron oxides) influence the performance of FMs [57]. Environmental conditions were chosen in order to achieve the typical tunnel conditions during experiments (high RH and low temperature). At the beginning of each experiment, FM/oxide mixtures were prepared where the mass concentration of oxides was changed from 25 to 43%. The results showed that the performance of mixtures containing FM and iron oxides is significantly affected by the change of RH and temperature, especially when the concentration of oxides is lower than 45%. It was found that adhesion decreases with increasing RH or temperature, see Fig. 2.32. Moreover, these effects become more significant for the typical tunnel conditions where RH is usually higher than 70% and temperature is about 10 °C. These experiments also showed that mixtures with black oxide provide a higher adhesion compared to that with red oxides. Apart from this, the experiments revealed that the lasting effect of mixtures is strongly affected, by the concentration of oxides. As is depicted in Fig. 2.33a, the adhesion coefficient decreases with the increasing concertation of oxides in the mixture. The authors revealed that mixtures with a higher content of oxides have higher viscosities; these mixtures cannot be easily pushed away from the contact unlike the mixtures with low viscosities (low content of oxides). Finally, this article also refers to a glow-discharge optical emission spectroscopy used to evaluate the depth of surface modification. It was found that this depth is much greater for the usual tunnel RH (70%) than for outdoor RH (40%), see Fig. 2.32b.

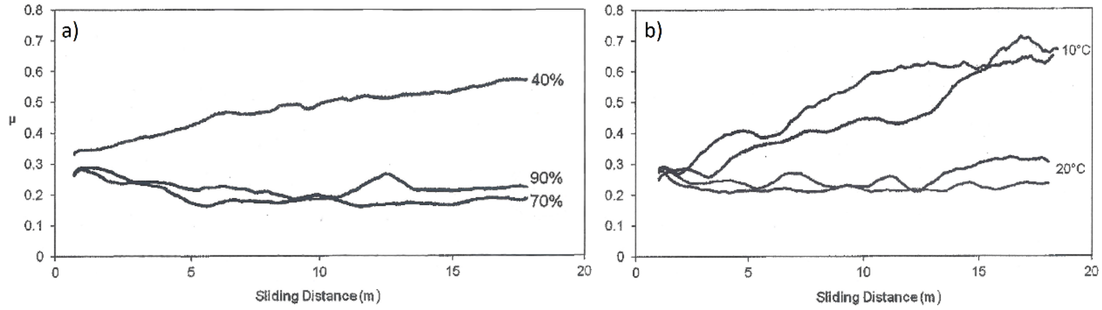


Fig. 2.32 Effect of RH (a) and temperature (b) on the performance of FM/red oxide [57].

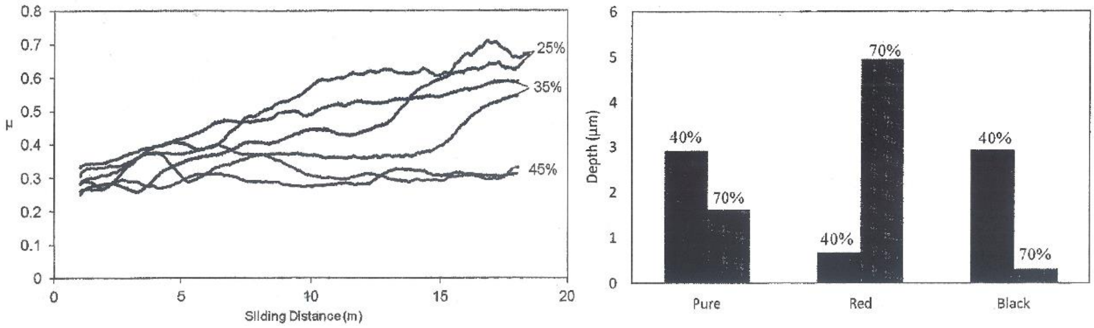


Fig. 2.33 Influence of mass concentration of red oxide on adhesion (a) and effect of oxides and RH on the depth of surface modification (b) [57].

Besides liquid FMs or TOR lubricants, some publications used only PFM as a TOR product, especially alumina particles [58],[59]. Both these studies showed that the application of alumina particles represents a suitable approach to a friction modification. It was revealed that alumina particles lead to a significant increase in adhesion, especially under water and oil-contaminated conditions. Moreover, alumina particles reduce wear in comparison with sand particles [58]. Cao et al. [59] dealt with the alumina particle parameters. It was found that adhesion decreases with the increasing size of alumina particles. In contrast, no clear trend of adhesion with respect to the feed rate was found.

One of the latest publications dealing with the effect of FM and two TOR lubricants on the trend of traction curve was published by Liu et al [60]. The experiments were conducted using a twin-disc machine enabling to set the angle of attack (AoA) between the discs; thus, the misalignment between wheel and rail can be adjusted. During these measurements, the adhesion coefficient and noise were monitored (results of noise measurements are discussed in.2.5.4). As is quite evident from Fig. 2.34, all tested TOR products exhibited a positive trend of traction curve. While FM reduced adhesion to approx. 0.3 for a wide range of speeds, TOR lubricants provided a critical adhesion (below than 0.1). It should be noted that a drop in adhesion in the case of TOR lubricants was previously observed by Ishida et al. [41] who used a hand-pushed tribometer. Besides the issues of low adhesion, the experiments conducted by Liu et al. [60] showed that if the TOR product is applied, then the adhesion coefficient increases with increasing rolling speed, while the opposite trend was found for experiments under dry conditions.

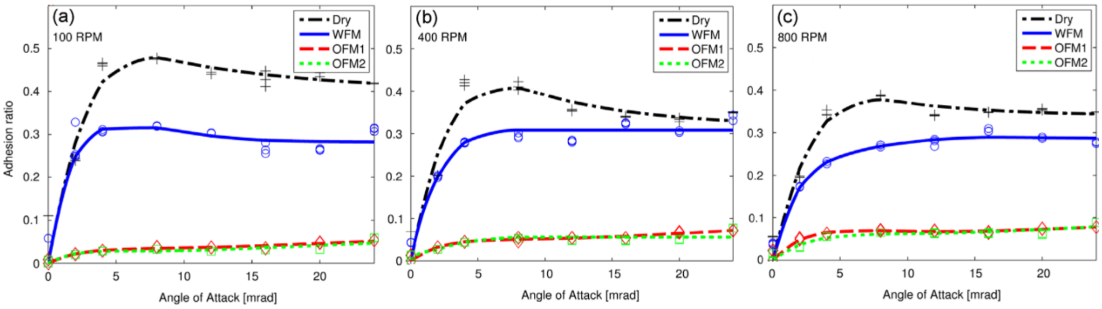


Fig. 2.34 Traction curve at 100 RPM (a), 400 RPM (b), and 800 RPM (c) [60].

2.6.3 Effect of TOR products on wear, surface damage and rolling contact fatigue

The ability of FMs to reduce wear, surface damage and RCF was investigated using a twin-disc machine [55],[56] and a full-scale wheel-rail rig [61],[62]. A detailed description of experiments which were conducted using a twin-disc machine [55],[56] was referred to in the previous subchapter. However, the effect of FMs on wear and surface damage was not discussed. The results of discs analyses from these papers are recorded in Tab. 2.6. It is obvious that the lowest parameters (wear rate, roughness and also hardness) were found for FMA which contains a smaller solid PFM than FMB. In the case of FMB, the parameters are relatively close to the baseline conditions. Moreover, FMB led to a severe surface damage, especially scratches and indentations, due to its hard PFM, see Fig. 2.35. The indentations were also observed on the discs when the performance of FMB was studied under the leaf contaminated contact in [56]. In contrast, no indentations were identified on discs surfaces which were run with FMA. The authors concluded that toughness, hardness and the size of solid particles of FMs should be optimized in order to achieve a balance between adhesion and wear.

Tab. 2.6 The results of discs analyses [55]

	Initial		**Baseline**		**FMA**		**FMB**	
Parameter	*Wheel*	*Rail*	*Wheel*	*Rail*	*Wheel*	*Rail*	*Wheel*	*Rail*
m_{loss} (mg)	-	-	114.9	90.1	30.3	28.4	109.6	70.5
Ra (µm)	1 ± 0.2	1 ± 0.2	7 ± 3	2.7 ± 1	3 ± 0.6	1 ± 0.3	4 ± 1	1 ± 0.3
HV_{20kg}	267	281	420	490	290	390	420	470

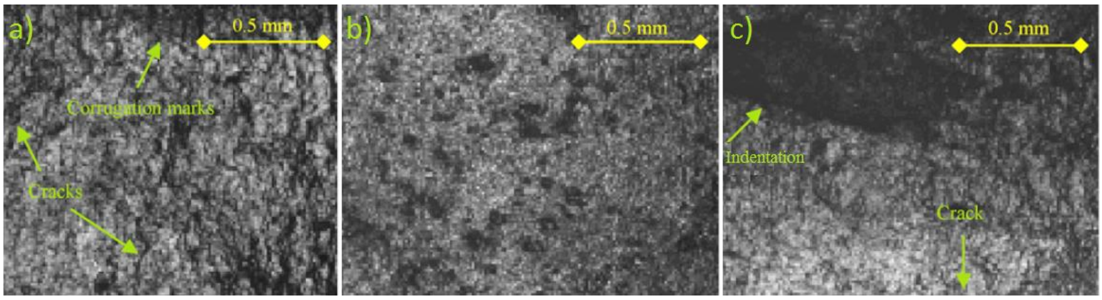


Fig. 2.35 Micro-photographs of the rail disc after 12 000 cycles in dry conditions with baseline (a), with FMA (b) and with FMB (c) [55].

Eadie et al. assessed the effect of FM on wear, RCF and plastic flow under the real load using a laboratory full-scale wheel-rail rig [61]. The employed FM was Keltrack™ which was applied to both the top of the rail and the gauge corner of the rail. A commonly used rail with a standard profile 60E1, which was made from steel R260 (non-head hardened), was used in this research. At first, wear tests showed that FM (application every 250 wheel passes) enables a reduction of rail wear, see Fig. 2.36a. It is evident that almost no change in the rail profile occurred under FM conditions while, under dry conditions, a dramatic change in the rail profile was found. It is noticeable that besides a small amount of wear, a plastic flow was observed at position *D* under FM conditions. Fig. 2.36b shows that FM was also beneficial for reduction of head checks where the application interval seems to be a key parameter. The obtained results indicate that an application at every 250 wheel passes can be considered as an optimal interval because a more frequent application had a negative effect on the propagation of surface cracks. In contrast, a less frequent application was only partially effective because a high number of head checks was detected. Finally, the analyses of plastic flow and surface roughness showed that the application of FM resulted in a reduction in both plastic flow and surface roughness.

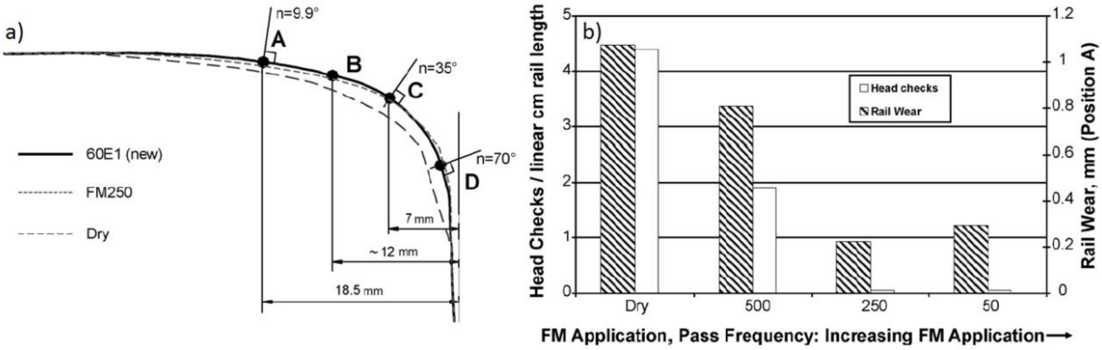


Fig. 2.36 Changes in rail profiles for dry and FM conditions (a) and effect of FM on wear and formation of head checks [61].

Afterwards, the same authors utilized the same test rig and the same FM in order to compare the properties of the above-mentioned rail R260 against a premium rail R350HT under dry and FM conditions [62]. This premium rail is characterized by higher hardness (350HB–450HB) but toughness of this rail is almost identical. It was revealed that a higher rail hardness is beneficial in terms of wear rate and crack depth, under both dry and FM conditions, see Fig. 2.37a. This figure shows how the maximum combined rail damage (wear and RCF at the point *C* according to Fig. 2.36) varied in dependence on the grade of the rail and conditions (dry or FM). It is obvious that the best results were achieved when the premium rail was run under FM conditions. Moreover, this combination (rail R350HT + FM) led to a significant reduction of the plastic flow. On the contrary, a surface analysis showed that the premium rail with FM had almost no positive effect on roughness in comparison with the rail R260 with FM, see Fig. 2.37b. The experiments with pre-existing cracks on the rail 350HT showed that the application of FM can reduce or even completely suppress a further crack growth. In general, these results give the evidence that under dry conditions, the premium rail can significantly extend the rail life, compared to the rail R260. Under FM conditions, the extension of the rail life was much more pronounced for both tested types of rails; however, the effect of the premium rail was not as noticeable as under dry conditions.

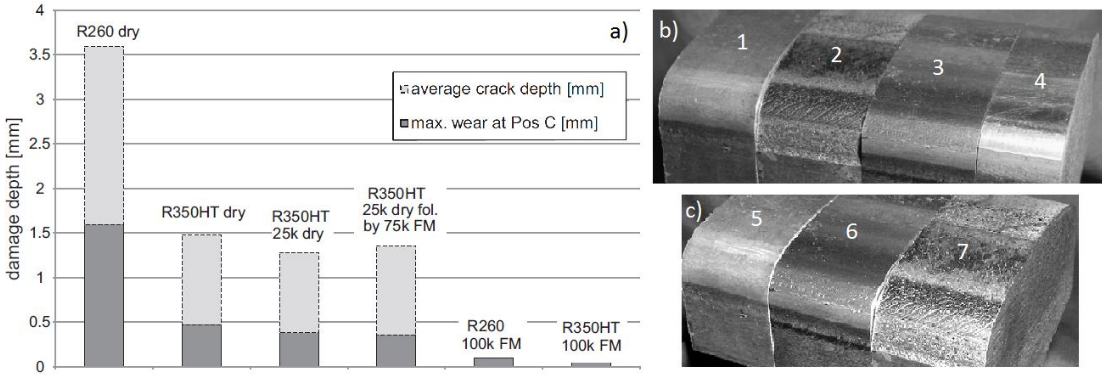


Fig. 2.37 Combined damage of wear and RCF under various conditions (a), comparison of samples of rail R350HT (b): new rail 1, dry 100,000 passes 2, FM 100,000 passes 3, and FM 400,000 passes 4, and comparison of samples of rail R260 (c): new rail 5, FM 100,000 passes, dry 100,000 passes [61],[62].

2.6.4 Effect of TOR products on noise

The effect of three TOR products, one FM and two TOR lubricants, on adhesion and noise was studied by Liu et al. [60]. Friction measurements were described in the previous subchapter. Although all tested TOR products reduced the sound pressure level, see Fig. 2.38, a squeal noise was not completely eliminated despite positive traction curve, see Fig. 2.34. Based on this, the authors developed a simplified model in order to explain why the squeal noise still exists. These simulations showed that there are some instantaneous variations of the lateral creepage (slip) as a result of the flexible nature of the wheel under squeal. It means that squeal vibrations probably still occur even in the case of positive traction curves. A possible explanation is that there are some instantaneous changes in the slope of traction curves, from positive to negative, which are excited by the effect of increasing temperature in the contact.

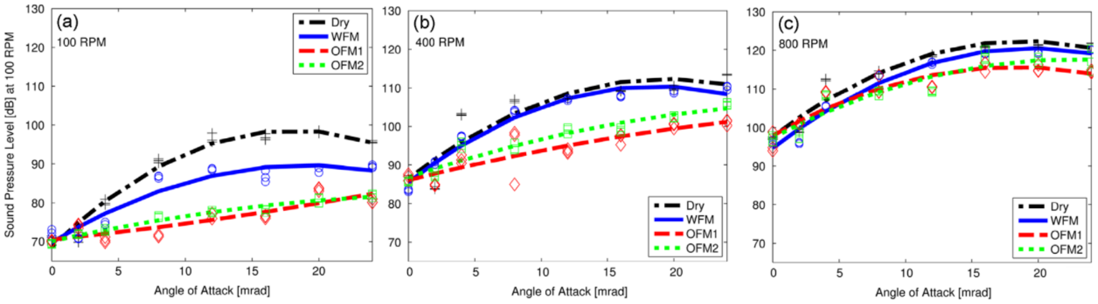


Fig. 2.38 Measured sound pressure level at 100 RPM (a), 400 RPM (b), and 800 RPM (c) [60].

3 ANALYSIS AND CONCLUSION OF LITERATURE REVIEW

At the beginning of the previous chapter, a general knowledge about friction management and mainly TOR products was introduced. It was noted that FMs, as well as TOR lubricants, are primarily used to achieve the positive traction curve and the intermediate level of friction in the contact [29],[30],[61],[62]. These key characteristics should ensure a reduction of wear and noise without a significant impact on traction and braking abilities. From the subsequent literature review, it is apparent that railway research dealing with a behaviour and effects of TOR products can be divided into laboratory and field research. The previous chapter showed that field investigations mainly discussed how the TOR products affect corrugation, noise, and contact forces while laboratory experiments with TOR products are mostly focused on the changes in adhesion, wear, and surface damage.

Field research of FM was started in 1992 by Kalousek et al. [25] who proved a positive effect of solid modifier on corrugation. Since 1996, when a liquid FM was developed, field research has revealed that FMs are able to reduce or completely avoid the evolution of corrugation. This ability was gradually verified using different railway systems, such as metro [30]-[32], tram [31], commuter rail [32], and light rail system [29],[31]. Besides this, a roll-slip oscillation, occurring due to the negative friction after the saturation point, was identified as the initiation mechanism of short pitch corrugation [29]. Field studies also investigated how FM changes the spectral sound distribution and the level of noise emitted from the wheel-rail interface when the vehicle passes through a curve [35],[36]. It was observed that FM reduces both the TOR squeal and flanging noise across a wide range of railway systems. Note that more significant reduction of TOR squeal and flanging noise was observed when FM was applied on both rails [36]. However, another study gives the evidence that the flanging noise is not affected by FM [31]. Subsequently, other conflicted results showed that the flange lubrication is more efficient for TOR squeal reduction compared to FM and TOR lubricants [37]. Moreover, it was established that if FM or TOR lubricants were applied only to the low rail, there were no benefits associated with noise reduction. Afterwards, other authors proved that FM reduces contact forces [30], [38] and also the adhesion coefficient [29],[40],[41]. It was observed that FM is able to provide the intermediate level of adhesion for both rails [29]; however, some cases indicate that a poor adhesion can occur under FM conditions [40],[41]. Low adhesion values were also observed when TOR lubricants were applied and the friction coefficient was measured using a hand-pushed tribometer [20],[42].

In the case of laboratory studies, many authors were interested in the third body layer which is formed between the rail and the wheel [4]-[7],[44]-[51]. At first, Beagley et al. investigated the effect of railhead contaminants on adhesion under dry [4],[7], wet [4],[5],[7] and oil conditions[4],[6],[7]. It was concluded that the boundary lubrication model cannot be used for third-body layers containing solid particles; therefore, the so-called solid and viscous models were introduced [7]. The authors mentioned that if a solid behaviour prevails, then the railhead debris with high shear strength maintain adhesion at an acceptable level [7], even under oily fluids contamination [6]. In contrast, if a viscous behaviour dominates, then poor adhesion conditions can occur [5]. The exact adhesion value is mainly given by viscosity and shear strength of the third-body layer [7]. Later, the elastic-plastic rheological model of the third-body layer was introduced and experimentally verified for three types of third-body layers (negative, neutral, and positive) [44],[45]. Afterwards, a difference between the natural and artificial third body layer was specified [46], and three possible rheological behaviours of the third body layer, which are activated at different slips, were defined [47]. Many researchers also dealt with the role of oxides in the third body layer [48]-[51]. These findings showed that the presence of oxide particles significantly affects adhesion and wear [48],[49].

The ability of FM to provide positive traction curve was first proven by Matsumoto et al. [52],[53], whose findings showed that FM provides this positive trend in both the lateral and longitudinal direction [52]. Moreover, this study [53] showed that the shape of the traction curve can be controlled by the applied amount. Subsequently, the study dealing with mixtures of FM and oxide particles [54],[57] proved the hypothesis that FM is able to control friction over a wide range of iron oxide concentrations because of high wear resistance of FM particles [54]. In the study [54], the so-called N-shape behaviour, providing a longer lasting effect, was introduced. Other authors observed that, under dry [55], wet [55], and leaf [56] conditions, the lasting effect of FM is mainly given by the size and hardness of PFM. Besides this, experiments clarified that FMs can provide a required intermediate level of adhesion for tested conditions. While one of the latest publications [60] again confirmed that FM is able to provide the positive traction curve and the intermediate level of adhesion, a critically low adhesion occurred when TOR lubricants were applied. On the other hand, TOR lubricants were more efficient in the case of noise reduction; nevertheless, a squeal noise was not avoided due to thermal effects. Apart from liquid TOR products, some authors used only PFM for top of rail friction modification [58],[59]. Although PFM are rather friction enhancers compared to typical TOR products, these findings can be useful because these particles (e.g. alumina particles) are the main part of TOR lubricants. Experiments showed that the alumina particles can ensure a required adhesion under water and oil-contaminated conditions and a wear rate is lower in comparison with sanding.

The following part of the literature review was devoted to the effect of TOR products on wear and surface damage [55],[56],[61],[62]. Using a twin-disc, it was proven that both tested FMs reduced wear and surface damage compared to dry conditions [55],[56]. As can be expected, FM with larger particles led to a higher wear rate and more serious surface defects. Experiments using a full-scale rig [61] revealed that FM is able to suppress changes in rail geometry occurring due to wear. Apart from this, FM reduced the number of head checks, plastic flow and surface roughness. A similar performance was also observed for a premium rail R350HT [62].

The literature review shows that TOR products have been intensively studied since 1996. There are a lot of articles dealing with the performance of FMs (water-based products) in terms of adhesion [52]-[60], wear [55],[56],[61],[62], corrugation [29]-[32], and noise [29],[31],[35]-[37]. However, it should be highlighted that almost all these works investigated the performance of one particular commercial product with the trade name KELTRACK™. It means that only a little is known about the effect of FM composition on adhesion, wear, etc. Hence, FMs can be seen as “a black box”. Apart from this, there is a very limited knowledge about the influence of FM amount on adhesion, e.g. when the contact is overdosed with FM. Particularly this may represent a possible risk for traction and braking. It should also be emphasized that the experiments with FMs usually started immediately after the application of FM in spite of the fact that FMs are designed as drying products. In this case, adhesion, as well as other parameters, are influenced by both solid particles and a base medium. However, so far, the articles concerned have not discussed the effect of base medium evaporation on the performance of FMs. The literature review also reveals that only a little has been reported about TOR lubricants even though these products are widely used. Recently published articles [37],[60] have indicated that TOR lubricants reduce noise (squeal noise usually persists); however, adhesion can be reduced to low values with respect to braking/traction capabilities [20],[42],[60]. Based on this, it can be reasonably expected that the performance of TOR lubricants is strongly dependent on the applied amount and the application methods (low rail only or both rails). However, the reviewed studies did not discuss these effects in spite of the fact that a braking/traction performance can be limited. Therefore, it seems necessary to clarify the effect of TOR lubricant amount on adhesion, wear, noise, and other parameters. The aim of the present thesis based on these facts is defined in a greater detail in the following chapter.

4 AIM OF THESIS

The aim of this doctoral thesis is to clarify the friction behaviour and impact of the TOR products on friction in the wheel-rail contact, while the main attention is paid to low adhesion issues related to the application of these substances. For this purpose, adhesion and noise measurements were conducted considering both the laboratory and field conditions. Moreover, a wear rate and wear mechanisms were evaluated. To achieve the main goal of this thesis, the solution to the following sub-aims is necessary:

- Development of twin-disc machine allowing for adjustment of AoA (for noise measurements) and friction and normal force measurement.
- Selection of suitable track for field investigations.
- Selection of appropriate TOR lubricants and preparation of water-based substances (FMs).
- Design of experiments and approaches for evaluating the performance of TOR products.
- Series of laboratory experiments focused on the performance of TOR products considering various operating parameters.
- Verification of some laboratory results by field measurements.
- Data analysis.
- Discussion and publication of obtained results.

4.1 Scientific questions

Q1. *What is the influence of applied quantity and chemical composition of TOR products on their performance?*

Q2. *Can a safe braking distance be guaranteed when the contact is overdosed with TOR products?*

4.2 Hypotheses

H1. *The larger is the applied quantity, the longer is the lasting effect.*

H2. *The shape of friction curve can be controlled by the applied quantity of TOR products; thus, the beneficial friction behaviour can be achieved.*

H3. *TOR products are able to substantially reduce noise without the adhesion drop leading to braking and traction difficulties.*

H4. *When the contact is overdosed with TOR products, the required adhesion level for traction and braking is ensured by PFM.*

H5. *The most significant extension of braking distance can be expected during the first pass of vehicle after the application of TOR product.*

H6. *It is expected that the effect of PFM on adhesion will be much more significant compared to other constituents of TOR products.*

H7. *The higher is the content of PFM, the shorter lasting effect can be expected.*

H8. *Substances without PFM cannot provide stable adhesion in the intermediate level of friction.*

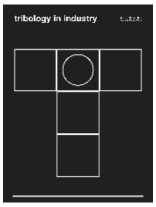
H9. *When a base medium of FMs is evaporated before the experiment, the shorter lasting effect and higher wear rate can be expected.*

4.3 Thesis layout

This doctoral thesis is composed of two papers published in journals with impact factor (Paper A and C) and one paper published in a peer-reviewed journal (Paper B). These three papers dealt with the performance of TOR products where the effect of applied quantity and chemical composition is mainly discussed with respect to possible risks associated with low adhesion. In Paper A, two commercial TOR lubricants, with a different content of PFM, were used in order to evaluate a dependence between the applied quantity and adhesion in the contact. Finally, the ability of both tested TOR lubricants to reduce wear and surface damage was clarified. The obtained results indicate that overdosing of contact with TOR lubricant can lead to adhesion losses. Following these findings, the inability of TOR lubricant to provide a sufficient braking performance in the case of larger applied quantities was verified under field conditions where a series of tram braking tests was carried out (Paper B). Besides this, the influence of TOR lubricant quantity on the noise level was studied under both laboratory and field conditions (Paper B). The last part of this doctoral thesis is focused on water-based TOR products (FMs) where the role of individual constituents of FMs on adhesion was investigated for the so-called “dry” and “wet” film (Paper C). In addition, the effect of FMs on wear and surface damage was discussed in this paper.

A. GALAS, R., M. OMASTA, I. KRUPKA and M. HARTL. Laboratory investigation of ability of oil-based friction modifiers to control adhesion at wheel-rail interface. *Wear,* 2016, 368–369, 230-238.
Author's contribution 50%
Journal impact factor = 2.531, Quartile Q1, CiteScore = 3.00

B. GALAS, R., M. OMASTA, M. KLAPKA, S. KAEWUNRUEN, I. KRUPKA and M. HARTL. Case Study: the Influence of Oil-based Friction Modifier Quantity on Tram Braking Distance and Noise. *Tribology in Industry*, 2017, 39(2), 198-206.
Author's contribution 50%
CiteScore = 1.32



C. GALAS, R., D. KVARDA, M. OMASTA, I. KRUPKA and M. HARTL. The role of constituents contained in water-based friction modifiers for top-of-rail application. *Tribology International*, 2018, 117C, 87-97, *article in press*.
Author's contribution 50%
Journal impact factor = 2.903, Quartile Q1, CiteScore = 3.16

5 MATERIALS AND METHODS

In order to answer the scientific questions presented in the previous chapter, experimental investigations were performed both in the laboratory and in the field. In the case of laboratory investigations, a ball-on-disc tribometer and a twin-disc machine were utilized to study the wheel-rail noise and adhesion. In addition, some experiments were performed via a ball-on-disc optical tribometer, employing the optical interferometry method and a high-speed camera, in order to observe a film formation between contact surfaces. To analyse a surface topography of specimens and a wear rate, a 3D optical profilometer and an analytical balance were used. Field measurements were conducted using a light rail system in Brno, where a curve with corrugated rails was chosen with respect to the high noise pollution in the vicinity of this curve. In this case, the impact of TOR lubricant on the braking distance and the level of noise was assessed. The overview of laboratory devices used in this doctoral study is shown in Fig. 5.1.

The field approach provides reliable results without any simplifications; however, it can be difficult to ensure the constant operating and environmental conditions. In contrast, the experimental conditions can be accurately controlled in the laboratory; thus, the effect of the individual parameters can be evaluated and a better repeatability of experiments can be expected. Apart from that, the laboratory approach represents a much more economical way of research. On the other hand, the obtained laboratory results can be difficult to directly apply to the real wheel-rail contact. In spite of this, the laboratory approach can provide useful findings about the influence of some parameters on adhesion and it can point out which potential risks can occur under various operating and environmental conditions.

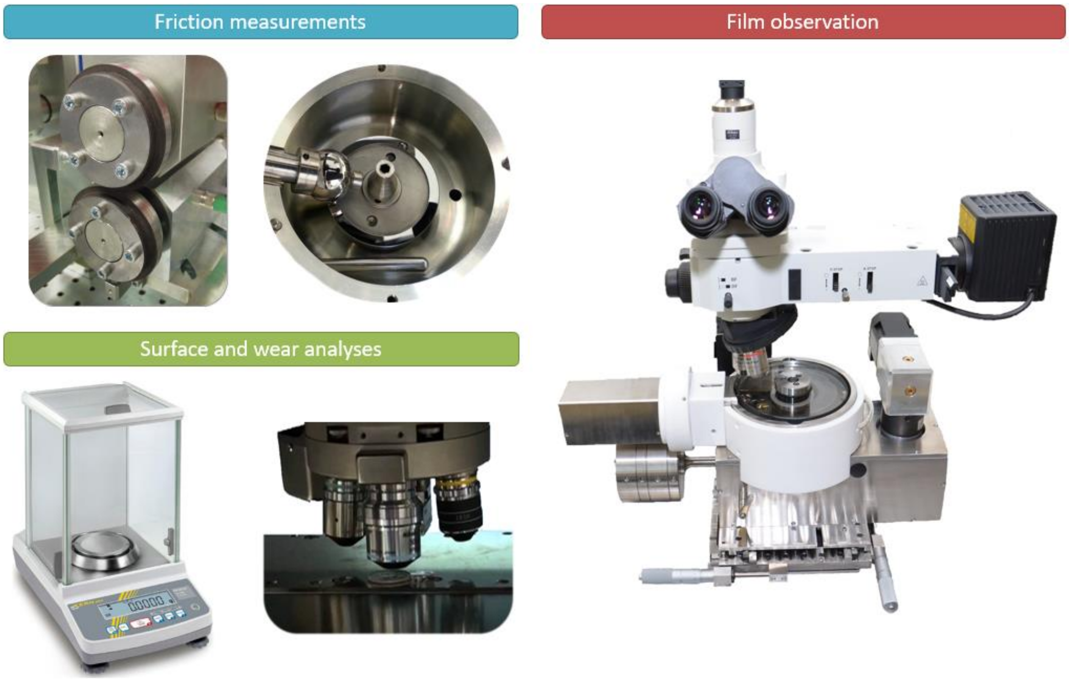


Fig. 5.1 Overview of experimental apparatus used in this doctoral thesis.

5.1 Laboratory measurements

5.1.1 Ball-on-disc tribometer for friction measurement

It is a commercial tribometer *Mini-Traction-Machine* (MTM, PCS Instruments, United Kingdom) enabling to evaluate friction properties of lubricants or unlubricated materials. There are three possible contact configurations: pin-on-disc, ball-on-disc with a ball diameter of 19.05 mm or the same configuration with a ball diameter of 12.7 mm. In this thesis, only the second configuration was used where a 19.05 mm ball is loaded against a 46 mm steel flat disc, see Fig. 5.2. MTM offers a wide range of available materials of specimens such as steel, ceramics, copper, glass, etc. The specification of materials used in this thesis is described in the subchapter 5.3. To evaluate the adhesion coefficient in the contact, MTM is equipped with two load cells enabling to detect both the normal and the friction force with a frequency of 1 Hz. These data are used for the calculation of adhesion coefficient according to Eq. 2.2. Additional sensors measure wear, pot and lubricant temperature, and the electrical contact resistance between the bodies. Both contact bodies are independently driven in order to set the accurate slip value in the contact, which is expressed using the so-called *Slide-to-roll-ratio* (SRR), see the following equation:

$$SRR = \frac{w_{ball} \cdot r_{ball} - w_{disc} \cdot r_{disc}}{w_{ball} \cdot r_{ball} + w_{disc} \cdot r_{disc}} \cdot 200\% \tag{5.1}$$

where w_{ball} and w_{disc} are the angular speeds of the ball and the disc, respectively and r_{ball} and r_{disc} are the radii of these bodies.

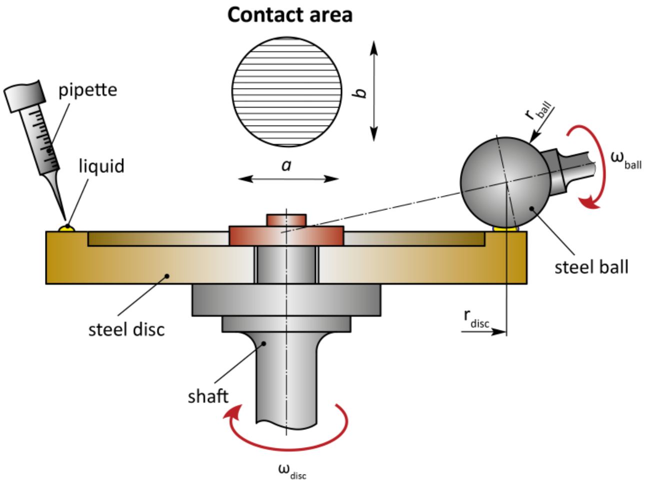


Fig. 5.2 Scheme of ball-on-disc tribometer (MTM) for friction measurement.

5.1.2 Twin-disc machine for friction measurement

The twin-disc machine depicted in Fig. 5.3a was developed as one of the partial aims of this doctoral thesis. The main part of this machine is a pair of steel discs leading to the elliptical contact area according to Hertz theory, see Fig. 5.3b. As in the case of MTM, both discs are independently propelled using electric motors with shaft encoders; therefore, the slip in the contact can be accurately controlled according to Eq. 5.1. The cylindrical upper disc represents the wheel disc, while the lower disc, which is rounded with a radius of 50 mm, represents the rail disc. Load is applied using the spring-screw loading system which is mounted, as well as the load cell of a normal force, at the end of the loading arm. The lower disc is hung on the flexible linkages enabling a transfer of the friction force from the contact to the second load cell. Based on the data from both load cells and Eq. 2.1, the adhesion coefficient is evaluated in real time. As is evident from Fig. 5.3c, the support of the lower disc enables to set different values of AoA in order to simulate a passage of vehicle through a curve. To minimize wear occurring during experiments, the twin-disc machine includes an AC motor-driven screw jack allowing for fast contact unloading. Both discs can be covered with an environmental chamber enabling to precisely control RH and temperature during experiments.

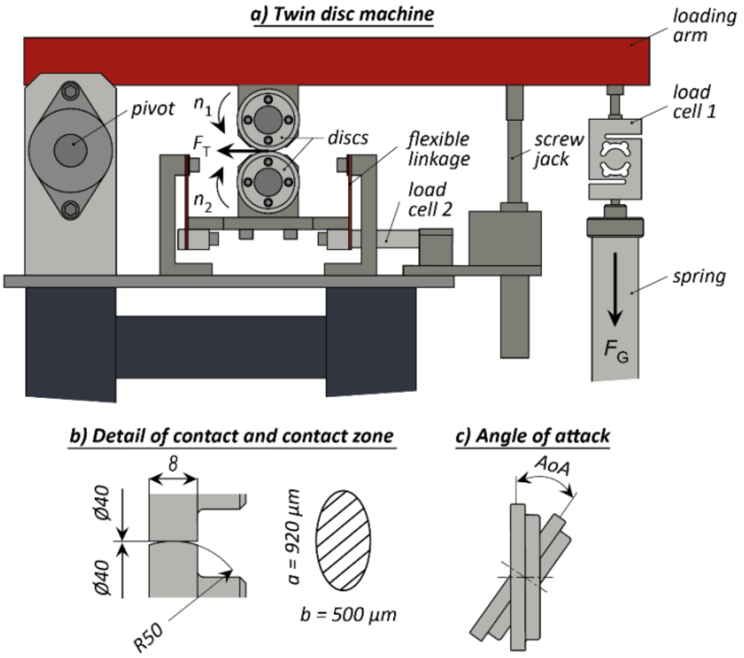


Fig. 5.3 Scheme of twin-disc machine (a), detail of contact (b), and adjustment of AoA (c).

In the case of sound measurements, a hand-held analyser type 2270 (Brüel & Kjær, Denmark) was used for both laboratory and field experiments. In the laboratory, the microphone of analyser was oriented towards the contact of discs. It was mounted 10 cm above the contact of disc (1 m above the floor) and 50 cm from the contact in the horizontal direction.

5.1.3 Ball-on-disc optical tribometer

5.1.3

As was mentioned above, some additional experiments were carried out using the ball-on-disc optical tribometer allowing for observation of a film formation of FM/TOR lubricant (especially PFM) in the contact. In this case, the contact is formed between the 25.4 mm steel ball and the glass or sapphire transparent disc with a chromium layer [63], see Fig. 5.4a. The requested entrainment speed and slip are reached using two independently driven servomotors. Contact load is applied using a lever and deadweight. FM/TOR lubricant with PFM is supplied to the contact with a syringe pump at the inlet to the contact, see Fig. 5.4b. Subsequently, lubricant film thickness is observed using a microscope objective, a high-speed camera, and PC. The exact value of lubricant film thickness is evaluated from chromatic interferograms using the optical interferometry; see Fig. 5.4c, which was described in detail in reference [64].

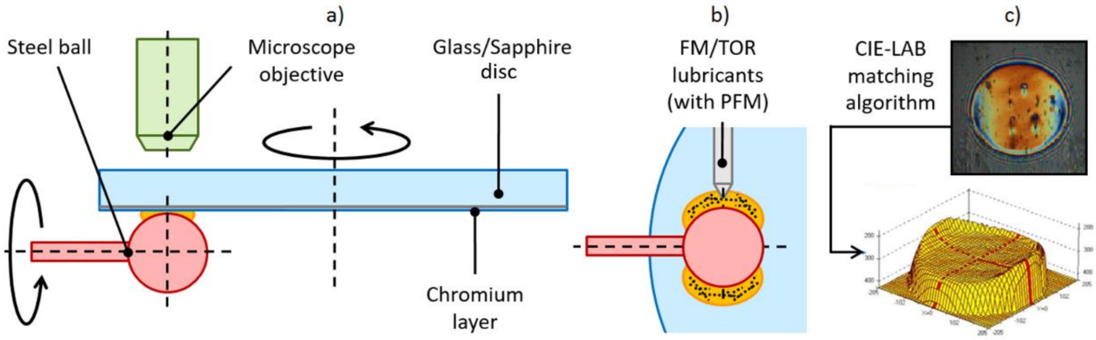
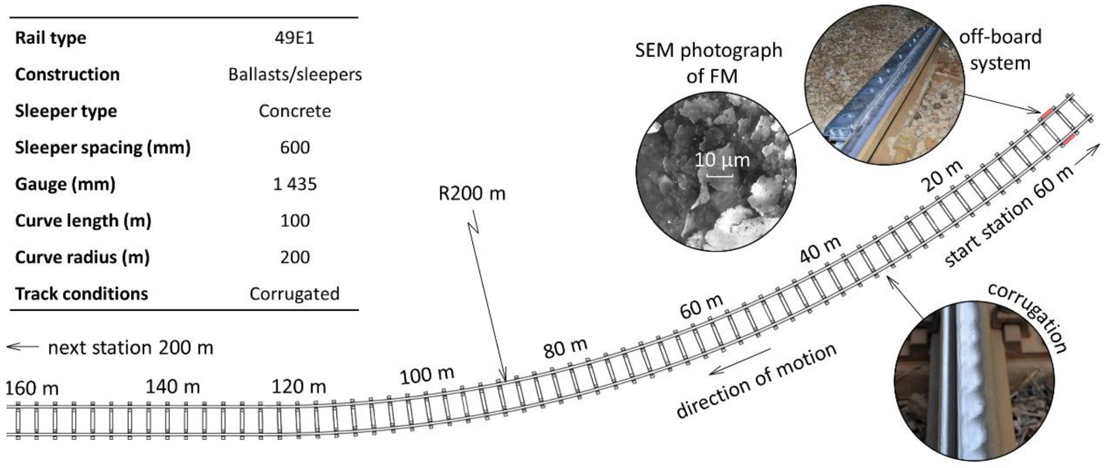


Fig. 5.4 Scheme of ball-on-disc optical tribometer (a), detail of application of FM/TOR lubricant (b), and detail of contact with TOR lubricant (c).

5.1.4 Analysis of wear and surface topography

A 3D optical microscope *ContourGT-X* (Bruker, USA) was utilized to analyse the surface topography of friction specimens, especially roughness and surface damage. This device enables to assess the surface topography with excellent vertical resolution of 0.01 nm using *Phase Shifting Interferometry* (PSI), *Vertical Scanning Interferometry* (VSI) or high-resolution mode of VSI (VXI). The analytic balance KERN ABS-N_ABJ-NM with distinctiveness of 0.1 mg was used to evaluate a wear rate of specimens after experiments.



Rail type	49E1
Construction	Ballasts/sleepers
Sleeper type	Concrete
Sleeper spacing (mm)	600
Gauge (mm)	1 435
Curve length (m)	100
Curve radius (m)	200
Track conditions	Corrugated

Fig. 5.5 Tested curve of light and technical details.

5.2 Field measurements

The ability of TOR lubricant to reduce noise and simultaneously to provide a sufficient traction and braking performance has been tested using the light rail system in Brno, Czech Republic. For this purpose, the curve section of the parallel track with the rail profile 49E1 and the curve radius of 200 m, depicted in Fig. 5.5, was chosen because of a high level of noise in the urban area, corrugation, and heavy traffic. It should be noted that the number of vehicles running through this curve section varies from 95 to 186 per day and that the maximum speed at this curve is 40 km/h. In the tested curve, both rails are corrugated with the predominant wavelength between 30–100 mm and with the average amplitude of 0.2 mm.

Fig. 5.6 Detail of wayside lubrication system.

A TOR lubricant application was realized using a commercial wayside lubrication system (Tribotec, Czech Republic), which was located near the curve and also sufficiently far from the next tram station, see Fig. 5.5 and 5.6 This wayside lubrication system is equipped with a high-pressure pumping device (working pressure of 250 bar) which delivers the required amount of TOR lubricant (viscosity class from NLGI-0 to NLGI-2) to the top of both rails as in the case of the measurements performed by Curley et al. [37]. As can be seen from Fig. 5.5, the TOR lubricant is applied on the top of both rail using the application strips without the need to drill holes in the rails. A lubrication process is started by the vehicle-presence sensor detecting the vehicle on the track. This sensor also sends the information on the number of passing axles of vehicles to the control system, based on which the application interval can be set and controlled. The applied amount is controlled by the pump run time.

A level of sound was measured using the same analyser as in the laboratory. In this case, the analyser was placed 7.5 m from the centre of the track with the microphone of analyser 1.2 m above the ground.

5.3 Test samples, experimental conditions and experiment design

5.3.1 Paper A

In this paper, the friction behaviour of two commercial TOR lubricants and castor oil were investigated using the MTM device. In the Paper A, the tested TOR lubricants are identified as FMA and FMB. However, these indications can be confusing because “FM” is the abbreviation of the term *Friction Modifier* (water-based product). Therefore, two tested TOR lubricants below are referred to as TORL-A and TORL-B instead of FMA and FMB.

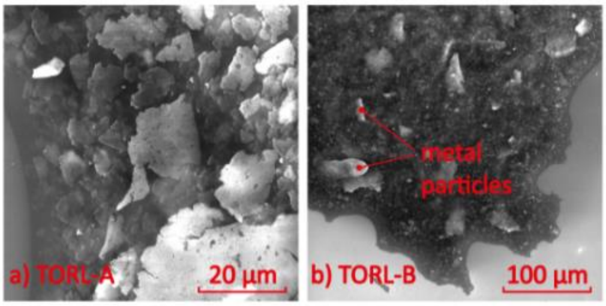


Fig. 5.7 SEM photographs of TORL-A (a) and TORL-B (b).

The base media of TORL-A and TORL-B are the plant oil and the ester oil, respectively. Both these products include PFM; particularly Cu and Zn particles are contained in TORL-A while TORL-B contains Cu and Al particles. The particles size distribution showed that the predominant size of PFM is between 4–10 µm for both TOR lubricants but the number of PFM is significantly higher in TORL-A, see Tab. 5.1 and Fig. 5.7.

Tab. 5.1 Particle size distribution of TORL-A and TORL-B

Particle size	**Number of particles per 1 ml**	
	TORL-A	***TORL-B***
4-10 µm	145 915 182	3 560 883
10-20 µm	12 171 798	147 966
20-30 µm	888 070	7 446
30-40 µm	69 201	512
40-50 µm	5 299	102
60-70 µm	474	0
70-80 µm	40	51
>80 µm	0	0

The MTM disc was made from C45; its chemical composition, as well as hardness, nearly correspond to the frequently used wheel steel R7T. In the case of the ball, the material was a low carbon steel AISI 1010 with a significantly higher hardness compared to a real rail. This material and hardness were chosen with respect to the machining requirements. An overview of used materials is shown in Tab. 5.2. The initial average roughness of specimens was Ra 0.45 µm (the disc) and 0.05 µm (the ball).

Tab. 5.2 Chemical composition of ball and disc

Material	Chemical compositions (wt%)					Hardness (HB)
	C	*Si*	*Mn*	*Ni*	*Cr*	
UIC 900A	0.70	0.35	1.10	-	-	280-300
R7T	0.52	0.40	0.80	0.30	0.30	245
AISI 1010 (ball)	0.13	0.10	0.60	-	-	650
C45 (disc)	0.46	0.25	0.65	0.3	0.25	245

Three different types of experiments are included in Paper A, namely: *friction test*, *Stribeck test*, and *lubricant volume test*, see Tab. 5.3. Moreover, a *run-in test* was performed at the beginning of each experiment to achieve a dry level of adhesion. In the case of new specimens, this run-in phase was accompanied by a significant change in roughnesses as is depicted in Fig. 5.8. After stabilization of roughness and adhesion, the required amount of TOR lubricant/oil was applied to the contact path with a micropipette and one of the experiments mentioned in Tab. 5.3 was subsequently started.

Tab. 5.3 Experimental conditions for MTM tests – paper A

	Run-in	Friction test	Stribeck test	Lubricant volume test
Pressure, GPa	0.75	0.75	0.75	0.75
Speed, mm/s	300	300	1 - 2500	300
SRR %	1, 3, 5, 10	1, 3, 5, 10	10	10
Conditions	dry	TORL-A, TORL-B, oil	TORL-A, TORL-B	TORL-A, TORL-B
Amount, µl	-	1	fully flooded	1 - 4

The contact pressure of 0.75 GPa was chosen regarding to the real contact pressure in light rail systems. The values of SRR (1, 3, 5, and 10%) were chosen with respect to the actual shape of the traction curve measured with the MTM device where the SRR values (1, 3, and 5%) did not lead to the full contact saturation. In other words, if the contact operates at these slips (1, 3, and 5%), then the contact is definitely composed of both the slip and stick regions, see *part I* in Fig. 2.4.

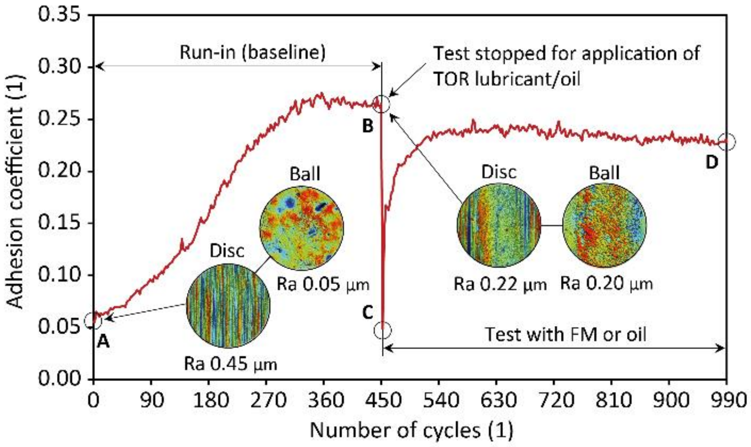


Fig. 5.8 Complete friction test including run-in phase and tests with TOR lubricant/oil

The rolling speed of 300 mm/s was selected based on the calculation of the film-thickness parameter Λ_l, see Eq. 5.2. This parameter expresses the ratio between the film thickness h_l and the combined surface roughness, where R_{q1} and R_{q2} are RMS surface roughnesses of the disc and the ball, respectively. The rolling speed of 300 mm/s should ensure that the contact with castor oil/TOR lubricants operates in the boundary lubrication where the film-thickness parameter Λ_l is less than 1.

$$\Lambda_{\mathrm{l}} = \frac{h_{\mathrm{l}}}{\sqrt{R_{\mathrm{q}1}^2 + R_{\mathrm{q}2}^2}} \tag{5.2}$$

As was mentioned above, Paper A includes three types of experiments. In the case of *friction* and *lubricant volume test*, the performance of TOR lubricants/oil was evaluated regarding to the following points:

- ***Lasting effect*** – the time period from the application of TOR lubricant/oil to the moment when the adhesion coefficient reaches a high adhesion according to Tab. 5.4.
- ***Critically low adhesion*** – the period when the adhesion coefficient is lower than 0.15 according to Tab. 5.4.
- ***Intermediate (optimal) adhesion*** – the period when the adhesion coefficient is in the optimal adhesion range according to Tab. 5.4.
- ***N-shape behaviour*** – the ability of TOR lubricants to provide the N-shape behaviour which was described by Liu et al. [60].

Tab. 5.4 Adhesion levels for evaluation of TORLs performance – paper A

SRR	Critically low adhesion	Low adhesion	Intermediate adhesion	High adhesion
1%	μ < 0.15	0.15 – 0.20	0.20 – 0.25	μ > 0.25
3%	μ < 0.15	0.15 – 0.20	0.20 – 0.35	μ > 0.35
5%	μ < 0.15	0.15 – 0.20	0.20 – 0.40	μ > 0.40
10%	μ < 0.15	0.15 – 0.20	0.20 – 0.40	μ > 0.40

It is noteworthy that the intermediate level of adhesion is usually considered 0.2–0.4. However, these values are valid especially for the case when the contact operates in the vicinity of the saturation point, see Fig. 2.4. Therefore, the intermediate level of adhesion from 0.2 to 0.4 can be used only for slip 5 and 10%, while the intermediate level of adhesion for lower slips (1 and 3%) should be recalculated with respect to the dry level of adhesion at these slips. At the end of each experiment, both contact bodies were ultrasonically cleaned with acetone.

Stribeck tests were conducted under fully-flooded conditions in order to investigate if TOR lubricants can cause poor adhesion conditions when the contact is overdosed with TOR lubricants. Based on the obtained results, some additional experiments, which are not included in Paper A, were performed using the ball-on-disc optical tribometer described above. The aim of these additional experiments was to clarify whether the PFM particles contained in TOR lubricants can easily enter the contact under fully flooded conditions, see Fig. 5.9. For this purpose, TORL-A and a mixture of castor oil and alumina particles (TORL-C) were used because these lubricants are transparent. To investigate the effect of PFM on a film formation, the same experiments with the base oils of TORL-A and TORL-C were subsequently conducted using an optical tribometer. The experiments performed via the optical tribometer are summarized in Tab. 5.5. As was mentioned above, these results are not included in Paper A; they are discussed in the following chapter. When all friction and Stribeck tests were accomplished, disc specimens were analysed using a 3D optical microscope and an analytic balance to evaluate the wear rate and mechanisms of wear.

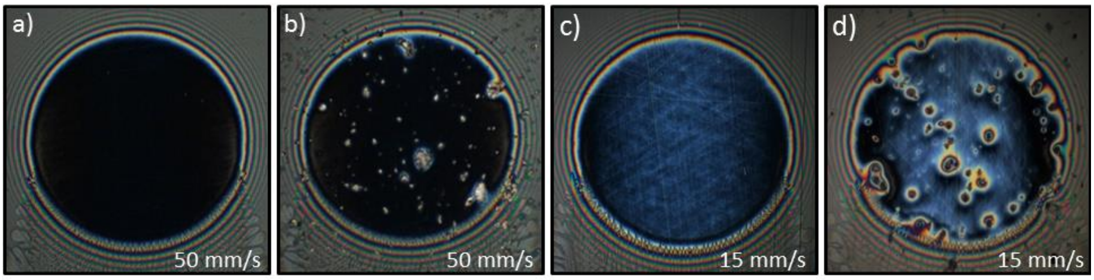


Fig. 5.9 Examples of interferograms under pure rolling conditions: base oil of TORL-A (a), TORL-A (b), base oil of TORL-C (c), and TORL-C (d).

Tab. 5.5 Experimental conditions for optical tribometer tests

	Pressure (GPa)	Speed (mm/s)	SRR (%)	Quantity of TORL
TORL-A	0.75	50–700	0, 50, 100	Fully flooded
TORL-C	0.75	15–700	0, 50, 100	Fully flooded

5.3.2 Paper B

In this paper, both laboratory and field experiments were conducted to determine the ability of TORL-B to reduce noise without a significant impact on the braking performance. At first, laboratory measurements using a twin-disc machine were performed where both discs were made from the bearing steel 100CrMn6 with hardness of 60 HRC and the initial roughness of Ra 0.4 µm. This harder contact pair should ensure that the contact width remains almost constant during experiments.

Tab. 5.6 Experimental conditions for twin-disc measurements – Paper B

Pressure (GPa)	Speed (mm/s)	SRR (%)	AoA (°)	Quantity (µl)
0.8	1 000	8	4	1, 2 , 3, 4

As in the case of Paper A, each laboratory experiment started with a run-in phase under dry conditions (without TOR lubricant), see Fig. 5.8. Then, TORL-B was applied, using a micropipette, and the trend of adhesion and noise over the time was recorded at AoA of 4°, see Tab. 5.6. This value of AoA represents a typical value for reversing loops. The adhesion and noise measurements were stopped when the adhesion coefficient reached a dry level of adhesion. In the case of noise measurements, the sound level L_{AF} was recorded and A-weighting was applied to the signal. The adhesion performance of TORL-B was assessed with respect to the adhesion ranges specified in Tab. 5.7. These ranges were chosen in the same way as in the case of Paper A. At the end of each experiment, both discs were ultrasonically cleaned with acetone.

Tab. 5.7 Adhesion levels for evaluation of TORL performance – Paper B

SRR	Critically low	Low adhesion	Intermediate	High adhesion
8%	$\mu < 0.15$	0.15 – 0.20	0.20 – 0.35	$\mu > 0.35$

Afterwards, the influence of TORL-B on adhesion and noise was studied under real operating conditions described in the subchapter 5.2. At first, three sets of braking tests were conducted where different amounts of TORL-B (1, 2, and 4 g of TORL-B per single rail) were successively examined to determine a suitable amount for long-term testing. Each particular braking test started at the tram station with acceleration of tram to 40 km/h. Once the tram reached this speed and the position of the off-board system, see Fig. 5.5, then, the maximal braking power was applied and the braking distance was recorded. It should be noted that this procedure represents the worst case which can hypothetically occur on the track (start of braking when the TOR lubricant is applied). For this purpose, the tram with four driven and braked wheel axles (axle load of 4 t) was utilized. It should be emphasized that no adhesion control system was applied during these braking tests. Each set of braking tests includes the following steps:

- Three braking tests under baseline conditions (without TORL-B) to determine the reference average braking distance under baseline conditions.
- Application of given amount of TORL-B (1, 2 or 4 g per single rail) on the top of both rails. Note that the amount recommended by the manufacturer is approx. 2 g per 100 axles.
- Several braking tests (3–6) under TORL-B conditions in order to investigate the changes in the braking distance under TORL-B conditions. Here, it should be emphasized that the tram went to the next station and back after each specific pass to spread TORL-B over the testing track as in the real operating conditions.
- Determination of spreading ability of TORL-B (the so-called *carry-down distance*) with the naked eye. This step was carried out only for the first set of the braking tests where the quantity of 1 g per single rail was used.
- After the completion of the above described points, the off-board system was turned off and the next set of the braking tests (another amount) was performed one week later. This time period should ensure that TORL-B was completely removed from the track by passing trams.

With regard to the results of above mentioned experiments, the appropriate amount of TORL-B was established, in terms of the braking distance extension. This amount was subsequently used for long-term experiments dealing with the effect of TORL-B on a noise reduction in real operating conditions. During these experiments, the sound of 40 passing trams was recorded under baseline and TORL-B conditions. The sound was always recorded for 10 seconds because this time approx. represents the duration of tram in the curve. Three following parameters were evaluated for each tram pass: minimum L_{Aeqmin}, average L_{Aeqavg} and maximum sound-level L_{Aeqmax}. As in the case of laboratory measurements, A-weighting was applied to the signal.

5.3.3 Paper C

The experiments were conducted using the MTM machine in an effort to investigate the role of the typical FM constituents in adhesion and wear at wheel-rail interface. Moreover, it should be highlighted that some experiments were conducted after the base medium evaporation of FM in order to investigate how this evaporation influences the performance of FMs. The experimental conditions of both the friction and wear test are summarized in Tab. 5.8.

Tab. 5.8 Experimental conditions for MTM measurements – Paper C

	Pressure (GPa)	Speed (mm/s)	SRR (%)	Quantity (µl)	Material of disc
Friction test	0.75	300	5	5–1000	AISI 52 100
Wear test	0.75	300	5	20	C45

For friction tests, a hard contact pair made from the bearing steel AISI 52 100 was used. The hardness of the ball and the disc was 800–920 HV and 720–780 HV, respectively. This hard pair provides a good repeatability of experiments because the changes in the contact area during experiments are almost negligible. It enabled us to evaluate the “true” performance of FMs because the effect of wear debris on adhesion is insignificant. The roughness of the ball and the disc after a run-in was 0.1 µm and 0.25 µm, respectively. Based on these values and the viscosity of water (η = 0.95E-03 Pa·s), the formula for isoviscous-elastic lubrication regime was employed in order to evaluate the rolling speed (300 mm/s) leading to the boundary regime of lubrication, see Fig. 2.6. Moreover, this relatively low speed did not lead to a removal of low-viscous substances from the contact path due to the action of the centrifugal force. The chosen value of SRR ensured that the contact operates in the vicinity of the saturation point. To evaluate the effect of the common constituents of FMs on adhesion, film formation and wear, various complex substances were tested. Each tested substance was prepared using the analytical laboratory balance and the magnetic mixer ensuring homogeneity of the substance. An overview of all tested FM constituents is listed in Tab. 5.9, and

Tab. 5.9 Overview of employed FM constituents – Paper C

	Particle size (µm)	Mohs hardness	Shape	Role
Bentonite	5.5	1	flake	Rheological agent
Zinc oxide	< 5	4–5	granule	PFM
Talc	D50: 4.7 D90: 12.3	1	flake	PFM
Molyka	D50: 4.2	1–1.5	flake	Solid lubricant
Graphite	7	1–2	flake	Solid lubricant

their SEM photographs can be seen in Fig. 5.10. The complete information on the compositions of the tested substances is listed in the appendix of Paper C.

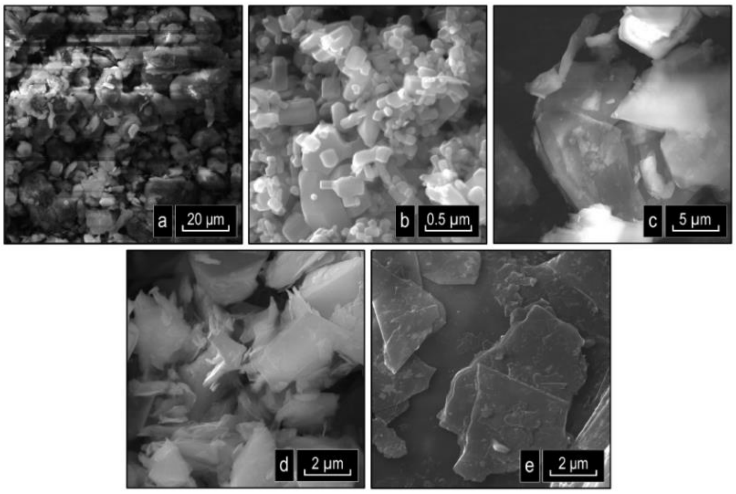


Fig. 5.10 SEM photographs of tested solid particles: (a) bentonite, (b) zinc oxide, (c) talc, (d) molyka, and (e) graphite.

After a substance preparation and completing a run-in, the substance was applied to the contact path using a micropipette, and then the friction test started either immediately or after evaporation of water. The friction test was stopped when the adhesion coefficient reached the value of 0.4 because it can be reasonably expected that the effect of FM at higher values is almost negligible compared to the effect of contact of surface asperities. During these experiments, the performance of substances/FMs was primarily assessed in term of the minimum adhesion necessary for a safe traction and braking (considered as 0.15). Besides that, the lasting effect of substances/FMs was monitored during these measurements. Both contact bodies were ultrasonically cleaned with acetone after the completion of each friction test.

In the case of wear tests, the disc was made from the steel C45 with hardness of 252 HV while the ball was made from the bearing steel AISI 52 100 with hardness in the range from 800 to 920 HV. A chemical composition and hardness of the disc are represented by frequently used wheel steel R7T, see Tab 5.2. No run-in phase was performed during wear tests because it can be expected that the wear rate and surface damage occurring through a run-in phase can be more significant in comparison with the subsequent test under FM conditions. Therefore, the run-in phase was skipped. Duration of each wear test was 60 minutes. Whenever the adhesion coefficient reached the value of 0.4, FM was reapplied. In the case of “dry” substance, the test was interrupted after each application/reapplication for several minutes needed for water evaporation. Then, the wear test was re-started. Finally, the surface damage and wear rate were investigated for five following conditions: baseline (dry), wet and dry complex substance with mineral particles, and wet and dry complex substance with oxide particles.

6 RESULTS AND DISCUSSION

The performance of two commercial TOR lubricants (identified as *TORL-A* and *TORL-B*) with different content of PFM was investigated using the MTM device (Paper A). Moreover, the performance of castor oil was examined for comparison purposes. At first, the performance evaluation criteria for TOR lubricants testing were designed because no testing standard for TOR products has been yet developed. For these purposes, four following adhesion intervals were proposed: *critical low adhesion*, *low adhesion*, *intermediate (optimal) adhesion* and *high adhesion interval*, see Tab. 5.4. More detailed information on how these adhesion intervals were chosen is described in the subchapter 5.3.1. Regarding to these intervals, four sets of friction tests with different slip values and a fixed quantity were conducted under baseline (dry – without TOR lubricants), TOR lubricants, and oil conditions. It was revealed that the lowest adhesion occurred immediately after the application of TORLs where the adhesion coefficient was lower than 0.15, representing the critical low adhesion interval. Then, a gradual increase in adhesion was observed for both tested TOR lubricants. It should be emphasized that TORL-A generally led to higher adhesion values than TORL-B for all tested slips. The reason is that the content of PFM in TORL-A was approx. 44 times higher than that of TORL-B. Despite this significantly larger content of PFM, TORL-A did not provide a shorter lasting effect, but vice versa, the lasting effect was even longer in most cases. This behaviour can be explained as follows: TORL-A has a large content of PFM which were gradually adhered to the contact surfaces. These adhered PFM form a thin friction layer providing the intermediate adhesion level. In contrast, no stable friction film, as well as no stable adhesion, was found under TORL-B conditions because the content of PFM was too low. In this case, the effect of fluid prevailed; therefore, the friction behaviour of TORL-B rather corresponded to the behaviour of castor oil where a gradual adhesion increase was observed during the entire test. With respect to these facts, it was suggested that TORL-A, which provides a higher and stable adhesion, can be applied especially in the areas where corrugation is formed and where the vehicle often needs to accelerate or decelerate. In contrast, TORL-B can be very suitable for noise reduction in urban areas because a reduction of noise can be reasonably expected as a result of lower adhesion in the contact.

Based on these friction measurements, the traction curves were evaluated for all tested conditions in order to clarify if the tested TOR lubricants are able to provide a positive traction curve. Although a positive trend of traction curve was established, a positive effect of TOR lubricants on the shape of traction curve could not be proven. The reason is that the positive traction curve was also found for baseline conditions where a negative trend is generally expected. Hence, it was suggested that a small-scale ball-on-disc apparatus is not a suitable approach for the investigation of TOR product ability to change the trend of traction curve.

Afterwards, the volume tests were performed to evaluate how strongly the performance of TOR lubricants is affected by the applied quantity. The obtained results are consistent with the above-mentioned friction tests because the optimal quantity of TORL-A exhibited the N-shape behaviour which was previously reported for the mixture of grease and FM [54]. This behaviour is beneficial in terms of lasting effect and wear. In the case of TORL-B, a gradual increase in adhesion was observed over time for all tested quantities but the slope of the curve was changed with regard to the applied quantity. This friction behaviour was previously observed typically for water-based products (FMs) [53],[55],[56]. In general, the results of volume tests showed that the higher was the applied quantity, the longer lasting effect was evaluated. Besides this, the lasting effect was significantly affected by the content of PFM. In terms of operating conditions, the lasting effect was significantly shortened with the increasing slip. The volume tests also gave the evidence that if the quantity is inappropriately large, then a critically low adhesion can occur. Following these findings, Stribeck tests were carried out under fully flooded conditions in order to investigate the worst case which can occur if the wheel-rail contact is overdosed with TOR lubricants. The results from Stribeck tests clearly showed that the over-application can lead to the extremely low adhesion which can cause braking and traction difficulties. For all these measurements, the adhesion coefficient was reduced to the values lower than 0.08 at low speeds where the boundary lubrication regime is generally expected, and friction was even lower than 0.04 at higher speeds. These results are in good agreement with reference [60] where TOR lubricants provided the adhesion coefficient about 0.05. Based on this, it was suggested that PFM likely cannot enter the contact under fully flooded conditions. However, this hypothesis was subsequently falsified through the additional experiments performed using a ball-on-disc optical tribometer. These measurements showed that PFM can enter the contact even under fully-flooded conditions as is evident from interferograms in Fig. 5.8. It is noteworthy that PFM enter the contact more easily in the presence of grooves and asperities on contact surfaces. Hence, it can be reasonably expected that the real contact roughness allows for the particles to pass the contact. At the end of Paper A, the ability of TOR lubricants to reduce wear and surface damage was proven. It was revealed that both tested TOR lubricants reduced wear compared to baseline conditions; however, the lowest wear rate was found, as was expected, for the specimen which was run under oil conditions. Although both TOR lubricants reduce wear, they are not able to completely avoid the formation of deep scoring marks on the surfaces which were also found for baseline conditions. A TOR lubricant with a lower content of PFM (TORL-B) led to a less substantial wear and surface damage than TORL-A.

The first paper of this doctoral thesis revealed that TOR lubricants can be a suitable approach to control of adhesion in the wheel-rail contact where a quantity and content of PFM play a key role. However, there are some possible adhesion risks associated with an over-application. Therefore, it seems to be necessary to verify and explain this undesirable friction behaviour of TOR lubricants using another experimental method or ideally using field experiments.

With regard to the findings from Paper A, the performance of TORL-A was investigated using a twin-disc device and also in field conditions, where the curve section of light rail system was utilized (Paper B). The aim of this paper was to confirm or falsify the statement about the possible adhesion risks when the contact is overdosed with TOR lubricant. In addition, the ability of TORL-A to reduce noise and simultaneously maintain an acceptable adhesion level was the subject of this study. The performance evaluation criteria (adhesion intervals) for TOR lubricants tests using a twin-disc were firstly suggested as in the previous paper, see Tab. 5.7.

At first, the effect of TORL-A on noise and adhesion was studied using a twin-disc machine where AoA of 4° was set for all measurements in order to achieve typical conditions occurring in curves. These experiments showed that there is a good agreement between the twin-disc and ball-on-disc adhesion results. It was found that there is a similar adhesion-quantity dependence of TORL-A in spite of the fact that the operating conditions were not completely the same. These investigations confirmed two following statements: (1) advantageous N-shape behaviour can be also reached in curves and (2) the adhesion coefficient is critically low immediately after the application.

The results of noise measurements showed that TORL-A is able to greatly reduce noise. A prompt decrease in noise, from 97 dBA (baseline) to 64-68 dBA, was detected for all the applied quantities. Then, a gradual increase in noise and adhesion was observed for larger quantities, while a rapid growth of both these parameters was revealed in the case of small quantities. It means that the effect of small quantities on noise was almost negligible because noise was reduced only for a few cycles after the application of TOR lubricant. These experiments also showed that a significant rise in noise occurs when the adhesion coefficient reached 0.35. Besides a higher adhesion and noise, a more significant scatter of sound data was recorded above this value. At the end of these laboratory measurements, some additional experiments under wet conditions were conducted to evaluate how the performance of TOR product is influenced by the presence of water (these results are not included in this paper). Important and consistent results were obtained for all considered TOR lubricant quantities. It was revealed that the interaction of water and TOR lubricant leads to a critically low adhesion (< 0.02), even with small TOR lubricant quantities. It is noteworthy that more types of TOR lubricants were tested to clarify this suggestion. The results indicate that the effect of fluid is much more significant compared to the effect of PFM which seems to be negligible. This is in good agreement with the previous results [13] where a low adhesion was revealed for the contact contaminated with a mixture of water and oil.

In the case of field experiments conducted in Paper B, the impact of various quantities of TORL-A on braking capabilities was initially studied in order to establish the optimal quantity ensuring a sufficient braking performance. As was mentioned in the previous chapter, TOR lubricants were applied on the top of both rails using a wayside lubrication system. A detailed experimental procedure of braking tests is described in subchapter 5.3.2. These results gave the evidence that if the applied quantity is inappropriately high, then a considerable extension of braking distance can be expected. Beside this extension, braking was accompanied by the wheels slide (complete wheels slip) resulting in the formation of the so-called flat spots on wheels leading to an increase in rolling noise and discomfort of passengers. Two of three tested quantities caused a significant extension of braking distance accompanied by wheels slide. The best results, in terms of braking distance, were achieved when the smallest tested quantity of TORL-A (1 g/rail) was applied. In this case, good braking capabilities were ensured for all tram passes. Hence, this amount was chosen for long-term experiments where noise was monitored. At the end of the above-mentioned braking tests, the carry distance of 100 m was determined with naked-eye. The observed value was significantly lower compared to the values reported in literature [65] where the carry distance was in orders of kilometres without causing any negative impact on a braking performance. However, in that case, a heavy haul train was utilized. It probably means that light rail systems are more prone to a wheel slide, causing an extension of braking distance. Note that a shorter carry distance may not be perceived as a disadvantage in the case of tram because such distance should avoid braking or traction difficulties near the next tram station.

It should be pointed out that the longest braking distance was always observed in the second and third tram pass after the application, while the closest braking distance to baseline conditions was found in the first tram pass (immediately after the application). It leads to the conclusion that a redistribution mechanism of TOR product in the real wheel-rail contact differs compared to the laboratory case where the lowest adhesion was usually observed during the first cycles after the application. The main difference can be that the TOR product mainly remains on the wheelset rather than being continually transferred between both bodies [22], while in the case of laboratory devices, both bodies are covered with a uniform layer of TOR product. Despite this discrepancy, laboratory measurements provide useful qualitative data which revealed that TOR lubricants can cause insufficient braking and traction capabilities. These findings are in good agreement with literature [20],[42],[60] where the effect of TOR lubricants on adhesion was evaluated.

The results of noise measurements involving more than 50 passes of trams were analysed and showed that the positive effect of TORL-A on noise reduction was negligible despite the fact that the TOR lubricant was visible on both rails. Although other authors reported a considerable noise reduction for both FMs [31],[35] and TOR lubricants [60], the impact on traction or braking performance was not discussed in these articles, except for [60] where low adhesion conditions were found after the application of TOR lubricant. Regarding these facts and results of both laboratory and field measurements, it seems to be difficult to achieve a reduction of noise without extension of braking distance for TOR lubricants.

Two above-mentioned papers of this doctoral thesis were focused on the performance of two TOR lubricants with different content of PFM. It should be highlighted that a special attention was devoted to possible adhesion risks associated with the application of TOR lubricant. Besides TOR lubricants, FMs represent another type of TOR products which is also a widely used approach to friction modification at the wheel-rail interface. Hence, the third paper (Paper C) dealt with the influence of chemical composition and the applied amount of water-based substances/FMs on adhesion and wear. For this purpose, the performance of various complex water-based substances was studied using the MTM device.

It should be pointed out that the performance of some substances was evaluated in both liquid and dried form in order to evaluate how much the drying effect influences the adhesion in the contact. At first, the effect of individual constituents of FMs (without the base medium) was investigated because the application of single particles represents a possible method how to manage adhesion at the wheel-rail interface. These findings showed that both considered PFM (talc and zinc oxide particles) are able to provide an intermediate and relatively stable level of adhesion without adhesion drops as was previously found for alumina particles [59].

Subsequently, the performance of two component substances was investigated for various applied quantities, even under fully flooded conditions, to determine the worst possible scenario which can occur in the contact. The following types of two-component substances were examined: substances containing water and a binding agent and substances containing water and PFM. For both of them, it was observed that even two-component substances can offer a beneficial friction behaviour, even under fully flooded conditions. However, some adhesion risks were identified for substances containing water and a high content of mineral PFM (talc particles). It was established that an inappropriately high content of PFM can cause a formation of a sufficiently viscous paste between the surfaces. This paste resulted in low adhesion values; moreover, the electric insulation of contact surfaces can cause a failure of vehicle detection system. In contrast, no adhesion risks were surprisingly identified for the substances free of PFM, even if the contact was overdosed. In this case, the performance of substances is significantly affected by the content of binding agent which influences the apparent viscosity of substance. Based on the experiments with two-component substances, it was concluded that the lasting effect of substances can be mainly controlled by the applied quantity, whereas the shape of friction curve is mainly affected by the chemical composition. The lasting effect seems to be insensitive to the changes in chemical composition.

When complex substances containing water, binding agent, and PFM were tested, it was surprisingly revealed that the performance of these substances is mainly given by the effect of water and binding agent, while the effect of PFM, when the mineral PFM were used, was negligible or rather negative for all tested contents of PFM. In this case, a critically low adhesion was observed immediately after the application as a result of presence of PFM. After that, the friction behaviour corresponded to the behaviour of substances containing water and a binding agent. Note that a similar trend of friction curve, where the gradual increase in adhesion was found over the time, was previously identified for complex FMs [55]. A different friction behaviour was found for complex substances where zinc oxide particles were used as PFM. In this case, PFM can advantageously control the lasting effect without adhesion drops. The higher was the content of oxide particles (PFM), the shorter was the lasting effect. This different behaviour of substances with different types of PFM can be attributed to a different Mohs hardness of mineral (talc) and oxide (zinc) particles. Note that the Mohs hardness of zinc oxide particles is five time higher compared to talc (mineral particles). It indicates that while softer mineral particles are quickly crushed in the contact and create a thin friction film, the effect of harder oxide particles is rather abrasive.

These results correspond with [54] where it was noted that hardness and wear resistance of PFM play a key role in terms of friction behaviour of FMs.

Afterwards, a solid lubricant (graphite or molyka) was added into the above-mentioned complex substances and their performance was investigated in both liquid (the so-called wet film) and dried form (the so-called dry film). These results indicate that the presence of solid lubricant in complex substances is beneficial only for dry films where molyka seems to be a more appropriate lubricant for top-of-rail friction modification in comparison with graphite leading to poor adhesion conditions. In the case of wet films, a critical low adhesion occurred for all the tested substances and quantities. On the contrary, a very appropriate friction behaviour was achieved for dry films, especially when PFM are mineral particles. It should be also noted that the performance of these substances was not significantly influenced by the quantity because a stable and constant adhesion (approx. 0.2) was found for all tested quantities. These findings gave the evidence that evaporation of base medium significantly changed the performance of water-based substances/FMs. It can also be concluded that the substances with zinc oxide as PFM are more beneficial in the case of wet film, while mineral particles as PFM provide better friction properties after evaporation.

Finally, the ability of complex water-based substances to reduce wear and surface damage was investigated for both dry and wet films in 60-minute friction tests. These experiments showed that all the tested substances are able to substantially reduce the wear rate, particularly in the range from 66–87%. Apart from wear rate, roughness and surface damage were considerably reduced compared to baseline conditions where deep scoring marks were identified on the disc surface. Unexpectedly, the substances that used mineral particles as PFM caused more than a double wear rate in comparison with substances containing zinc oxide particles in spite of the fact that the average adhesion during the experiment was almost the same. These results correspond to the study [59] where mineral (quartz) and metal (alumina) particles were used for top-of-rail friction modification. This study [59] revealed that softer quart particles caused a higher mass loss than harder alumina particles. It can be explained by the differences in the shape and sharpness of the used particles. Besides this, it was also revealed that dry films (substances) caused a lower wear rate compared to wet films. The possible explanation is that the dry films are able to form a more durable friction layer (compared to the layer with water); this reduces or even avoids the contacts of surface asperities during experiments. The result is that this dry layer provides an intermediate level of friction. When this layer becomes too weak to withstand the shear stress, it is quickly removed from the contact surfaces and then the substance is re-applied. It means that there is only a very short time period when the partial or complete metal-to-metal contact occurs. In contrast, a gradual increase in adhesion was observed for wet films. In this case, there was a relatively long-time period when the contact of surfaces asperities occurred; therefore, a higher wear rate was evaluated in this case. It should be emphasized that wet substances resulted in a longer lasting effect; therefore, fewer applications were needed for wet substances during 60 minutes.

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Laboratory investigation of ability of oil-based friction modifiers to control adhesion at wheel-rail interface

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ABSTRACT

In the last few years, top-of-rail friction modifiers have been designed and used in many railway systems all over the world. These adhesion enhancers are applied by either off-board or on-board system in order to achieve the intermediate level of friction and positive adhesion curve. Previous scientific effort was mainly focused on the effects of water-based friction modifier on adhesion, rolling contact fatigue, railway noise and corrugation formation. The objective of this study is to investigate the abilities of oil-based friction modifiers to control adhesion and reduce wear at wheel rail interface. For this purpose, two commercial oil-based friction modifiers were particularly utilised. A ball-on-disc tribometer was employed to investigate their traction and braking performance for various slip ratios under dry conditions. Furthermore, the effect of friction modifier amount has been studied. At the end of the performed tests, wear rate, surface damage and changes of surface topography were determined and compared to dry and oil-contaminated contact. The results indicate that oil-based friction modifiers are able to control adhesion in wheel-rail contact but it is strongly dependent on the applied amount of friction modifiers. Regarding to the friction behaviour and wear, the content of metal particles seems to be the crucial parameter.

1. Introduction

Rail transportation is one of the most environmentally favourable, effective and safe modes of transport. With respect to safe braking and adequate traction, a critical issue is wheel-rail adhesion. This phenomenon has been extensively investigated in the last decades. Since the wheel-rail contact is an open system, adhesion is strongly influenced by environment and operating conditions. Therefore a great deal of research was focused on adhesion loss under various contact conditions. The effects of water, humidity, oil and wear debris on adhesion were particularly investigated [1–7]. Under these conditions, traction and braking difficulties can occur as a consequence of poor adhesion. Serious adhesion problems occur especially in the autumn when leaves fall on the train track. Crushed leaves together with other contaminants can form a leaf residue layer which is strongly adhered to the rail surface. Formation of this layer can cause a track circuit isolation and critically low adhesion in the range of 0.03–0.06 [8]. In order to remove the leaf layer and increase adhesion in the contact, sanding is commonly used. Therefore, several investigations of sanding parameters, such as feed rate and particle size, on adhesion were carried out [9,10]. Although sanding is a widely used method how to increase adhesion, there are important side effects such as wear, dustiness and electrical insulation [11–13].

A more sophisticated system allowing a friction control on top-of-rail is the application of friction modifiers (FMs). FMs are substances with a complex composition that keep adhesion at the level required for a specific type of rail transport. This level should by sufficiently high with respect to traction and braking demands, but on the other hand not very high with respect to wear and lateral forces. Moreover, the friction modifiers should provide positive friction behaviour of the contact which means that the adhesion coefficient increases with increasing sliding velocity. This behaviour prevents squeal and rail corrugation. A proper choice of lubricant and the amount applied is essential for the effective functioning of the system.

Several experimental approaches have been used in order to study the effects of water-based FMs under various environmental conditions. One of the approaches is measurements in laboratory conditions using full-scale devices or devices at different scales [14–16]. Laboratory studies confirmed that a positive trend of adhesion curve and intermediate level of friction can be achieved if the water-based FM is applied to the wheel-rail contact [15,17]. Moreover the ability to improve adhesion using a water-based FM was clarified in leaf contaminated contact [18]. In addition the impact of water-based FMs on RCF and wear was investigated

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using a full scale wheel-rail test rig [14,19]. These investigations showed that water-based FMs are able to reduce wear and crack generation as well as to stop the growth of pre-existing cracks. Performance of water-based FMs is strongly affected by composition and behaviour of interfacial layer which is formed on the rail surface. Results show that if the interfacial layer is composed of hard α-Fe_2O_3, abrupt increases in adhesion coefficient can be observed. On the contrary, the lower adhesion coefficient is reached if the interfacial layer is composed of soft Fe_3O_4 [20]. With respect to composition and properties of this layer, three types of friction characteristics (positive, neutral and negative) can occur [21]. Other authors dealt with the interaction between the interfacial layer and FMs for different weight ratio of oxides and FM and for various environmental conditions. It was found that a small amount of FM, in comparison with the amount of iron oxides, can control adhesion in the contact due to the fact that FM solid particles have a higher wear resistance compared to oxides particles [22]. For FM/oxide mixture, relative humidity and temperature were identified as parameters which substantially affect adhesion in the wheel-rail contact [23]. The influence of interfacial layer on adhesion was verified by a numerical model where the elastohydrodynamic lubrication theory and multi-grid method was used [24].

In the case of field studies, effects of water-based FMs on railway noise and corrugation growth were investigated. For a wide range of wheel-rail systems, it was found that FM can reduce squeal and flanging noise in curves [25,26]. It was observed that the application of FM is able to delay or completely avoid the corrugation formation [26,27] because the presence of FM in the wheel rail contact leads to a positive slope of adhesion curve. Positive friction precedes stick-slip oscillation which is considered as an initiation mechanism of corrugation formation [28].

The performance of FMs has been studied intensively during the last decade. A larger number of studies were related to the performance of water-based FMs in wheel-rail contact [14–19,22,23,28]. In spite of great practical importance of oil-based FMs, only little has been reported on their behaviour in wheel-rail contact and the effects on adhesion. The present paper is focused on the laboratory investigation of oil-based FMs behaviour in wheel-rail contact. The main goal is to clarify the effect of oil-based FMs on adhesion and wear for different contact conditions.

2. Material and methods

2.1. Test apparatus

In order to investigate adhesion in the wheel rail contact, a Mini-traction-machine device was utilised where a steel ball is loaded against a steel flat disc as shown in Fig. 1. This configuration leads to a point contact which enables to achieve the maximum contact pressure of 1.4 GPa. Both contact bodies are independently driven in order to control the slip that is expressed by the following equation:

$$s = \frac{w_{ball} \cdot r_{ball} - w_{disc} \cdot r_{disc}}{w_{ball} \cdot r_{ball} + w_{disc} \cdot r_{disc}} \cdot 200 \tag{1}$$

where w_{ball} and w_{disc} are circumferential speeds of the ball and the disc respectively and r_{ball} and r_{disc} are diameters of these bodies. This apparatus is equipped with load cells for measurement of the normal and friction forces. Based on the force data, the adhesion coefficient can be calculated according to the following equation:

$$\mu = \frac{T}{W} \tag{2}$$

where T is traction force and W is normal force in the contact. An integral part of this device is a pot which enables to simulate different environmental conditions, preventing lubrication leakage during the test.

2.2. Materials

Test specimens used in this study were a 19.05 mm steel ball and a 46 mm diameter steel disc. The disc was made from C45 steel in order to reflect a chemical composition of commonly used wheel steel R7T, see Table 1. Also the same Brinell hardness of 245 HB was achieved. Material of ball is a low carbon steel AISI 1010 with a considerably higher hardness due to machining requirements. The initially average roughness of disc and ball was measured as Ra 0.45 μm and Ra 0.05 μm respectively.

In this study, two oil-based top-of-rail friction modifiers identified as FMA and FMB were used. The base medium of FMA and FMB is the plant and ester oil respectively. Desired traction properties are ensured by presence of metal particles: Cu and Zn in FMA and Cu and Al in FMB. Table 2 shows the particle size distribution obtained using a laser particle analyser. The predominant size of metal particles in both FMs is in the range of 4–10 μm, while the particle concentration is significantly higher in FMA. Metal particles included in both FMs are in the form of flakes, see Fig. 2; so, the dimension represents lateral size.

Considering that the metal particles are flakes with the most common size less than 10 μm and thickness in hundreds of nanometres, it can be assumed that the particles should be able to enter the contact area with diameter of 200 μm where the fluid-film thickness according to elastohydrodynamic lubrication (EHL) theory should vary from hundreds of nanometres to micrometres, see Fig. 3. To compare the behaviour of FMs with the base oil, the castor oil was used in the study.

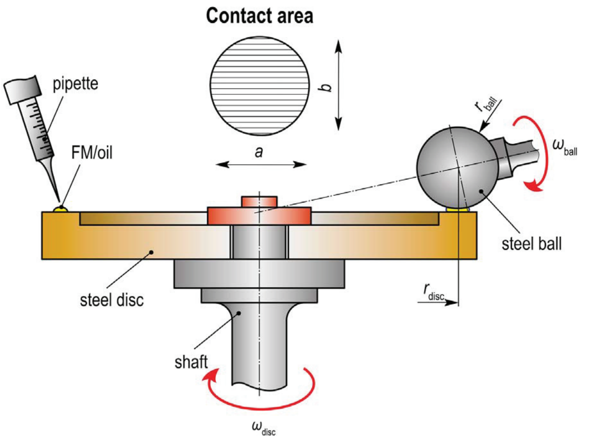

Fig. 1. Scheme of traction device with shape of contact area.

Table 1
Chemical compositions of contact bodies.

	Chemical compositions (wt%)					Hardness (HB)
	C	Si	Mn	Ni	Cr	
UIC 900A	0.70	0.35	1.10	–	–	280–300
R7T	0.52	0.40	0.80	0.30	0.30	245
Ball	0.13	0.10	0.60	–	–	650
Disc	0.46	0.25	0.65	0.3	0.25	245

2.3. Experimental conditions and procedure

All tests in this study were carried out under the normal load of 16 N ± 0.01 N which corresponds to Hertzian pressure of 0.75 GPa. This value represents real contact pressure in light rail systems where the contact area is almost circular as in the case of employed ball-on-disc tribometer. According to the type of test, the mean speed varied in the range of 1 to 2500 mm/s, and the slip in the range of 1–10%. All tests were performed under ambient temperature of 23 °C and relative humidity of 35–40%.

At the beginning of each test, dry run-in was carried out in order to ensure the same initial conditions. Although, both contact bodies were ultrasonically cleaned at the end of each test, oxides remained on the surfaces. These oxides significantly affect the adhesion level and therefore it is necessary to removed them from the surfaces by the run-in. It enables to evaluate effect of FM on adhesion only. It means that the run-in was finished when the adhesion coefficient stabilised at the level of dry friction. Durations of these run-in tests varied depending on the contact conditions, especially slip. The time necessary for reaching the dry level of adhesion was shorter with increasing slip. Test conditions of run-in test were chosen according to the friction tests. It should be noted that in the case of new contact bodies, the run-in was always accompanied by a significant change in contact body roughness, as depicted in Fig. 4.

Three types of tests were performed in this study after the run-in. The test conditions are summarised in Table 3. FMs were applied into the contact using a micropipette (error ± 0.04 μl) in required amount. The first of the tests is the friction test where the performance of FMs after the application was investigated for typical values of slip occurring in railway systems, such as 1%, 3%, 5% and 10%. In this paper, the performance of FMs means the ability of FMs to provide adhesion in the optimal adhesion range for a certain number of cycles. For comparison, a dry test (baseline) and a test with base oil were carried out. The friction test procedure is shown in Fig. 4. After stabilisation of adhesion at dry level, the test was stopped (point B) and FM or oil was applied to the contact patch on the disc. Then several cycles were run under pure rolling conditions in order to form a thin uniform FM film around the circumference of the disc. These cycles are not shown in Fig. 4. Finally the test was replicated (point C) and the change of adhesion was investigated for 540 cycles (C–D).

Table 2
Particle size distribution of FMA and FMB.

Particle size (μm)	Number of particles per 1 ml	
	FMA	FMB
4–10	145,915,182	3,560,883
10–20	12,171,798	14,966
20–30	888,070	7446
30–40	69,201	512
40–50	5299	102
60–70	474	0
70–80	40	51
> 80	0	0

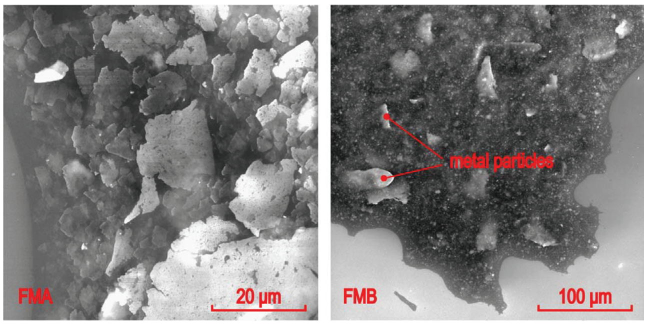

Fig. 2. SEM photographs of FMA and FMB.

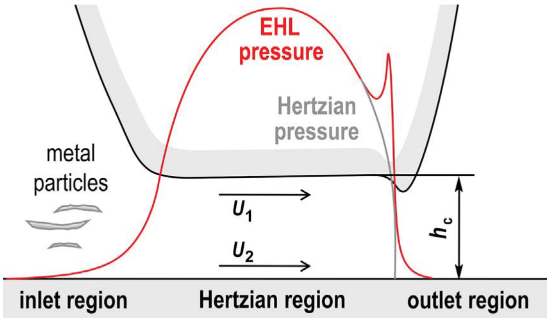

Fig. 3. Detail of elastohydrodynamic (EHL) contact.

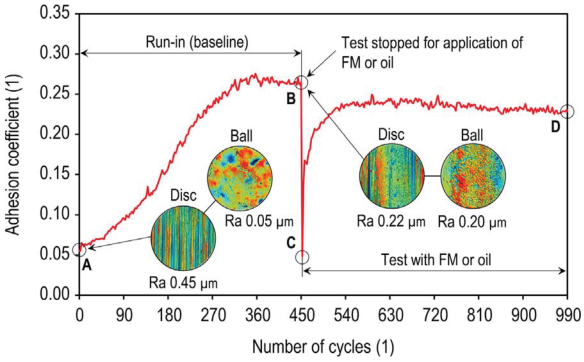

Fig. 4. Complete friction test including run-in phase and test with FM.

Table 3
Experimental conditions.

Test	Run-in	Friction test	Stribeck test	Lubricant volume test
Hertzian pressure, GPa	0.75	0.75	0.75	0.75
Speed, mm/s	300	300	1–2500	300
Slip ratio, %	1, 3, 5, 10	1, 3, 5, 10	10	10
Contact conditions	dry	FMA, FMB, oil	FMA and FMB	FMA and FMB
Lubricant amount, μl	–	1	Fully flooded	1–4

As was mentioned above, the performance of FMs or oil was assessed from the perspective of adhesion level and a number of cycles during which the adhesion remains at the same level. Different adhesion levels can be recognised as indicated in Table 4. A critically low adhesion level does not provide a sufficient friction for traction or braking and thus represents a potential safety risk. It is complicated to define the minimum adhesion which is required for safe traction and braking because this value can vary depending on the number of driven/braked wheel axes, the diameter of the wheels and also on the axle load. However, the most common presented values of minimum adhesion coefficient is in the range from 0.10 to 0.15. Based on this, adhesion lower than 0.15 was considered as the critically low adhesion in this study. The low adhesion level meets mild traction requirements. The optimal adhesion level offers the intermediate adhesion which, compared to baseline conditions, reduces wear without a significant impact on traction and braking performance. This level is

Table 4
Adhesion levels for evaluation of FM performance.

Slip (%)	Critical low adhesion	Low adhesion	Optimal adhesion	High adhesion
1	μ < 0.15	0.15–0.20	0.20–0.25	μ > 0.20
3	μ < 0.15	0.15–0.20	0.20–0.35	μ > 0.35
5	μ < 0.15	0.15–0.20	0.20–0.40	μ > 0.40
10	μ < 0.15	0.15–0.20	0.20–0.40	μ > 0.40

also beneficial for energy savings. Below this level, high adhesion accompanied by large wear occurs. The exact limits depend on the specific type of rolling stock operation and other factors, so the values indicated in Table 4. represent, considering dry friction, rather estimation. The adhesion in the range from 0.2 to 0.4 is usually considered as an optimal level. However, these values are valid especially for saturation point on traction curve. At this point, the entire contact area is in a state of pure sliding and; therefore, the adhesion coefficient reaches the same value as the friction coefficient. Hence, the optimal adhesion level which was mentioned above (0.2–0.4) was defined for 5% and 10% slip, as under these conditions, the adhesion levels almost corresponded to dry level of friction. At 1% and 3% slips, the optimal adhesion ranges were recalculated according to the dry level of friction.

The aim of the second test is to investigate the influence of speed on adhesion coefficient under fully flooded conditions. Fully flooded conditions provide the lowest level of adhesion that can occur immediately after the application of FMs into a contact. Results of the test represent a Stribeck curve. For a given speed, adhesion value from the Stribeck test can be compared with the one point C in Fig. 4.

The third test describes the effect of applied amount of FMs on adhesion. This parameter is a crucial factor influencing the adhesion level. As shown in Table 3, this test was performed for four amounts of FMs.

After the completion of these tests, surface topography and wear were evaluated by the analytical balance (distinctiveness 0.1 mg) and 3D optical profilometer.

3. Results and discussion

3.1. Friction tests

Friction test results are summarised in Figs. 3–6. The baseline results show that the adhesion coefficient increases with increasing slip. Depending on the slip, the maximum values of adhesion coefficient during friction tests were approximately in the range from 0.3 to 0.6.

These results show a relatively good agreement with another laboratory study employing a ball-on-disc apparatus [29]. Nevertheless, it is well-known that dry adhesion obtained in laboratory conditions is higher compared to field tests. This is mainly due to natural contaminants occurring even under “dry” conditions in real track.

At higher slips, the baseline data in Figs. 7 and 8 exhibit unstable behaviour. These changes in trend of adhesion may be associated with formation and a subsequent partial or complete removal of interfacial layer (containing wear debris and their oxides) formed between the surfaces during the wear process. For the cases of 1% and 3% slip, the adhesion coefficient is relatively stable during tests because the thickness of interfacial layer did not reach a certain critical value which results in breakdown of this layer due to low layer stiffness. This observation is consistent with findings in Ref. [21] where the formation of interfacial layer was described as a consequence of sliding motion.

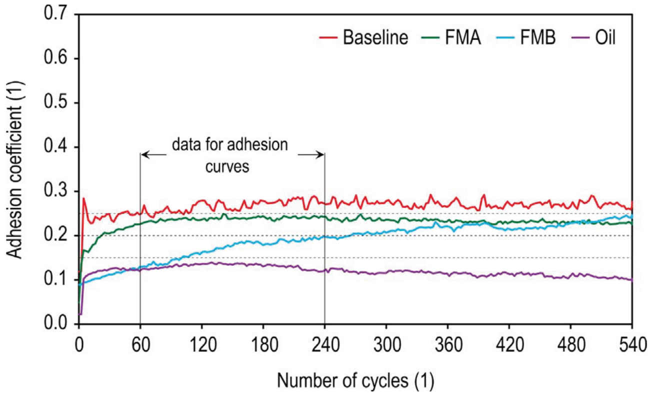

Fig. 5. Friction tests at 1% slip for FMA, FMB, oil and baseline conditions.

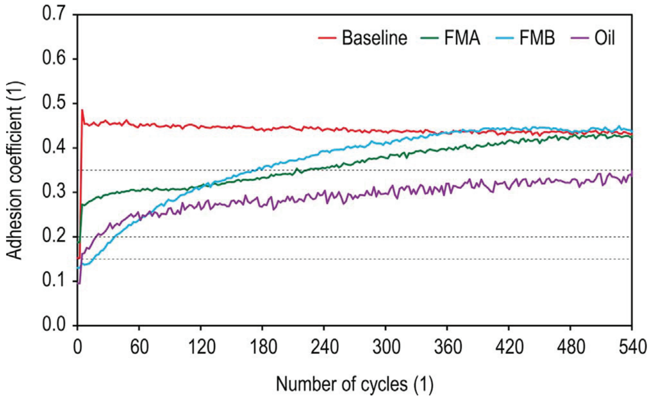

Fig. 6. Friction tests at 3% slip for FMA, FMB, oil and baseline conditions.

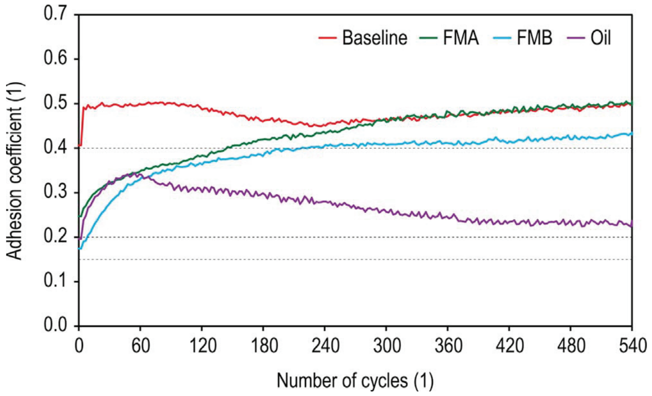

Fig. 7. Friction tests at 5% slip for FMA, FMB, oil and baseline conditions.

Application of FM or oil is accompanied by a sudden drop in adhesion. During this drop, critically low adhesion may occur mainly under low slip, as shown in Fig. 5. At 1% slip, FMA leads to critically low adhesion only during the first cycles whereas, under these conditions, FMB caused critically low adhesion for a longer period. After a drop, adhesion gradually increases during the entire test with FMB whereas FMA leads to stable adhesion which was approximately 15% lower compared to the baseline. This difference between the behaviour of FMA and FMB can be attributed to a different amount of solid metal particles contained in FMs, see Table. 2.

The test with FMA at 3% slip shows that the initial adhesion increase is followed by a stable value of adhesion in time.

Moreover, this stable part of time curve is at optimal adhesion level, see Fig. 6. After this stable period, the adhesion increases up to a dry level. This trend of time curve was described and designated by Lu as “N”-shape behaviour [22]. This behaviour means that the time curve can be divided into three following parts: (1) initial adhesion growth (film forming), (2) relatively stable part of adhesion (film-contact) and (3) adhesion re-growth due to a partial metal-to-metal contact. Finally, the presence of slip in the contact causes a complete removal of FM film, resulting in a dry level of adhesion. If the time curve shows this behaviour and simultaneously there is a sudden initial growth of adhesion to the required level, it can be concluded that the applied amount of FM is appropriate for these operating conditions. FMB leads to a positive trend of time curve during the entire test. In the case of oil, adhesion falls within the optimum level. This is because a small amount of low-viscous oil leads to a partial metal-to-metal contact, which is also apparent from the marked fluctuations of time curve.

In the case of 5% slip, the stable part of time curve for FMA entirely disappears due to a more significant action of slip in the contact. Under this contact conditions, time curves have a positive trend during the entire experiment for both FMs. FMB achieves good results under these conditions because the adhesion coefficient persists in the optimal adhesion range or close to this range for high number of cycles. The oil contaminated contact exhibits a decrease in adhesion that is lower than in the case of 3% slip. This deviation is due to a high sensitivity to a dosing process in the mixed lubrication regime. Moreover, the accuracy decreases with decreasing amount of lubricant. A negative slope of time curve can be associated with a higher amount of lubricant in wear track in comparison with other tests under oil-contaminated conditions. It probably means that only a small amount of lubricant was likely pushed out of the contact during the first cycles; the result was that the resistant boundary film consisting of castor oil and wear particles was formed between contact surfaces.

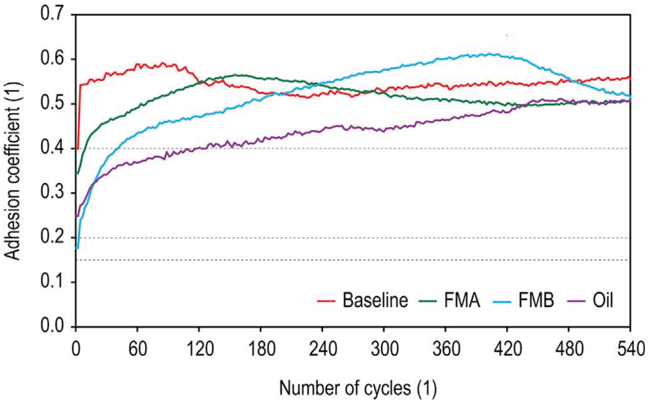

Fig. 8. Friction tests at 10% slip for FMA, FMB, oil and baseline conditions.

At 10% slip, the applied amount of 1 μl seems to be insufficient for both FMs, as is apparent from Fig. 6. In this case, the metal-to-metal contact, either partially or completely, occurred shortly after application of FMs. It means that a higher slip ratio in the contact has a tendency to a faster removal of FM film. It can be assumed that a higher amount of FMA could lead to a stable period of adhesion even at 10% slip, as will be discussed in Section 3.3. Based on the results from this section, it can be concluded that the oil based FMs are able to control adhesion according to the amount of solid metal particles. In the case of the test under oil contaminated conditions, it is evident that a small amount of oil can cause traction and braking difficulties at low value of slip. Based on the data from friction tests, the performance of both FMs and castor oil were evaluated according to the adhesion levels specified in Table 4, see Fig. 9. From this figure, it is evident that applied amount (1 μl) was not appropriate at high slip. At 10% slip, adhesion was in the high adhesion range during almost whole the test. Hence, the application of larger amount of FMs seems to be necessary to reach the optimal adhesion range at high slips. On the contrary, the smaller amount of FMB can be suitable for low slips.

As can be expected, the particular values of adhesion and applied amount of FMs which were investigated in this study cannot be easily generalised to real wheel-rail contact due to different operating and environmental conditions. Nevertheless, qualitatively, the effect of FM applications and operating conditions should be valid. As the laboratory approach tried to analyse the effect of FMs themselves, future study should be focused on the interaction with natural contaminants that occur in real wheel-rail contact.

3.2. Adhesion curves

Based on the data from friction tests, adhesion curves have been evaluated, as shown in Fig. 10. Each point represents the average value of adhesion coefficient calculated in the range of 60 to 360 cycles. During this period, the FM film was already formed and simultaneously it was not completely removed.

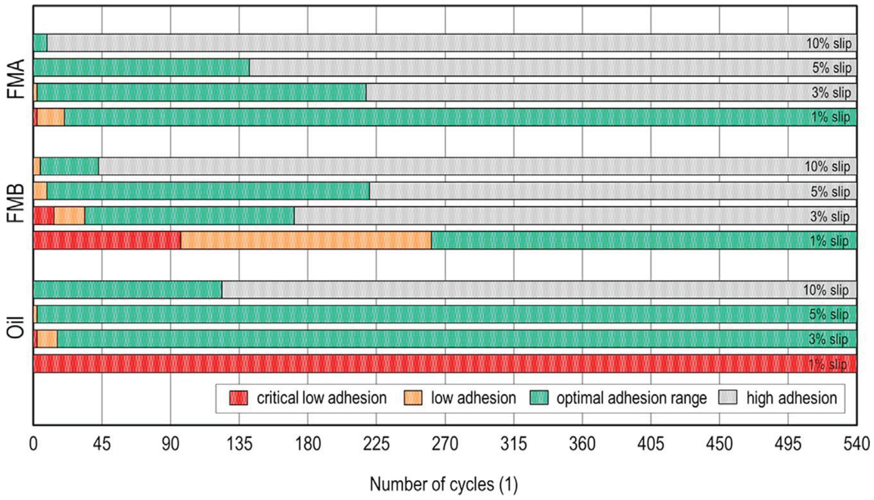

Fig. 9. Adhesion levels of FMs and oil according to the friction tests.

It is evident that all the curves exhibit a positive trend without an apparent saturation point and a decrease in adhesion at higher slip. This behaviour is beneficial because it prevents a stick-slip effect responsible for a short pitch corrugation of rail. However this positive trend, occurs even under baseline conditions where, according to field and large-scale experiments, negative behaviour is suspected. This discrepancy can be explained by different dynamic properties of the small-scale ball-on-disc configuration used in this study. In this configuration, the adhesion coefficient reaches the maximum value at much higher slip, more than 20% [29] compared to the slip of 1–3% in real wheel-rail contact. Moreover, a negative trend can increase with increasing speed. In this study, the speed is much lower compared to the real application. It is also necessary to notice that the adhesion curves are constructed from the time period in which the adhesion changes because of running wear process.

Regardless the above trend, the curves show that both FMs lead to the intermediate level of adhesion for all slips. As expected, FMA with higher content of metal particles provides higher average adhesion during the same period of time.

3.3. *Influence of FM amount*

From the results in Section 3.1 it is obvious that the applied amount of FM (1 μl) seems to be unsuitable for higher slip ratio, especially in the case of 10% slip. Hence, the tests with various amounts of FMs were carried out at 10% slip in order to investigate the effect of FM amount on adhesion. Figs. 11 and 12 show the adhesion propagation after the application of a given amount of FM. All the tests were interrupted when the adhesion reached the value of 0.4.

As mentioned above, the amount of 1 μl is unsuitable for both FMs because the adhesion increases rapidly after the application of FMs. It is evident that a larger amount of FM leads to a longer lasting effect. The lasting effect can be defined as a number of cycle from the application of FM until the moment when the adhesion coefficient reaches dry level of friction (effect of FM disappears). In addition, the amount strongly influences the level of adhesion. A large amount of applied FM can lead to insufficient adhesion. Similar findings were reported in [30]. There is also a noticeable difference between the behaviour of FMA and FMB. In the case of FMA, the amount of 3 μl provides a stable period of adhesion at optimal adhesion level ("N"-shape behaviour). In addition, the initial adhesion growth is sufficiently sharp, which prevents traction and braking difficulties. A higher amount of FMA shows much more stable adhesion, but at a low level. It can be assumed that the adhesion will increase after some time; however the adhesion level is critically low before reaching the increase. This finding is very important for practice since it indicates that the applied amount and the re-application period should not be substituted during a design of FM application system.

In contrast, FMB does not lead to stable adhesion for any applied amount. This amount influences the gradient of adhesion increase and the initial level of adhesion. With respect to traction and braking requirements, 1.5 μl appears to be optimal for FMB. The amount of 2 μl could be more appropriate because of a much more lasting effect, but lower initial adhesion must be accepted. The difference in the behaviour of FMA and FMB could be ascribed to a different content of metal particles. It is believed that the metal particles in FMA form a layer of proper friction properties. Once this layer is worn out, a direct contact of surface asperities heads adhesion to a dry level. This is apparent from the increase in adhesion data scattering for 3 μl in Fig. 11. On the other hand, FMB contains a higher proportion of fluid lubricant, which is unable to ensure a stable adhesion at higher adhesion level. Nevertheless, this does not mean that FMB should be worse than FMA. In these cases, the content of metal particles seems to be a key factor influencing the effect of FM on adhesion. These findings are in good agreement with Ref. [31], where the amount of aluminium

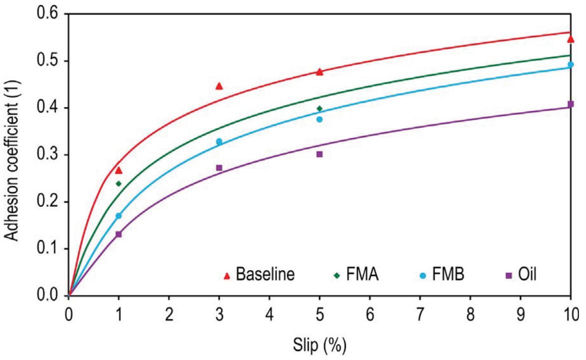

Fig. 10. Adhesion curves of baseline, FMA, FMB and oil.

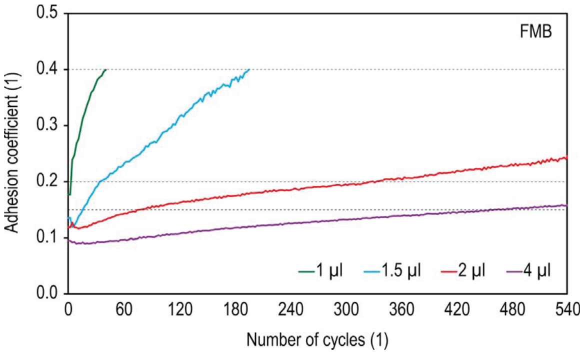

Fig. 12. Effect of FMB amount on adhesion coefficient.

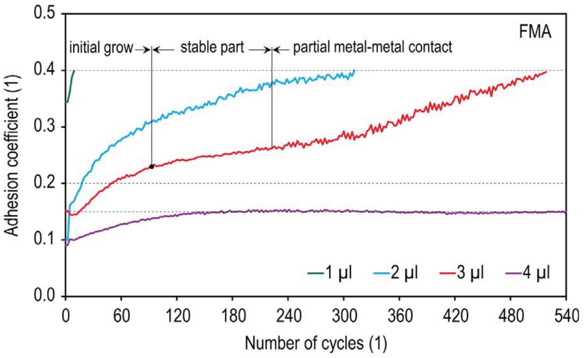

Fig. 11. Effect of FMA amount on adhesion coefficient.

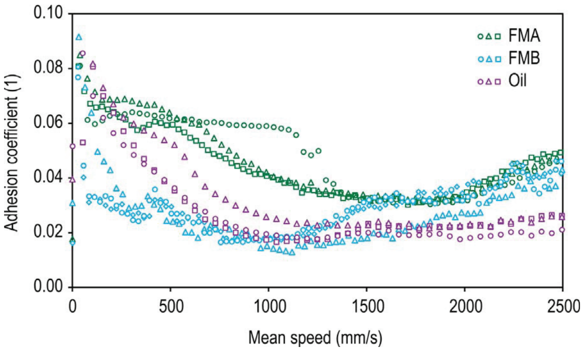

Fig. 13. Stribeck curves at 10% slip for contact with FMA, FMB and oil.

particles and the feed rate were identified as crucial parameters which influence the adhesion coefficient and the surface damage.

3.4. Influence of speed

In order to identify the minimum adhesion which can occur immediately after the application of FMA, FMB or castor oil to the contact, tests under fully flooded conditions were carried out. The results in Fig. 13 show the effect of mean speed on adhesion at 10% slip. The curves can be designated as Stribeck curves in which the transition from mixed to elastohydrodynamic and hydrodynamic regimes of lubrication can be identified. The three data sets for each material suggest a pretty good repeatability under the fully flooded conditions.

It is obvious that the results show fluid-film friction even at very low speed. Moreover, FMB provides lower adhesion than the castor oil at these speeds. This indicates that the metal particles contained in the FMs do not contribute to friction. As the Hertzian contact area is relatively small compared to particle dimensions, it can be assumed that the particles do not enter the contact under fully flooded condition. This finding suggests potential adhesion problems due to over lubrication and should be verified in larger contacts.

3.5. Disc surfaces analysis

Disc surface analyses were carried out after completion of all friction tests described in Section 3.1. As is clear from Fig. 14, four parameters were evaluated, namely wear rate, roughness average of worn path, worn path width and scratch depth. Surface topography of the four samples is shown in Figs. 15–18.

As can be expected, the largest wear rate, roughness, path width and scratch depth were observed for baseline conditions. The predominant wear mechanism for dry contact as well as contact with FMs seems to be scoring. In this study, the term scoring is considered as a result of adhesive wear. Scoring was indicated by scratches in the sliding direction as a consequence of plastic deformation of both surfaces that lead to ploughing of both the materials. The worn and plastically deformed material is strain-hardened and creates aggregations that further participate in the wear process. Even when the ball hardness was much higher, the surface roughness of both contact bodies was more or less equalled after run-in, which further supports the wear mechanism.

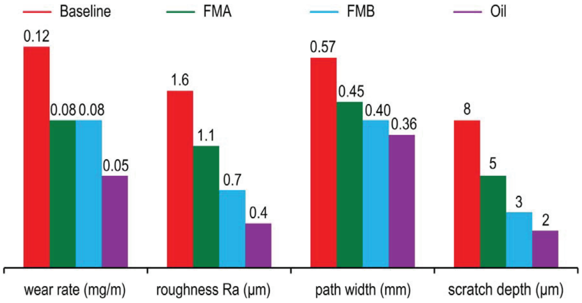

Fig. 14. Average values of wear rate, roughness, path width and scratch depth for different contact conditions.

The observed worn path width is much higher than the diameter of Hertzian contact that is 0.2 mm. One of the reasons is that the wear of surfaces results in the increase of real contact area due to a point contact configuration. Another reason is that the path is also influenced also by the contact surroundings where the worn material is dragged and pressurised by contact bodies. It is obvious that the wear scratches in the case of dry contact and FMs are not aligned along the sliding direction in the contact centre. This is a result of a ball-on-disc contact configuration. Because of a relatively low disc diameter compared to the influenced contact area, a disc spinning motion is noticeable. Entrainment velocity in the “inlet” zone is slightly inclined, so the wear debris and FM's metal particles are dragged in this direction. If, because of their size, the particles do not pass through the entire contact, they could be pushed out in the inclined direction. This can explain the material adhered to the outer side of worn patch on discs.

Compared to a baseline, both FMs significantly reduce surface damage. The wear rate is lower by 33% in the case of both FMs; although the parameter does not consider plastic deformation. Based on other parameters, FMB provides lower wear than FMA. This is a logical consequence of lower content of metal particles and, generally, lower adhesion during the tests with FMB. The average depth of scratches for FMA and FMB is 5 μm and 3 μm respectively.

The lowest wear parameters were found for oil conditions. In this case, only few shallow scratches can be observed, as is shown in Fig. 18. Thus we can conclude that the metal particles in FMs have a negative effect on wear compared to oil, even under mixed lubrication regime.

As was mentioned in the material section, the hardness of the ball was significantly higher compared to real hardness of rails or wheels. Nevertheless, according to the results from studies reported in Refs. [32,33], it is believed that higher rail hardness should not affect adhesion coefficient and wheel wear significantly. On other hand, rail wear and whole system wear decrease which causes a reduction of amount of wear debris. Therefore, it is expected that higher hardness of the ball can reduce abrasive wear but it is believed that this effect was not significant.

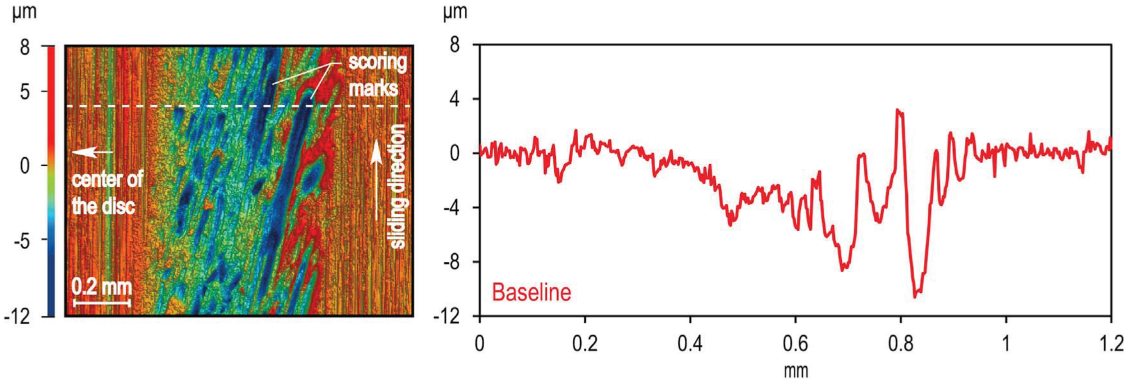

Fig. 15. Disc surfaces analysis after baseline test.

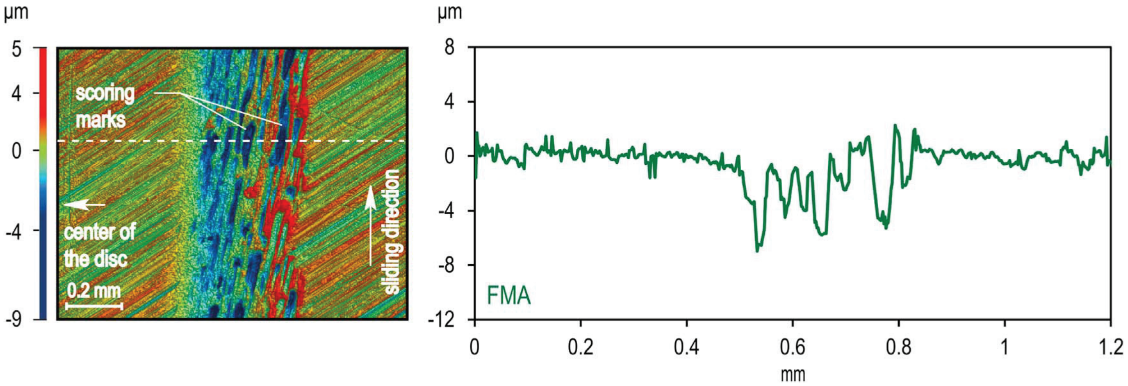

Fig. 16. Disc surfaces analysis after test with FMA.

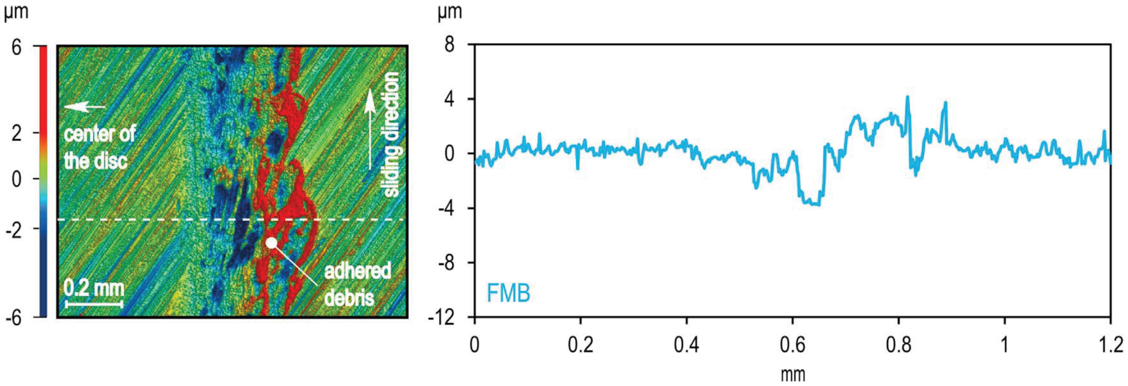

Fig. 17. Disc surfaces analysis after test with FMB.

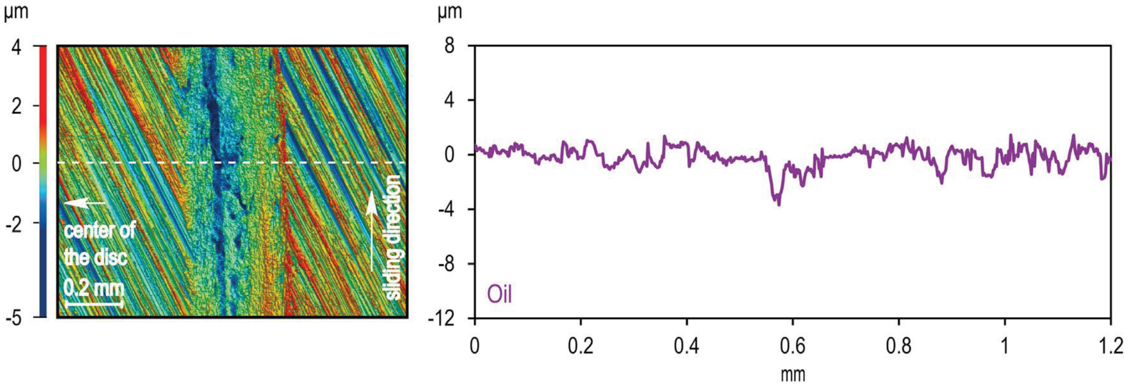

Fig. 18. Disc surfaces analysis after test with oil.

4. Conclusions

The ball-on-disc traction device has been employed to study the effects of two oil-based FMs on adhesion in rolling-sliding contact. A series of friction tests were carried out at different slips whereby the adhesion curves have been evaluated. In addition, tests with various amounts of FMs were performed in order to assess the optimal amount of FM. Finally, wear and surface damage of specimens were evaluated. The main conclusions of this study are as follows:

- Friction tests show that the oil-based FMs are able to control adhesion without significant impact on traction and braking. Behaviour of these FMs is mainly influenced by the content of solid particles. The lasting effect of both FMs is similar and is significantly reduced with increasing slip.
- No saturation points were observed on adhesion curves, even under baseline conditions, when saturation is expected. It means that the small-scale ball-on-disc apparatus is not suitable for investigation of FMs ability to change the trend of adhesion curves from negative to positive.
- The lasting effect of FMs increases with increasing amount of applied FM. FM with higher content of solid particles (FMA) is able to provide a period of stable adhesion at an optimal adhesion level and; therefore, it can be applied especially in areas where corrugation is formed. On the contrary, FM with lower amount of metal particles (higher oil content) does not offer a stable behaviour; an increasing amount of oil leads to insufficient adhesion. It means that FM with higher oil content (FMB) can be suitable especially in areas where the railway noise represents one of the most important problems.
- Adhesion is reduced to critically low values, even at low speeds, under fully flooded conditions. The metal particles are not likely to enter the contact under these conditions.

- The predominant wear mechanism for dry contact as well as contact with FMs seems to be scoring. The largest wear parameters were observed for baseline conditions. Both FMs are able to reduce wear, but it is still much higher compared to oil-contaminated conditions. FM with lower content of metal particles provides lower wear than the others.

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RESEARCH

Case Study: the Influence of Oil-based Friction Modifier Quantity on Tram Braking Distance and Noise

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ABSTRACT

In the present study, the twin disc machine and the light rail system was employed in order to investigate the ability of oil-based friction modifier (FM) to optimize adhesion and to reduce noise. The risks associated with poor adhesion conditions after the application of FM were evaluated. Both laboratory and field experiments showed that if the contact is overdosed by FM, the poor adhesion, which results in the extension of braking distance, can occur. In contrast, the smaller quantities do not cause critical adhesion but the effect of FM on the noise reduction is negligible. This study indicates that it can be quite difficult to achieve a reasonable noise reduction without a significant impact on braking distance of tram when the oil-based FM is applied. The field experiments also showed that the carry distance of FM is rather limited, approximately 100 m.

1. INTRODUCTION

In the last decade, friction modifiers (FMs) have been used in order to control friction in wheel-rail contact. The solid FM was already employed in Vancouver, Canada by the end of the eighties because the new track was corrugated a few months after its opening [1]. This investigation showed that the application of solid FMs can suppressed roll-slip oscillation which is a one of the initiation mechanisms of corrugation [1]. Subsequently, the liquid version of FM (water-based FM) was developed in 1996. Eadie et al. [2] reported that the water-based FM can reduce both squeal and flanging noise. Then, other authors showed by field tests that the water-based FMs are able to delay or completely avoid the corrugation formation for different wheel-rail systems [3-5]. Tomeoka [6] and Suda [7] reported on-board friction control systems for trains where FMs were sprayed on the top of the inner rail at curves. Their findings have shown that both lateral and tangential forces as well as lateral force fluctuation were reduced after the application of FM [7]. The positive influence of water-based FM on wear and, in particular, on rolling contact fatigue was described in [8] where coal trains were used.

Beside the noise and corrugation reduction, the effect of FMs on adhesion has been studied in recent years [9-11]. Areiza et al. [9] measured the coefficient of friction (COF) on the rail using a hand-pushed tribometer when oil-based FMs were manually applied on the top of rail. It was observed that FMs can cause a low COF, even lower or the same as in the case of flange lubricants. Similar findings were reported for the laboratory investigations where commercial oil-based FMs and a ball-on-disc apparatus were used [10]. Moreover, Lundberg et al. [11] reported that too much FM results in an unacceptably low friction coefficient (0.13-0.16), also for water-based FMs. All these studies pointed out that FM can be risky in terms of critical adhesion which can result in an unacceptably long braking distance.

An application of FMs seems to be a suitable approach to the reduction of noise, vibrations and corrugation which represent one of the most important problems of railway transportation, especially in urban areas. However, the recently published articles [9-11] indicate that oil-based FMs can have a negative impact on traction or braking. With respect to these articles, the aim of this case study is to clarify the hypothesis that oil-based FMs are able to optimize adhesion and reduce noise emitted by the contact without a serious risk of adhesion loss. For this purpose, the laboratory experiments using twin-disc machine was carried out at first. Subsequently, FM was used in a real track in Brno (Czech Republic). This track is characterized by corrugation and unpleasant noise which represent the typical problems in curves [12]. The conclusions of this article can bring important findings both for safety of rail transportation and for railway owners.

2. MATERIAL AND METHODS

2.1 Twin-disc machine

The used twin-disc machine is schematically depicted in Fig. 1. The wheel-rail contact is simulated using a pair of discs with a diameter of 40 mm. Both discs are made from the bearing steel 100CrMn6 with hardness of 60 HRC and initial roughness of Ra 0.4 μm. The upper disc representing the wheel is cylindrical whereas the lower disc is rounded with a radius of 50 mm. This contact configuration leads to the elliptical contact area (according to the Hertz theory, see Fig. 1b) which is typical for the real wheel-rail contact. Each disc is independently driven by an AC motor with shaft encoder; thus, the slide-to-roll ratio (SRR) in the contact can be accurately set and controlled according to the following equation:

$$SRR = 2 \cdot \frac{u_1 \cdot r_1 - u_2 \cdot r_2}{u_1 \cdot r_1 + u_2 \cdot r_2} \quad (1)$$

where u_1 and u_2 are the entrainment speeds of discs and r_1 and r_2 are the disc diameters. The mean speed can be controlled over the range of 0 to 2 m/s.

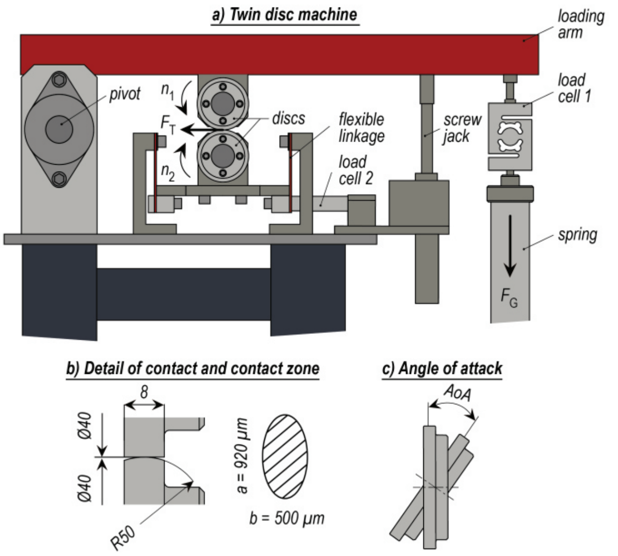
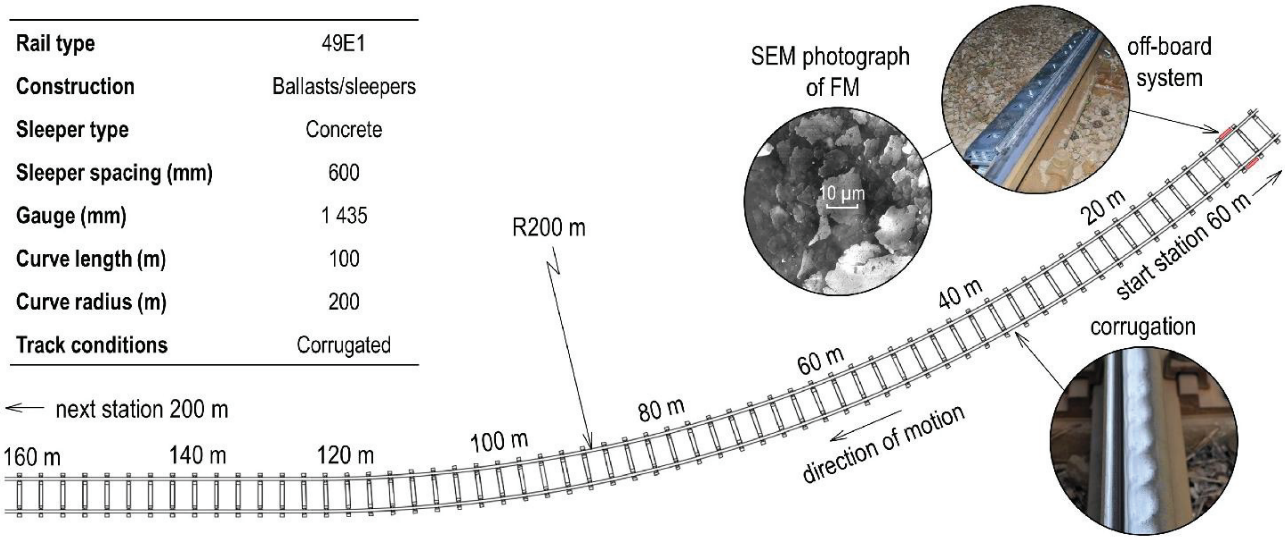


Fig. 1. (a) Twin-disc machine, (b) detail of contact and (c) AoA.

The required contact pressure is realized by the spring-screw loading system which is located, as well as the load cell for normal force, at the end of the loading arm, see Fig. 1a. Quick unloading of the contact is ensured by an AC motor-driven screw jack. The lower disc is mounted on the steel plate which is suspended on the flexible linkages. These linkages allow for a transfer of friction force from the contact to the load cell for friction force. Based on these data, the adhesion coefficient is evaluated:

$$\mu = \frac{F_T}{F_N} \quad (2)$$

where F_T and F_N are the friction and normal force respectively. Beside the friction and normal forces, temperature and air humidity can be measured and controlled using the environmental chamber. Moreover, the support of the lower disc enables to set a different angle of attack (AoA); thus, the passage of a vehicle through a curve is simulated, see Fig. 1c. AoA can be adjusted in the range from -10° to 10°.



Rail type	49E1
Construction	Ballasts/sleepers
Sleeper type	Concrete
Sleeper spacing (mm)	600
Gauge (mm)	1 435
Curve length (m)	100
Curve radius (m)	200
Track conditions	Corrugated

Fig. 2. Testing curve of light rail and technical details.

2.2 Wheel-rail system

The employed wheel-rail system is a light rail in Brno, Czech Republic. For testing purposes, a curve with a radius of 200 m (parallel tracks with rail profile 49E1) was employed because of unpleasant railway noise and corrugation of both rails, see Fig. 2 where the complete track characteristics can be viewed. The off-board system for FM application is located near the curve and simultaneously far enough from the next station where the trams need to decelerate. The tram with four driven and braked wheel axles with axle load of 4 t was used. It should be noted that no adhesion control system was applied during tests.

2.3 Off-board system and friction modifier

The used wayside lubrication system is depicted in Fig. 3. This system allows to apply FM with lubricant viscosity class from NLGI-0 to NLGI-2. FM is applied on the top of the rail using the application strip and the high-pressure pumping device with working pressure of 250 bar. The entire lubrication process is activated by the vehicle-presence sensor which detects the individual tram axles. Based on the signal from this sensor, the control unit applies a dosage of FM. This system enables to set a duration of dosage and also a specific number of axles to pass before the system is activated. It should be emphasized that application bars (strips) are on both rails, see Fig. 3.

Fig. 3. Detail of new-developed off-board system.

In this study, the oil-based FM with NLGI number 1 was utilized. This FM contains plant oil, thickener, and Cu and Zn flakes with the predominant size in the range of 4-10 as was described in [10]. This range of particles is typical for the so-called High Positive Friction modifier (HPF) providing the intermediate level of adhesion and positive friction characteristic. This FM was chosen based on the suitable friction behaviour, particularly N-shape behaviour, which was found in the previous authors' study [10]. Another reason is the fact that this FM is already commonly used in Europe.

2.4 Experimental procedure

Laboratory tests

During laboratory experiments, the adhesion coefficient and level of noise were evaluated. All tests were carried out under the following conditions: contact pressure p_h = 0.8 GPa, mean speed u_m = 1 m/s, SRR = 0.08 and under ambient temperature t_a = 23°C and humidity of 40%. FM was applied on the disc using a micropipette which is able to apply liquid substances from minimum of 1 μl (error ± 0.04 μl). In this study, the effect of FM quantity was investigated for four quantities: 1, 2, 3 and 4 μl. The experimental procedure was as follows:

1. To reach the dry level of adhesion the run-in test was carried out.
2. Setup of required AoA. The value of AoA was 4° for all laboratory experiments in this study. This value is typical for reversing loops.
3. Application of given quantity of FM into the contact path on the disc.
4. Start of the main experiment with FM: adhesion and sound level measurements. The experiment was finished when the adhesion coefficient was recovered to the dry level of adhesion.
5. Ultrasonic cleaning of discs.

Field tests

Two different types of field tests were performed in this study. At first, the braking tests with various quantities of FM were conducted to evaluate the appropriate quantity in terms of the braking distance extension. Each braking test started in the station by acceleration of the tram to the required speed of 40 km/h. This speed has to be reached before the tram approaches the off-board system. Subsequently, when the off-board system is reached, the tram driver applies the maximal braking power and the braking distance is recorded. This represents the worst case scenario which can occur in real operation. Each braking test includes the following procedures:

1. Tests under baseline (dry) conditions. These tests were carried out three times in order to investigate the repeatability of experiment. Based on these tests, an average value of braking distance under baseline conditions was calculated. Subsequently, this average value was used as a reference value for test with FM.
2. Application of given quantity of FM on the top of both rails. In this case, the sensor detecting the vehicle was not used because the tested quantity was always applied prior to the beginning of the experiment.
3. Tests with FM included several passes of the tram in order to determine the changes in braking distance. It should be noted that the tram went to the next station and back after each individual pass in order to spread FM all over the tested track.
4. Comparison of braking performances under baseline and FM conditions as is depicted in Fig. 7.

Once a braking test was completed, the off-board system was turned off for one week. This time period should ensure that almost all FMs were removed from rails by passing trams. After one week, points 1-4 were conducted again for another quantity of FM. In this study, three different quantities of FM were successively tested, specifically 1, 2 and 4 g. Manufacturer's recommended quantity of tested FM is approximately 2 g per 100 axles.

The second type of field tests dealt with the sound level measurements. These measurements were conducted for both baseline conditions (without FM) and the conditions with application of FM. For these measurements, only one quantity of FM was tested with respect to the results of braking tests. These measurements were conducted in real operating conditions.

Sound measurements

Sound level measurements were carried out using a hand-held analyser, Brüel & Kjær type 2270. During the laboratory experiments, the microphone of analyser was mounted 1 m above the floor (10 cm above the contact of discs) and 50 cm from the contact in the horizontal direction. Microphone was oriented towards the contact of discs. The sound level L_{AF} was evaluated from the application point to the moment when the adhesion coefficient was recovered to the dry conditions.

During field tests, the analyser was placed 7.5 m from the centre of the track with the microphone of analyser 1.2 m above the ground. Each particular sound measurement took 10 seconds. This time period approximately represents the time of train in the curve. The sound measurements were made for 40 trams under both baseline conditions and the conditions with FM. A minimum L_{Aeqmin}, average L_{Aeqavg} and a maximum sound-level L_{Aeqmax} were evaluated during these measurements. With respect to the fact that the testing track is near the urban area, A-weighting was applied for all field and laboratory sound measurements.

3. RESULTS AND DISCUSION

3.1 Laboratory tests

The adhesion measurements are collected in Fig. 4. During these measurements, the lasting effect and the time period when a critical adhesion occurs were evaluated. In this study, the lasting effect is considered as the time period between the application point and the moment when the adhesion coefficient reaches the value of 0.35 as is depicted in Fig. 4. Above this value, the effect of FM on adhesion as well as on the reduction of sound level is nearly negligible.

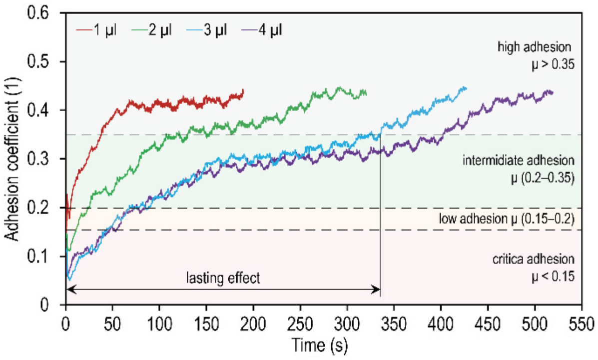


Fig. 4. Friction curves for various quantities of FM.

From Fig. 4, it is obvious that the lasting effect of FM extends with an increasing quantity of FM. A similar trend of friction curves, depending on the applied quantity, was previously found for both oil-based and water-based FM [10, 11]. In the present study, the results showed that the smaller quantities (1 and 2 µl) do not provide the stable level of adhesion at the intermediate adhesion level, see Fig. 4. In these cases, the performance of FM is markedly affected by starvation of contact, which was described in detail in [14]. In contrast, the quantities 3 and 4 µl can be considered as the suitable quantities because they exhibit the so-called N-shape behaviour which was described in [15]. This behaviour is characterized by the stable part of adhesion after the initial adhesion. This N-shape behaviour extends the lasting effect of FM; thus, also the wear rate is also reduced. However, it should be emphasized that the quantities providing the N-shape behaviour (3 and 4 µl) cause a critical adhesion during the first 50 cycles after the application of FM, see Fig. 4. The tendency to poor adhesion conditions after the application of both water-based and oil-based FM was previously observed in both laboratory and real conditions [10, 11]. These adhesion losses can have a large impact on braking/traction performance; thus, the safety of railway transportation can be affected especially near the station or when climbing a slope.

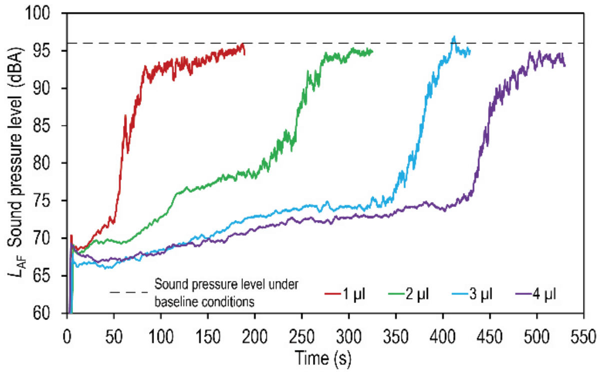


Fig. 5. Effect of FM quantities on sound level.

Sound level measurements showed that all tested quantities of FM reduce noise from 97 dBA (baseline conditions) to 64-68 dBA immediately after the application of FM, see Fig. 5. Subsequently, a gradual increase in adhesion and sound level pressure occurs when the adhesion coefficient reaches the high adhesion level (µ > 0.35), see Fig. 6. Then, the slope of sound and friction curves was changed and a higher scatter of sound data was observed. Based on these experiments, it can be concluded that the quantities 2, 3 and 4 µl provide a significant noise reduction for tested conditions. In contrast, the effect of 1 µl seems to be almost insufficient for noise reduction because of the fast recovery of sound level pressure to baseline conditions.

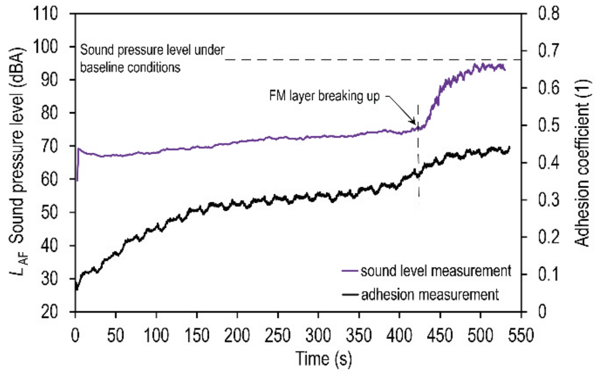


Fig. 6. Comparison of friction and sound pressure measurement.

These laboratory measurements show that the quantities exhibiting advantageous N-shape behaviour ensure a substantial decrease in sound level; moreover, a reduction of wear rate can be expected. On the other hand, the critical adhesion can easily occur during the first passes of the tram.

3.2 Field tests

With respect to the laboratory investigation, the experiments with various quantities (4, 2, 1 g/rail) were performed first to evaluate their impact on braking distance of the tram. The first braking test was conducted with 4 g of FM per single rail, see Fig. 7. This figure shows the change of tram braking distance for several consecutive tram passes. It is evident that the braking distance was considerably extended in all tram passes in comparison with baseline conditions. It should be noted that the longest braking distance was observed in the second and third tram pass while the braking distance closest to baseline conditions was found for the first pass after the application of FM. During the second and third pass, slide of wheel (complete wheels slip) occurred as a result of high quantity of FM on the rails. This slide of wheels has a negative impact on both contact bodies (flat spot, rail joints, etc.) and also on a brakes of vehicle as a result of high temperature between wheel and brake shoes [16, 17]. On the contrary, in the fourth pass, wheels slide was not detected but some wheels were still under slip. In the case of the following passes, no slip was observed; thus, the shorter braking distances were evaluated.

At the end of the braking test No.1, the spreading ability (carry distance) of FM over the rails was evaluated, see Fig. 8. From this figure, it is evident that FM was found at the distance of 100 m from the application point, observed with naked eye. This observation suggests that if the reasonable quantity of FM is applied, the carry distance is rather limited compared to the previous published results where these distances reached several miles [18]. However, this shorter carry distance can be advantageous to light rail systems or metros because a braking performance of vehicle near the next station should not be already influenced.

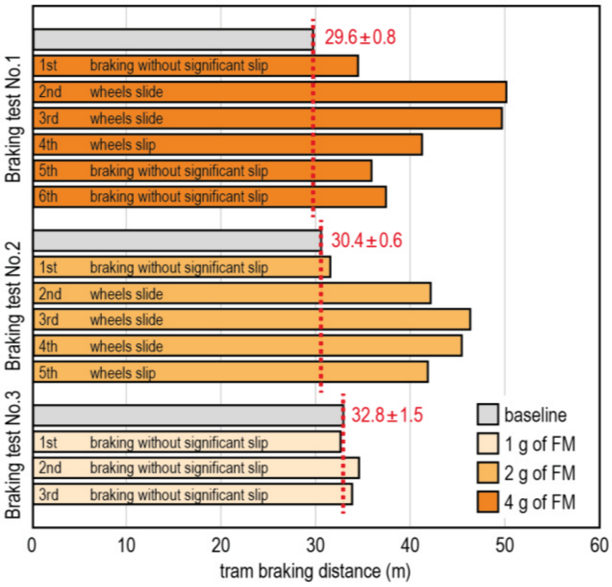


Fig. 7. Testing curve of tramway track and technical details.

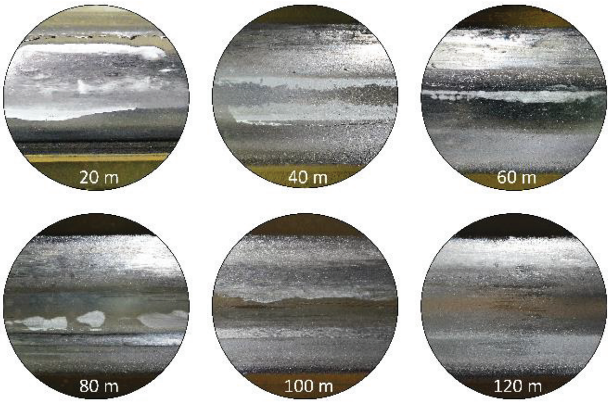


Fig. 8. The spreading ability of FM depending on the distance from the application point.

The braking test No.2 was conducted with 2 g of FM per single rail. The results showed that the trend of the braking distances was almost the same as in the braking test No.1. While the effect of FM on braking distance was almost negligible during the first pass, it became essential for the next three passes. It should be noted that the braking distance started to decrease after the third pass although the slide of wheels occurred in the following two passes. It can be expected that if the next pass was carried out, the braking distance would be the shortest and simultaneously the slide of wheels would not occur as well as in the case of the braking test No.1.

The last braking test (No.3) was performed with FM quantity of 1 g/rail. The results showed that the extension of braking distances was negligible for all passes. Moreover, no slide of wheels was observed. It is apparent that the trend of braking distances was the same as in the previous braking test. It should be noted that the braking distance was even slightly shorter during the first pass with FM than under baseline conditions.

The above-mentioned braking tests give the evidence that the larger quantity of FM (4 and 2 g/rail) can endanger the safety of rail transportation especially during the second and third passes after the application of FM where inadequate long braking distances were found. On the contrary, in the first pass, the effect of FM on braking performance was not as significant as expected. This behaviour can be explained as follows: the FM film is formed on top-of-rails during the first pass. It means that the braking performance during the first pass is influenced both by FM and the braking ability of dry contact. Regarding the safe braking distance of tram, the quantity of 1 g/rail seems to be the optimal quantity (from among the tested quantities).

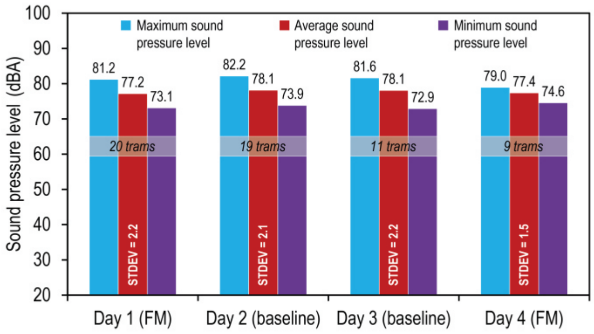


Fig. 9. Sound pressure measurement for contact with FM and for baseline conditions.

With regard to the braking tests, the quantity of 1 g/rail was selected as a suitable quantity in terms of braking distance for investigation of FM effect on noise. The quantity of 1g/rail of FM was applied every 100 axles. As it is clear from Fig. 9, FM was applied on the day 1 and 4 whereas the experiments during the day 2 and 3 were carried out under baseline conditions (without FM).
Fig. 9 shows that there is no positive effect of FM on noise reduction in spite of the fact that FM was visible on the top-of-rails. These findings showed that the quantity of 1 g/rail appears to be inefficient in terms of noise reduction. This is in accordance with laboratory measurement with 1 μl where the effect of FM on noise reduction was almost negligible because of rapid increase of sound level to baseline conditions. Other authors reported that water-based FM can reduce a squeal noise about 12 dB for tram/light rail system [2]. However, the effect of FM on adhesion or braking distance was not studied in [2]. It can be reasonably expected that the larger quantities used in this study (e.g. 4 g/rail) are able to considerably reduce noise as in the case of [2] but there is a significant impact on braking distance. Inability of FM to reduce noise can be explained by the absence of squeal noise on the test track. It suggests that FM is probably not able to reduce the other type of wheel/rail noise.

This study suggests that if the wheel-rail contact is overdosed by oil-based FM, the slide of wheels can occur; it results in significant impact on the length of the tram braking distance. Moreover, flat spots can be formed on wheels due to the wheel slide. This conclusion is in a good agreement with the previous field study conducted by Lundberg et al. [11]. They revealed that the adhesion coefficient was strongly dependent on the quantity of FM in the contact, and the application of large quantity of FM led to unacceptably low adhesion coefficients (on average 0.13-0.16). This decrease of adhesion can be catastrophic with respect to the length of braking distances. A similar drop of COF was observed in [9] where a hand-pushed tribometer in real railway system was used. In this case, COF was reduced to 0.15 and 0.13, depending on the contact pressure, when FM was applied. Beside the field tests, the laboratory experiments also show that oil-based FMs can cause adhesion losses after application of FM [10]. In [10], this behaviour was explained as an effort of metal particles to avoid the point contact under fully flooded conditions. However, considering that the width of the real contact area is several times larger compared to the ball-on-disc apparatus employed in [10], it can be assumed that the metal particles enter the contact. Furthermore, the metal particles were identified on the top-of-rail surfaces after the braking test with high quantity of FM, see Fig. 8. In author's opinion, adhesions, as well as the braking distance, are controlled by the metal particles contained in FM only in the case of small quantity of FM. Provided that the quantity of FM is high, adhesion is controlled especially by the base oil and it results in poor adhesion conditions.

It should be noted that the results mentioned above do not correspond with the field study carried out by Yu et al. [18]. This study reported that FM has no negative impact on the train braking. However, FMs used in this research were water-based and petroleum-based. Moreover, a heavy haul freight train with many wagons was employed, so the operating conditioned significantly varied. Based on this, it can be expected that the oil-based FM can cause a poor adhesion and wheels slide in an easier way than the water-based (drying FM) or petroleum-based FM. In addition, commuter trains and trams are probably more prone to wheels slide in comparison with heavy haul freight trains, as was reported in [19]. It should be noted that poor adhesion occurring immediately after the application of oil-based FM may be suppressed using the on-board system. In this case, FM is gradually sprayed over the rails thus avoiding an overdose of contact by FM.

4. CONCLUSION

The laboratory and field investigations focused on the effect of quantities of commercial oil-based FM on sound level and adhesion or tram braking distances have been presented in this paper.

The laboratory measurements showed that the larger quantities provide the significant noise reduction but critical adhesion occurs immediately after the application of FM. In contrast, smaller quantities are able to decrease both sound and adhesion without the risk of braking performance. However, these smaller quantities did not lead to the N-shape behaviour; thus, the lasting effect is rather limited.

In the case of field experiments, it was suggested that if the contact is overdosed by FM, then the braking distance can be significantly extended. The most critical passes were especially the second and third one after the application of FM which was accompanied by wheel slide. It means that under these conditions, the braking performance is significantly limited. It can be assumed that there is a limit for FM quantity below which the adhesion is mainly controlled by metal particles contained in FM, while above this quantity the adhesion is mainly given by the base medium. With regard to both laboratory and field results, the applied quantity appears as a crucial parameter for top-of-rail friction modification.

From laboratory and field investigations it is evident that it is quite difficult to achieve a reduction of sound level without the significant extension of braking distance as a result of critical adhesion.

The sound level measurements under real operating conditions showed that there is no positive effect of FM (1 g/rail) on noise reduction in spite of the fact that FM was visible on the top-of-rails.

Acknowledgement

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NOMENCLATURE

Subscripts:

1	Relation to the wheel disc
2	Relation to the rail disc
AoA	Angle of attack
F_N	Normal force in the contact
F_T	Friction force in the contact
L_{AF}	A-weighted, Fast, Sound level
L_{Aeqmin}	A-weighted, Fast, Minimum, Equivalent sound level
L_{Aeqavg}	A-weighted, Fast, Average, Equivalent sound level
L_{Aeqmax}	A-weighted, Fast, Maximum, Equivalent sound level
$n_{1;2}$	Revolutions of discs
p_h	Hertzian pressure in the contact
$r_{1;2}$	Diameters of discs
SRR	Slide-to-roll ratio
t_a	Ambient temperature
$u_{1;2}$	Entrainment speeds of surfaces
u_m	Mean speed; $(u_1 + u_2)/2$
μ	Adhesion coefficient

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The role of constituents contained in water–based friction modifiers for top–of–rail application

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A R T I C L E I N F O

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Adhesion coefficient
Friction layer
Friction modifier
Wheel–rail tribology

A B S T R A C T

Top–of–rail friction modifiers (FMs) represent an up–to–date approach to managing adhesion in the wheel–rail interface. The aim of this study was to investigate the role of typical water–based FM constituents in terms of adhesion and film formation. The ball–on–disc apparatus was employed to reach a rolling–sliding contact. The friction behaviour of various complex substances with different compositions was investigated in terms of adhesion and wear. The results showed that less complex substances, e.g. free of particles for friction modification, can provide required adhesion. Moreover, adhesion was not markedly decreased when the contact was overdosed. The performance of water–based substance/FM is greatly affected by evaporation of water. Surface analyses showed that substances are able to reduce wear and surface damage.

1. Introduction

Efficiency and safety of rail transport is influenced by tribology of the wheel–rail contact, especially by adhesion which is usually expressed using the adhesion coefficient. The exact value of this coefficient depends on the actual environmental and operational conditions [1–5].

An effort to manage friction between the wheel and rail is an idea older than a century. A widely used approach to overcome traction/braking difficulties due to poor adhesion is a sanding process. In last decades, many papers were focused on the improvement of sanding where some important parameters were described, such as feed rate or suitable particle size [6–10]. Other important approach is wheel flange lubrication which enables wear, friction, and noise reduction in curves. Although both these methods are effective and proven, there are still important issues which persist, e.g. rail corrugation, wear and noise generation. With respect to these undesirable effects of rail transportation, friction modifiers (FMs) for top–of–rail application have been recently developed. The main target of FM application is to achieve the intermediate level of friction at wheel–rail interface. In addition, the presence of FM in the contact ensures the change in a trend of creep force characteristic (adhesion curve) after the saturation point from negative, typical for dry conditions, to neutral or positive friction [11]. The negative friction is considered as one of the initiation mechanisms of the rail corrugation which has the impact on wear, dynamic loads, comfort of passengers, and safety of rail transportation.

FMs were originally developed as a solid stick and their ability to overcome corrugation formation and squeal noise was firstly proven by Kalousek et al. using the Vancouver mass transit system [12]. A great deal of research has been focused on a liquid version of FMs which was developed in 1996 [13]. The exact composition of these liquid FMs is designed with respect to the required adhesion level. In general, water–based FMs contain water, solid lubricant, binding agent, friction modifier, and wetting agent. Since 1996, many laboratory and field studies have been conducted in order to better understand the FM effects. Tomeoka et al. [14, 2002] conducted both laboratory and field experiments which demonstrated that spraying of water–based FM can ensure an adequate and stable adhesion in the wheel–rail contact. The positive impact of water–based FMs on squeal and flanging noise was clarified for various railway systems in different countries [15,16]. The authors revealed that a squeal reduction occurred as a consequence of the positive creep force characteristic which was given by suitable properties of so–called "third body" in the wheel–rail interface. Beside noise reduction, the effect of FMs on corrugation formation and growth of amplitude of existing valleys was intensively studied [16–18]. Obtained results clearly showed that the presence of FMs on rail can reduce or completely avoid the evolution of corrugation.

Apart from the field tests, laboratory experiments are a common approach to the railway tribology research. The ability of liquid FMs to change the trend of the creep force characteristic from negative to positive was clarified, both in lateral and longitudinal direction, using a 1/5

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scaled roller stand [19]. Afterwards, the performance of water–based FMs was investigated in dry, wet and leaf contaminated contact a using twin–disc machine [20,21]. Positive effect on the creep force characteristic, corrugation and noise was reported.

On the contrary, traction and braking difficulties can occur under wet and leaf contaminated conditions depending on the amount and size of hard mineral particles contained in FMs. Another study dealt with the interaction of iron oxides and FM was published by Lu [22]. Oxide particles can build up a durable third body layer which can affect the adhesion coefficient in the contact. The thickness of this layer can reach up to 50 μm; thus, the rubbing surfaces can be partially or completely separated [23,24]. Subsequently, Lewis et al. investigated the effect of atmospheric conditions and iron oxide content on the performance of water-based FMs [25]. It was found that the presence both Fe_3O_4 (black oxide) and Fe_2O_3 (red oxide) leads to the faster growth of friction than that of pure-FM. The significant influence of iron oxides on the adhesion coefficient under dry and wet conditions (without FM) was investigated by Nakahara et al. [26]. While α-Fe_2O_3 increases adhesion for both dry and wet conditions, Fe_3O_4 is considered to suppress the increase in adhesion. Experiments using a full–scale rail wheel test rig confirmed that water–based FMs can simultaneously reduce wear and rolling contact fatigue (RCF) [27,28]. If the FM was applied at appropriate application interval, no head checks and no surface cracks were developed, and simultaneously the pre–existing cracks could not grow under FM conditions.

Recent laboratory studies dealt with an interaction of FM with various oxides and components of natural third body; however, the friction modifier itself has been seen as a “black box”. It is known that different commercial FMs provide different frictional behaviour, but the contribution of different FM constituents and their combinations has not been published yet. The main objective of this work is to describe the effect of individual constituents of water–based FMs on adhesion and wear. Substances with various complexities are investigated in both liquid and dried form in order to describe how far the drying effect influences adhesion. This study focuses in detail on a time evolution of the adhesion coefficient, which is required for consideration of the FM reapplication interval. Special attention is placed on the lowest adhesion occurring after the application with respect to possible traction/braking difficulties. These findings can be helpful for modelling of FM behaviour and for a design of FMs and traction enhancers.

2. Material and methods

2.1. Test setup

The frictional behaviour of water–based FMs was studied using a commercial ball–on–disc apparatus (Mini–traction–Machine, PCS Instruments) with circular contact area, see Fig. 1. The main parts of this apparatus are as follows: 19.05 mm ball which is loaded by the flexible arm against a 46 mm diameter flat disc. The disc and the ball are driven independently by servomotors, so the value of slide-to-roll ratio (SRR) can be accurately set according to the following equation:

$$SRR = \frac{w_{ball}\cdot r_{ball} - w_{disc}\cdot r_{disc}}{w_{ball}\cdot r_{ball} + w_{disc}\cdot r_{disc}}\cdot 200\% \qquad (1)$$

where w_{ball} and w_{disc} are the angular speeds of the ball and the disc respectively and r_{ball} and r_{disc} are denote the radii of these bodies. Friction and normal force is measured with two force transducers and the resulting adhesion coefficient is evaluated as a ratio of the friction to the normal force.

Both the disc and the ball were made from bearing steel AISI 52 100. Vickers macro–hardness of ball and disc was 800–920 HV and 720–780 HV respectively. The initial roughness of the ball and the disc surfaces was Ra 0.01 μm and Ra 0.02 μm respectively. The chemical composition of specimens, as well as their hardness, is different compared to a commonly used wheel or rail steel. This configuration is more suitable for determining the frictional properties of the applied friction layer itself. Otherwise, wear process substantially influences contact conditions. Harder surfaces provide excellent repeatability of friction results and are reasonable in the small-scale point contact device.

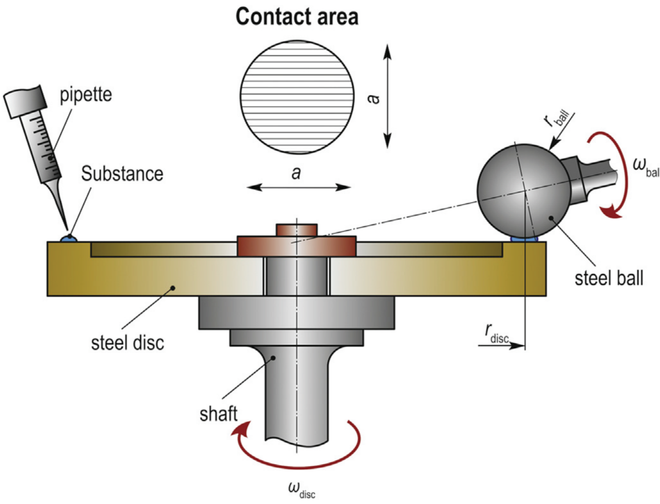

Fig. 1. Scheme of ball–on–disc apparatus.

2.2. Tested substances

This study deals with water–based FMs. Substances with various complexity were used where the following components had been combined: water, binding agent, friction modifier and solid lubricant. The composition of the substances is listed in Appendix. Any other additives, e.g. preservatives, were not used. Binding agents are usually clays, such as bentonite (sodium montmorillonite, which was used in this study) or casine. Particles of the binding agent together with water form a colloidal suspension therefore the apparent viscosity increases, as was previously observed by Dangler [29] and as is evident from Fig. 2. Both mineral

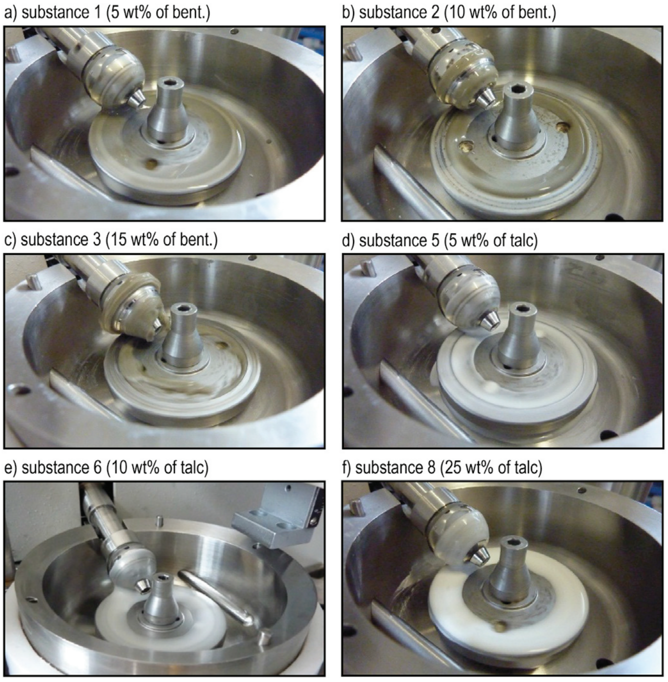
a) substance 1 (5 wt% of bent.)
b) substance 2 (10 wt% of bent.)
c) substance 3 (15 wt% of bent.)
d) substance 5 (5 wt% of talc)
e) substance 6 (10 wt% of talc)
f) substance 8 (25 wt% of talc)

Fig. 2. Illustration of experiments with various substances.

(talc) and oxide particles (zinc oxide) were employed as particles for friction modification. The last component used in the substances is a solid lubricant. Two solid lubricants were preferred, namely molyka (molybdenum disulphide) and graphite. Complete information about all used particles is listed in Table 1 and their detailed SEM photographs are depicted in Fig. 3.

All the substances were prepared using an analytical laboratory balance and a magnetic mixer ensuring homogeneity of the substance. Components were added and mixed together in this order: water, binding agent, particles for friction modification and lubricant. Before each experiment, the tested substance was again mixed manually to prevent heterogeneity of the substance due to sedimentation. Substances were applied to the disc surface using a single step of electronic micropipette before the test. A dosing speed was almost independent of an applied amount because each amount was dosed by a single step of electronic micropipette. At the beginning of friction tests, the effect of solid particles (without the base medium) on adhesion was investigated. For this purpose, solid particles (5 g) were added continuously to the contact path by a pipe.

2.3. Experimental conditions and procedure

Two types of experiments were conducted: friction tests and wear tests. For both these types of experiments, the normal force was maintained at 16 N ± 0.01 N, which resulted in the contact pressure of approximately 750 MPa. The rolling speeds of the disc and the ball were kept at 307.5 mm/s and 292.5 mm/s respectively, resulting in the mean speed of 300 mm/s and SRR of 5% for all tests. This value of SRR corresponds to a slip of 2.5%.

At the beginning of each experiment, both the ball and the disc were ultrasonically cleaned with acetone in order to remove any residual substances from previous experiments. Before the application of substance, a run–in phase was conducted to reach a stable level of adhesion corresponding to a dry adhesion level. The roughness of both specimens was stabilized at the value of 0.25 μm (disc) and 0.1 μm (ball) during this run–in.

Although water–based FMs are commonly designed as drying products applied via trackside applicators or directly from vehicles, two different cases can occur on rails: water is completely evaporated and a friction film is composed of only solid particles or water continues forming a wet friction film. Although the first case is probably expected by producers of FMs, the second case can arise immediately after the application, due to a frequent application or at high air humidity. Moreover, most of the previous papers have investigated the frictional properties of FMs only in a wet form [19–21,38]. Since the friction behaviour strongly depends on the occurrence of water in a friction layer, both situations were tested in this study. Experiments with a "wet" friction film started immediately after the run–in phase and the application of substance. These experiments were carried out for large (1 ml) and small (5, 10, 20, and 50 μl) amount of substances. The large amount should represent fully flooded lubrication regime with emphasis on the minimum adhesion which can occur in the contact. In the case of "dry" film, the substance was applied along the contact path after the run–in phase and the friction test started after the base medium evaporation (app. 5 min). During the friction tests, a lasting effect of substances was observed. The lasting effect is the time period starting from the application to the moment when adhesion reaches the value of 0.5.

Table 1
Technical specification of used FM components.

	Particle size (μm)	Mohs hardness	Shape
bentonite	5.5	1	flake
zinc oxide	<5	4–5	granule
talc	D50: 4.7 D90: 1 2.3	1	flake
molyka	D50: 4.2	1–1.5	flake
graphite	7	1–2	flake

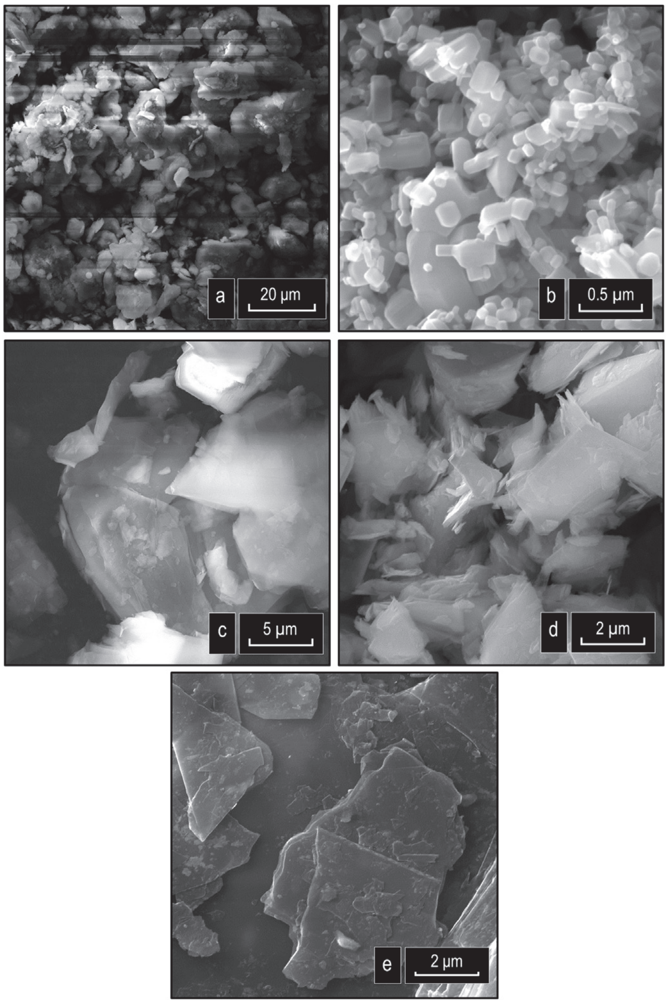

Fig. 3. SEM photographs of tested solid particles: (a) bentonite, (b) zinc oxide, (c) talc, (d) molyka and (e), graphite.

The second type of test was the wear test. Unlike the friction test, the disc was made from C45 steel, whose chemical composition as well as hardness (245 HB) are similar to the commonly used wheel steel R7T, in this wear test. New contact pairs were used for each test which was run for 60 min under the same operating conditions as the friction tests. At the beginning of wear test, no run–in was conducted because surface damage and wear occurring during run–in can be more significant compared to the subsequent test with substance. During the long-time test FM was reapplied whenever the adhesion coefficient reached the value of 0.4. After the completion of the wear test, the surface topography and the mass loss were evaluated using the 3D optical profilometer and the analytical balance respectively.

3. Results and discussion

3.1. Effect of individual components on adhesion

Prior to the experiments with the substances listed in the Appendix, the effect of individual constituents of water–based FMs on adhesion was investigated, see Fig. 4. The results show that talc, zinc oxide and bentonite are able to achieve an intermediate level of adhesion in the contact. At the beginning of the test, a friction film containing crushed particles was formed on the disc surface, leading to the adhesion

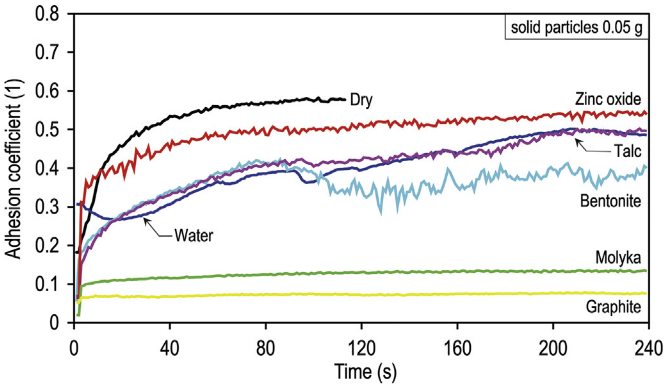

Fig. 4. Friction curves of solid components.

coefficient of about 0.4. Subsequently, this friction film began to be removed by the effect of slip and surface asperities. In the case of bentonite this removal was responsible for large fluctuations of adhesion and also for decrease in adhesion after 90 s. Only a negligible fluctuation of adhesion was observed for zinc oxide particles. The hardness of zinc oxide particles (Mohs' Hardness 4–5) is markedly higher than that of talc or bentonite (Mohs' Hardness 1). It seems that hard zinc oxide particles are not able to form a uniform layer consisting of crushed particles with low shear strength; therefore, a higher adhesion, wear rate and surface damage can be expected. It should be emphasized that zinc oxide can provide adhesion close to dry conditions as well as alumina particles with Mohs' Hardness 9, which caused significant wear [32]. On the other hand, a higher hardness can be more beneficial for removal of various layers (e.g. leaf layers), which can be present on actual rail surface.

When pure water was applied into the contact, the adhesion coefficient started at about 0.3 and subsequently increased up to almost 0.5. This behaviour corresponds to the predicated boundary regime of lubrication. This result is in good agreement with the previous publications [5,30–32]. The tests with molyka and graphite showed that both solid lubricants can significantly reduce adhesion and keep it at a stable value. The same behaviour was previously observed by Hou [23].

3.2. Wet film: base medium and binding agent

3.2.1. Large amounts

The effect of the bentonite content under “fully-flooded” conditions is shown in Fig. 5. The adhesion coefficient stabilized at 0.2 for substances 1 and 2 having the lower bentonite content. It can be expected that if these experiments lasted longer time, there would be an increase in adhesion as a result of action of the slip in the contact. The adhesion value of 0.2 is very suitable in terms of traction, braking, and wears reduction. Moreover, the results show that the overdosing of the contact by water–based products could not lead to the critically low adhesion which was previously observed for oil–based FMs [33–35] and which is also expected for non-drying materials when the applied amount is out of the recommended range [36]. In contrast the substance 3 with the higher content of bentonite exhibits a steady growth of adhesion. This increase in adhesion is mainly caused by the squeeze out of the high viscous substance from the contact path. The replenishment of the substance is markedly limited and the residual friction film is continuously removed from the contact path by the sliding action resulting in the gradual growth of adhesion. Photographs of discs during the tests are shown in Fig. 2a–c.

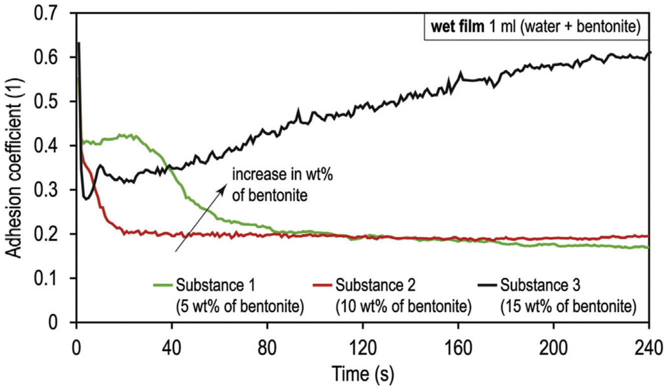

Fig. 5. The effect of bentonite content on adhesion under fully flooded conditions.

3.2.2. Small amounts

The results of friction tests with small amounts of substances 1–3 are summarized in Fig. 6a–c. Moreover, the effect of the substance amount is also investigated here. Friction curves can be divided into two parts. During *part I*, the substance forms a friction layer, which is able to partially or completely separate the contact surfaces. The substance is gradually squeezed out of the contact which results in thinning of the layer leading to a decrease of the adhesion coefficient. Once the layer is

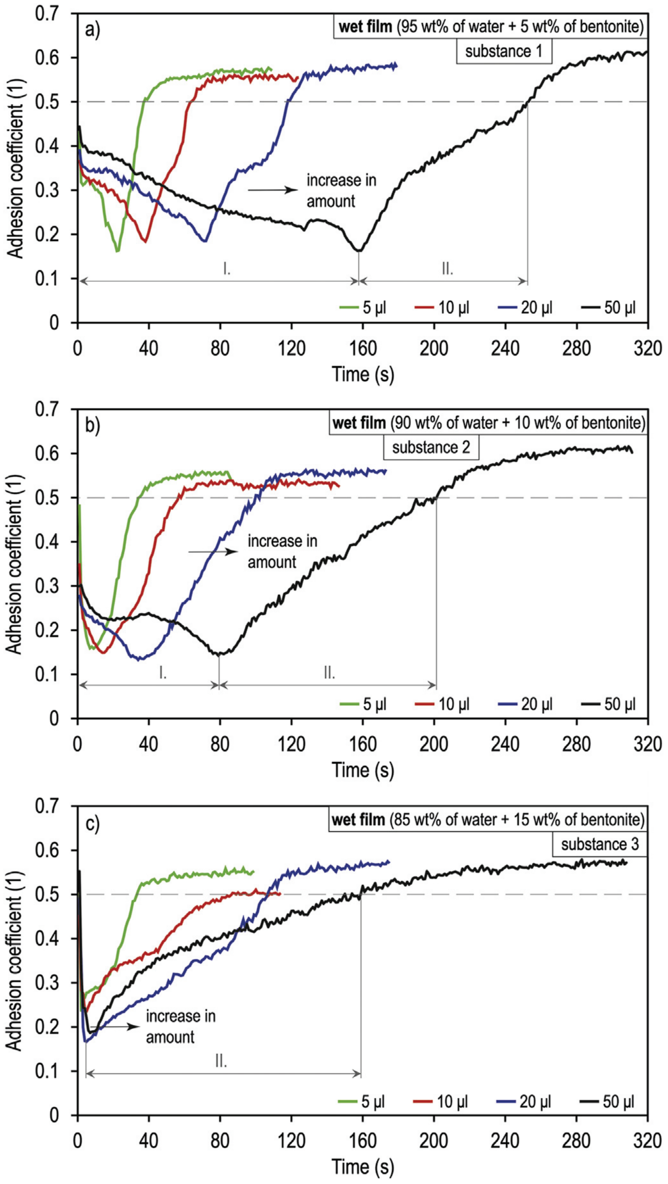

Fig. 6. The effect of substance amount and content of bentonite on adhesion.

too thin, the interaction of the asperities of contact surfaces accompanied by the increase in the adhesion coefficient occurs and the dry level of adhesion is reached, see *part II* in Fig. 6a–b.

In the case of substance 3 (Fig. 6c), the high apparent viscosity caused that *part I* almost disappeared as in the case of the experiment with the large amount of substance. It can be concluded that the substance with high apparent viscosity was not able to form a wet film in the contact path after the application; only a thin solid layer was formed which was gradually removed by the effect of the slip. The same trend in the gradual increase in adhesion was observed in Ref. [20] where the complex water–based FMs with both mineral and steel particles were used. It indicates that a substance free of particles for friction modification might not cause traction or braking difficulties because the required level of adhesion is ensured by particles of binding agent.

Despite of suppressing of *part I*, it is evident that there are no significant differences in the lasting effects for various substance compositions with the exception of amount of 50 ml, see Figs. 6 and 11. The small differences in lasting effect occur because of the applied quantity and roughness. Moreover, the dosage precision is not completely the same during each experiment.

The lowest adhesion observed during these experiments was almost insensitive to the applied amount. The friction layer provided the minimum adhesion coefficient in the range from 0.15 to 0.2. These values are slightly lower than the minimum level of adhesion under fully–flooded conditions where the measurements with substance 2 and 3 were not affected by the effect of starvation. Similar friction behaviour was described in Ref. [30] where the paste consisting of water and particles of iron oxide was applied into the contact, and subsequently a very similar trend of adhesion was found.

A summary of the above described experiments is depicted in Fig. 11, which shows how the applied amount and the composition of substances affect the lasting effect. The dark shade represents *part I* of friction curve while the bright one represents *part II*. It is quite evident that the lasting effect was almost constant for various substance compositions while the duration of both parts of the friction curves was controlled by the substance composition. The higher is the content of binding agent, the shorter is the duration of *part I* and simultaneously the longer is the duration of *part II*. On the other hand, the lasting effect increases with the growing amount of substance. Based on this, it can be concluded that the average value of adhesion coefficient during experiments can be managed by the composition of substance whereas the lasting effect is mainly controlled by the applied amount.

3.3. Wet film: base medium and particles for friction modification

3.3.1. Large amounts

In this part the effect of talc content in water (substances 4–8) was investigated under “fully-flooded” conditions, as shown in Fig. 7. The lower content of talc (substances 4 and 5) give the stable adhesion coefficient in the intermediate level of friction. A different case arose for the substances with the higher talc content where the adhesion coefficient decreased with the increasing amount of talc particles. This unexpected adhesion decrease was caused by the presence of sufficiently viscous paste–like layer formed in the contact from crushed talc particles and water, even though talc is insoluble in water. This durable layer is sufficiently strong to support the normal load while has a low shear strength. As a result, adhesion much lower than for water or talc itself was achieved. Low shear strength was also reported in Ref. [30] where a mixture of water and iron oxide was used [30]. The results also indicate that the layer can completely isolate the contact, which causes a problem with detection of vehicles on the track. This mechanism was reported for sanding [37] where silica and filter sand were used. The smaller particles generally cause more electrical insulation in the wheel–rail contact. Photographs of discs during the tests are shown in Fig. 2d–f.

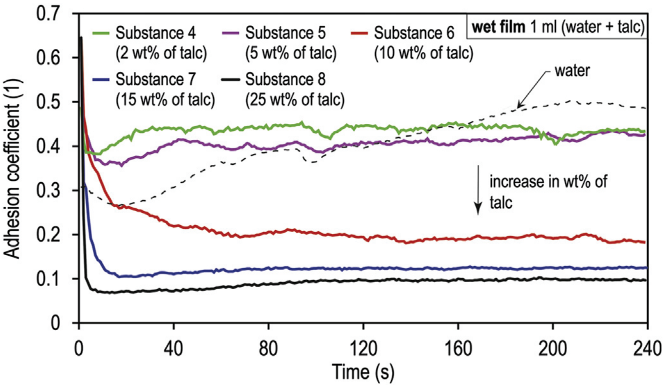

Fig. 7. The effect of talc content on adhesion under fully flooded.

3.3.2. Small amounts

The effect of the talc content for small amounts is depicted in Fig. 8a–c. In this case, the friction curves can be divided into three parts. In *part I*, the friction behaviour of contact was controlled, as in the case of

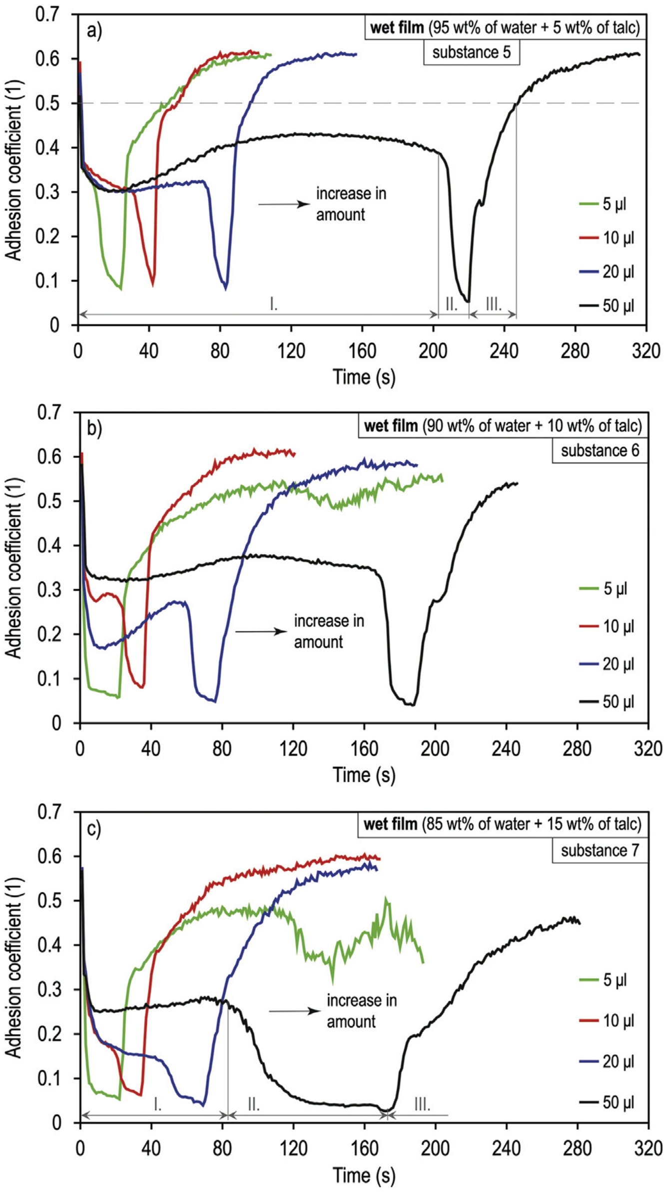

Fig. 8. The effect of substance amount and content of talc on adhesion.

substances of water and bentonite, by the boundary friction film containing talc particles and water. This boundary film results in almost constant adhesion at the intermediate level of friction. After the evaporation of water, a sudden drop of adhesion occurs in *part II*. In this second part the entire contact path is covered by the friction layer consisting mainly of talc. This almost dry friction layer separates the contact surfaces and provides the adhesion coefficient less than 0.1 due to its low shear strength. Subsequently, the layer starts to be removed from the contact due to the wear process and the adhesion coefficient increases to the dry level of friction in *part III*.

The results show that the increasing amount of substance 5 and 6 leads to a longer duration of *part I* while the duration of other parts is not substantially affected. According to these results and the fact that the contact was predominantly run at the intermediate level of adhesion during experiment, the applied amounts of 20 and 50 μl seem to be very appropriate in spite of the following sudden drop. The higher content of talc (higher than 10% for substance 7) seems to be inappropriate because *part I* with constant adhesion disappears; and the duration of *part II*, where the poor adhesion conditions occur, is significantly longer.

The above-mentioned experiments showed that the substance of water and talc (max. 10 wt%) allows to control adhesion at the required level if the suitable amount of a substance is applied into the contact. Although the drop in adhesion was observed for these compositions, it can be assumed that if the duration of *part II* is sufficiently short, then this adhesion drop may not even occur in a real wheel–rail contact. The formation of a layer in real wheel–rail contact is different compared to the ball–on–disc tribometer where both contact bodies are uniformly covered with a layer of substance. Therefore, the future work should be focused on the differences between the formation of layer in laboratory and in real conditions, and the redistribution model of lubricant or FM could be developed.

3.4. Wet film: complex substance

In this section, substances with three or more constituents were analysed. At first, the substance containing a base medium (water), binding agent/thickener (bentonite), and particles for friction modification (talc or zinc oxide) were employed, specifically the substances 10–14 according to Appendix. It was found out that the higher apparent viscosity of substance due to presence of bentonite caused that the stable part of friction curve disappeared, see Fig. 9a. It means that the behaviour of these complex substances was rather similar to the substance containing water and bentonite because the effect of particles for friction modification did not have any positive effect on adhesion for all tested content of talc. Furthermore, the presence of talc particles caused even a decrease in adhesion in comparison with a mixture of water and bentonite (substance 2), see Fig. 9a. Moreover, it seems that the lasting effect was almost insensitive to the increasing content of talc particles in the substance; see Figs. 9a and 11. It should be noted that none of the tested substances with talc particles led to stable adhesion; moreover, a critically low adhesion occurred after their application. The same trend of the friction curve was found previously [20] via a twin disc machine where the commercial water–based FMs were used.

Fig. 9b shows the effect of zinc oxide. One of the dashed lines indicates substance 9 containing only zinc oxide and water. This combination provides relatively high adhesion without a significant drop after water evaporation. In this case, no uniform friction layer was formed on the surfaces, i.e. adhesion was predominantly influenced by free zinc oxide particles while the effect of base medium on adhesion seems to be almost negligible. Combination with bentonite ensures the stabilization of adhesion at app. 0.25, while the lasting effect is significantly affected by the content of zinc oxide particles for the content higher than 5 wt%. A growth of adhesion in dependency on the amount of metal particles was reported in Ref. [34] where two commercial oil–based FMs with metal particles were used. As was described, a higher content of zinc oxide particles led to a faster growth of adhesion. From the obtained results, it is apparent that the adhesion as well as the lasting effect can be advantageously controlled by the content of zinc oxide particles whereas the impact of higher content of mineral particles on adhesion was rather negative in the case of wet complex substances.

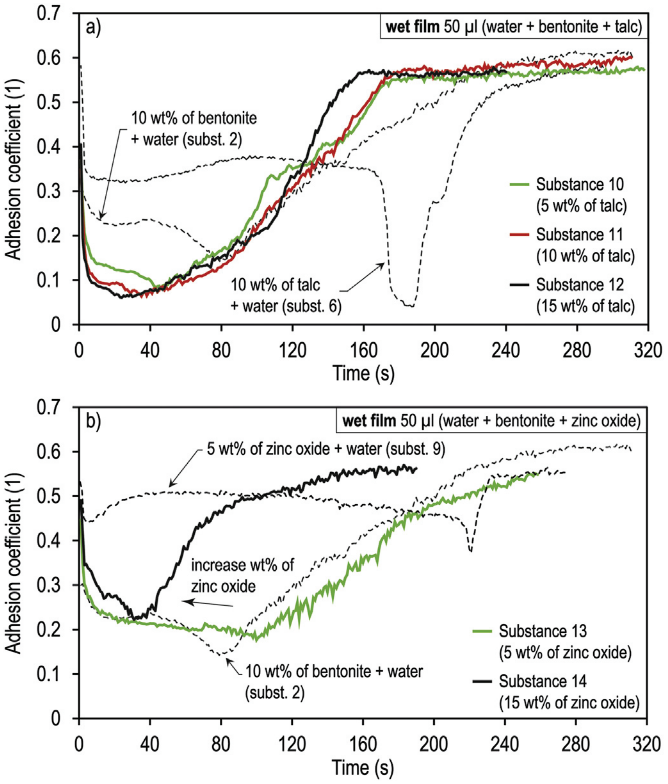

Fig. 9. Complex substances: substance with mineral particles (a) and substance with zinc oxide particles (b).

The last set of experiments with wet film was carried out with substances containing water, bentonite, talc or zinc oxide and also a solid lubricant (substances 15–18). Based on the experiments in section 3.1, molyka (5 wt%) was chosen as the suitable solid lubricant because a decrease in adhesion was not so significant as in the case of graphite particles. As is shown in Fig. 10a–b, 5 wt% of molyka completely changes the friction characteristics of substances 15 and 17. The presence of solid lubricant in the substances caused the critically low adhesion for all tested substances. Surprisingly, zinc oxide is not able to significantly increase adhesion compared to talc, although the situation with complex substances without molyka is different. Based on these results, it can be concluded that if the substance is considered as “wet” FM, the presence of solid lubricant in the substance seems to be undesirable in terms of traction and braking or the content of solid lubricant should be significantly lower than 5 wt%.

3.5. Dry film: complex substance

Under dry conditions, the complex substances with molyka or graphite were tested. Results in Fig. 10c–d shows that the substances with both mineral and zinc oxide particles and molyka provide more appropriate adhesion than those with graphite. Dry substances with mineral particles and molyka are able to give almost constant adhesion at the intermediate level of friction. A similar trend of adhesion can be also shown for substances with zinc oxide particles and molyka; in this case, a gradual decrease in adhesion occurs after approximately 80 s, see Fig. 10d. Based on these results, it is assumed that adhesion is controlled by the hard zinc oxide particles only during the first cycles of experiments (approximately 80). During these cycles, larger particles are squeezed out of the contact while the smaller particles are crushed in the contact due to

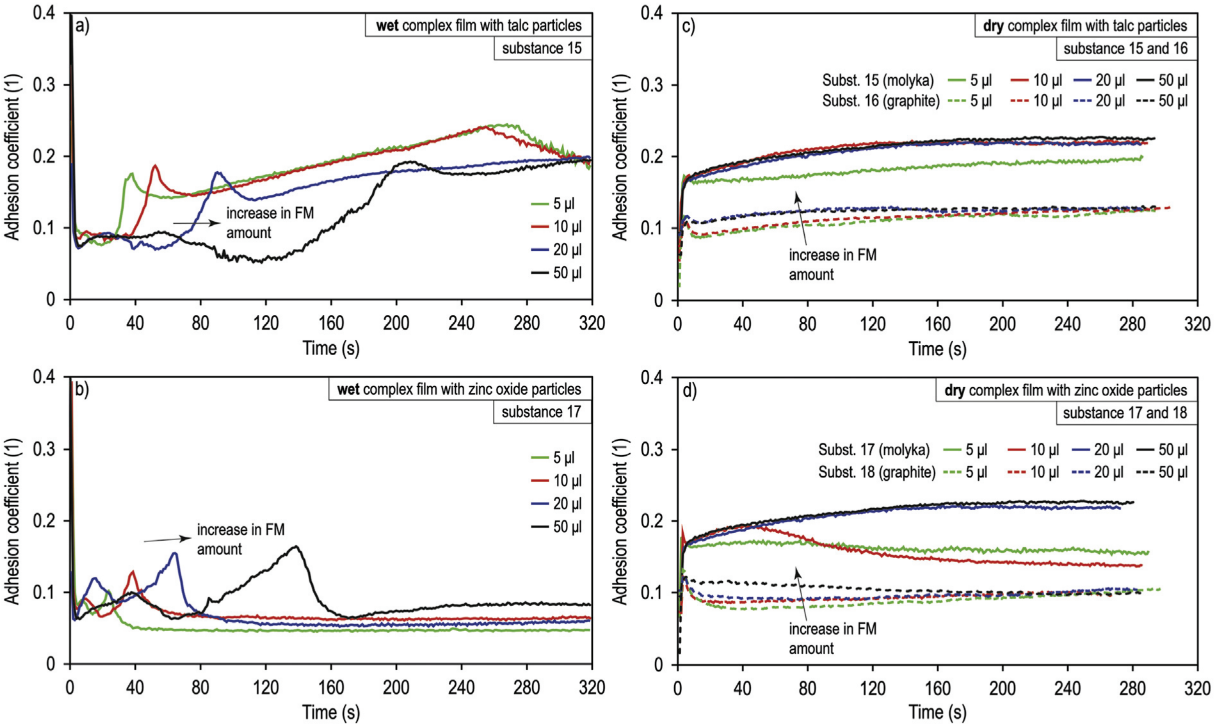

Fig. 10. Complex substances with solid lubricant: wet substance 15 (a), wet substance 17 (b), dry substance 15 and 16 (c), and dry substance 17 and 18.

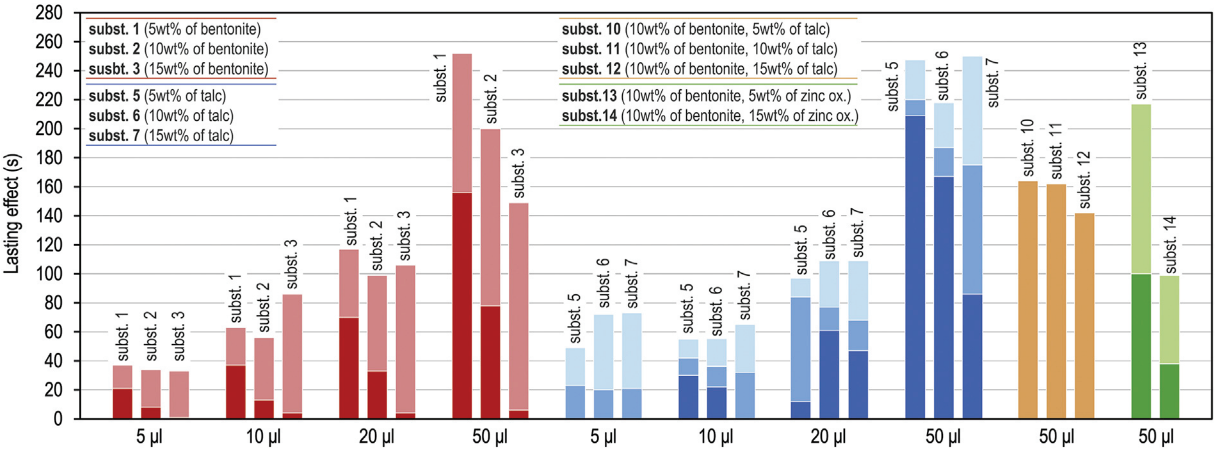

Fig. 11. Overview of substance performance.

the high contact pressure. These crushed particles are trapped among the surface asperities forming a friction film on the disc which is visible with naked eye. However, it seems that the friction behaviour of this very thin film (free of large particles) is mainly controlled by the effect of solid lubricant which is adhered on the surface asperities. This hypothesis was clarified by other long-term experiments which confirmed that the adhesion coefficient gradually decreased to the value of 0.1 corresponding to the adhesion coefficient of a solid lubricant, specifically molyka. On the contrary, no drop of adhesion occurred for the substance with mineral particles during these long–term experiments. In this case, only a gradual growth of adhesion was observed.

Experiments with a dry friction film confirmed that the performance of water–based FMs is greatly affected by evaporation of the base medium. Whereas substances with oxide particles lead to the very appropriate trend of adhesion in the case of wet film (Fig. 10b), dry complex substances cause a low adhesion. On the contrary, substances with mineral particles have a better ability to manage the adhesion between the wheel and the rail after evaporation of base medium. According to the experiments in section 3.1 where a better lubrication ability of graphite was evaluated, the substances with graphite particles led to the adhesion of about 0.1 for all tested substances. This value of adhesion can cause insufficient traction and braking; therefore, molyka seems to be the more suitable solid lubricant for top–of–rail application.

3.6. Wear test and surface analysis

With respect to the results in previous section where the substance with 5 wt% of solid lubricant caused poor adhesion conditions, the substances 19 and 20 with 2 wt% of molyka were chosen in order to investigate the mass loss and the change in surface topography of the disc. Wear tests were carried out for both “dry” and “wet” contact conditions.

The results of wear tests and the disc surface analyses are summarized in Fig. 12 and Fig. 13. It is evident that both tested substances for both

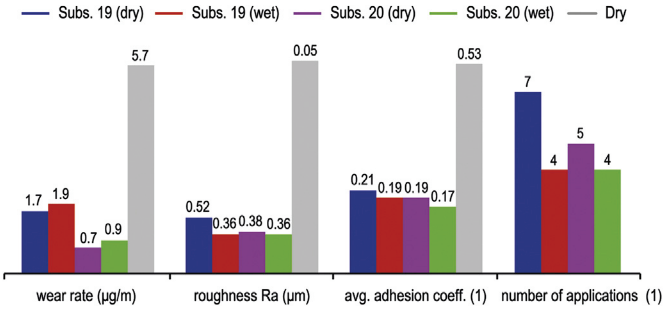

Fig. 12. Summary of wear tests and surface analyses.

wet and dry film considerably reduce wear, in the range of 66–87% compared to dry conditions where the highest wear rate was found. Under dry conditions, deep scoring marks (see Fig. 13e) were identified on the disc due to the action of plastically deformed asperities which are often called riders [39]. Hardness of riders is higher compared to that of base material; therefore, they are able to score disc surfaces. The same mechanism of wear was previously recognized for experiments under both dry conditions and the conditions where oil–based FMs with zinc and aluminium particles were applied [34]. In the present study, no significant scoring marks were observed on the disc surface after the application of water–based substances 19 and 20, see Fig. 13a–d.

The substance 20 with zinc oxide particles led to the lower wear rate compared to the substance with mineral particles, although the average adhesion coefficient was almost the same during the experiments, see Fig. 12. On the other hand, the surface analysis shows that harder oxide particles caused a more serious damage to discs, particularly the indentations can be observed, see Fig. 13c–d. The similar effect was previously found for water-based FMs with mineral particles [20,21]. These indentations can contribute to the development of RCF.

Fig. 13a exhibits that the large portion of contact path is covered with the thick dry adhered film with average film thickness of app. 2 μm. This adhered film can be easily removed from the disc surface using a scalpel. After that, the surface had almost the same topography as a new disc. After the experiment with “dry” substance 20, no adhered film was observed on the disc and the surface of contact path was more plastically deformed, see Fig. 13c. When the “wet” substance 20 was applied, the disc surface was also covered with a very thin friction film (beside the thicker adhered film mentioned above) containing crushed zinc oxide particles which provides further protection of the disc surface. The presence of this very thin friction films explains why the lowest roughness was found for these conditions.

The obtained results showed that both tested substances are able to significantly reduce wear, roughness, and surface damage (especially scoring) in comparison with dry conditions. The ability to reduce wear is mainly given by the low shear strength of the tested particles. This behaviour is similar to the behaviour of commonly used solid lubricants. Contrary to the expectation, the substances with mineral particles cause more than a double wear rate compared to the substances with zinc oxide particles although the average adhesion coefficient was almost the same during the experiments. On the other hand, a more serious local damage to disc surface was revealed for substances with zinc oxide particles. These findings are in good agreement with [32] who mentioned that mineral particles (quartz with hardness about 7 Mohs) caused a higher mass loss than metal particles (alumina particles with hardness 9 Mohs) despite of the fact that metal particles maintained a higher adhesion during the experiments. These wear tests also showed that the lasting effect of “dry” substance was shorter; therefore, a higher number of applications was needed during a 60 min test.

3.7. Limitations of the study and future work

In this subchapter, some limitations of the applied method should be mentioned. In addition, the recommendations for future research are discussed.

3.7.1. Speed, lubrication regime and roughness

The rolling speed of 300 mm/s was chosen with respect to the lubrication parameter lambda defining the relative roughness and the central film thickness h_c. A higher value of speed can lead to a removal of low–viscous substance from the contact path due to the centrifugal force. To be able to determine the film-thickness of water ($\eta = 0.95E\text{-}03$ Pa·s), formula for isoviscous-elastic lubrication regime was used. The results of film thickness and lambda predictions for both laboratory and field measurements are shown in Table 2. The typical speed for a light rail system in a city is 40 km/h (11.1 m/s) and the average roughness of the contact surfaces can vary in the range from 0.4 to 2.4 μm [27], whereas the roughness of the ball and the disc was between 0.01 and 0.25 μm. From Table 2, it is evident that the contact contaminated by water

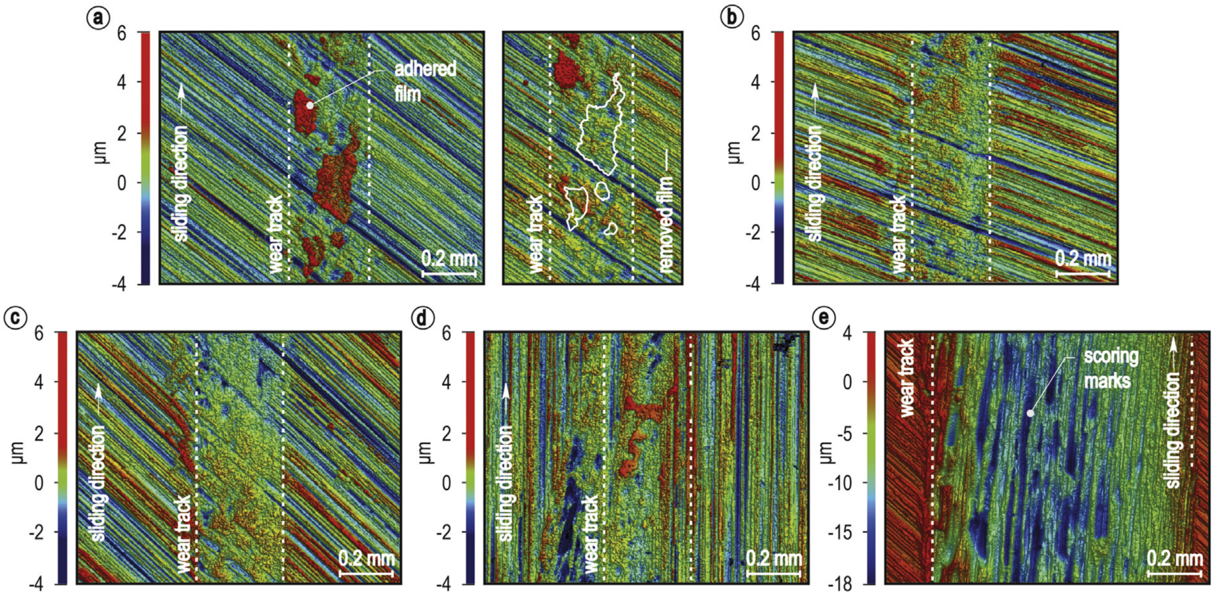

Fig. 13. Disc surface analyses after tests with “dry” substance 19 (a), “wet” substance 19 (b), “dry” substance 20 (c), “wet” substance 20 (d) and without substance – dry conditions (e).

Table 2
Lambda prediction for laboratory and real operating conditions.

	v (m/s)	R_a (μm)	h_c (nm)	Λ_c (1)
Light rail system	11.1	0.4–2.4	64	0.04–0.25
Ball-on-disc	0.3	0.01–0.25	4	0.02–0.18

operates in the boundary regime of lubrication under both real and laboratory conditions [42]. This regime of lubrication is common for the wheel-rail contact.

3.7.2. Slip

The value of SRR was set to 5%, corresponding to the slip of 2.5%, for all measurements. The typical slip occurring in the real operating conditions can vary between 0.5 and 3%. The value of 2.5% was chosen regarding to the actual shape of the adhesion curve, which was obtained using the ball-on-disc tribometer. In this case, the saturation point is reached at the higher value of slip, e.g. 3–5%. It means that a full saturation would not occur if the contact operates at 2.5% of slip.

3.7.3. Material and hardness

The chemical composition of specimens, as well as their hardness, is different in friction tests compared to actual wheel or rail steel. Different material properties may influence a wear regime and a wear rate. In actual wheel/rail contact worn material is an integral part of the third body layer. Preliminary results suggest that wear debris rather increases adhesion when FM is applied and decreases its value under “dry” conditions. Anyway the effect on real contact area and repeatability of friction results makes it difficult to fully incorporate the wear process in the small-scale experiments. On the other hand, frictional properties of FM itself are well represented with the hard contact pair. In addition, the change of contact area during experiments should be less significant in the case of bearing steel.

3.7.4. Contact pressure and contact area

All the experiments were conducted under the contact pressure of 0.75 GPa, which represents a real contact pressure in a light rail system, where the contact area is almost circular as in the case of the employed tribometer, which is commonly used to study the wheel-rail contact [34,40,41]. The diameter of the contact area is 200 μm, which is significantly smaller compared to the real contact area, where the diameter is about 8 mm. This scaling effect could be important considering the size of the used particles is real. Nevertheless, almost all the tested particles are flakes with the thickness in units or tens of nanometres, so the ability of the particles to enter the contact seems to be unaffected. More important is the scaling effect when the applied quantity of FM is assessed. In the boundary lubrication regime, FM quantity should be recalculated on the basis of the different contact width, roughness, and diameter of ball/wheel. The scale is in the order of $1{:}10^4$ which results in FM quantity in the order of tens of grams for the full-scale contact. In real application, the lasting effect will be further reduced due to the redistribution of the friction layer between the wheels and the rail. On the other hand, when using ball-on-disc apparatus, FM is considerably squeezed out of the contact area. These two effects should be also considered.

3.7.5. Future work

As already mentioned, components forming a natural third body should be included in future studies; namely, iron oxides, wear debris, biological contaminants, etc. There is also concern about the interaction with climate conditions, such as humidity and temperature. The used experimental approach provides excellent repeatability of friction results. They are necessary for validation of models of shear properties of solid and liquid friction layers for adhesion and wear prediction. The current study did not concern the effect of FM/substances on a trend of the creep force characteristic.

4. Conclusion

The ball–on–disc apparatus has been used to study the behaviour of water–based FMs in terms of adhesion in the wheel–rail contact. A series of experiments were performed in order to investigate the effect of both individual constituents of water–based FMs and various complex substances on adhesion and film formation for two contacts states: “wet” and “dry” film. For this purpose, a wide range of substance compositions was used where the content of base medium, binding agent, particles for friction modification, and solid lubricant varied. Finally, the effect of selected substance on wear and surface damage was analysed. The conclusions of the present article are as follows:

1. Substances consisting of water and bentonite are able to provide the intermediate level of adhesion without the risks of traction or braking difficulties even under fully flooded conditions when the contact is overdosed. The lasting effect of these substances is controlled by the applied amount whereas the average adhesion during the experiment is mainly affected by the substance composition. The content of binding agent seems to be a crucial parameter because it influences a replenishment ability of substance, thus affecting the lasting effect significantly.
2. For the substance composed of water and talc, the adhesion coefficient decreased with increasing content of talc in the substance. A high content of talc can lead to the critically low adhesion as was observed under fully flooded conditions. In the case of smaller applied amounts, the substance containing less than 10 wt% of talc ensures a very appropriate shape of friction curves in terms of traction, braking and wear.
3. In the case of a complex substance containing water, bentonite and mineral particles, adhesion is especially affected by water and binding agent while the effect of mineral particles as particles for friction modification was rather negligible or even negative depending on their content. The opposite effect was observed for zinc oxide particles where a larger content of zinc oxide particles ensures a faster growth of adhesion.
4. The performance of substances is greatly affected by evaporation of base medium. Substances with zinc oxide particles are able to provide a stable and very suitable adhesion in the case of wet film whereas the abilities of complex substances with mineral particles are significantly better after evaporation of base medium.
5. Both “wet” and “dry” complex substances are able to considerably reduce wear rate, roughness, and surface damage in comparisons with dry conditions. More than a double wear rate was found for substances with mineral particles in comparison with substances with zinc oxide particles.

Acknowledgments

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Appendix

Substance no.	Base medium	Binding agent	Friction modifier	Lubricant	Dynamic viscosity (Pa·s)
1	water	5% bentonite			0.025
2	water	10% bentonite			1.2
3	water	15 %bentonite			15
4	water		2% talc		
5	water		5% talc		
6	water		10% talc		
7	water		15% talc		
8	water		25% talc		
9	water		5% zinc oxide		
10	water	10% bentonite	5% talc		
11	water	10% bentonite	10% talc		
12	water	10% bentonite	15% talc		
13	water	10% bentonite	5% zinc oxide		
14	water	10% bentonite	15% zinc oxide		
15	water	7.5% bentonite	5% talc	5% molyka	
16	water	7.5% bentonite	5% talc	5% graphite	
17	water	7.5% bentonite	5% zinc oxide	5% molyka	
18	water	7.5% bentonite	5% zinc oxide	5% graphite	
19	water	7.5% bentonite	5% talc	2% molyka	
20	water	7.5% bentonite	5% zinc oxide	2% molyka	

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7 CONCLUSIONS

The present doctoral thesis deals with the performance of TOR products which are used in rail transportation as a part of the so-called friction management methods. This new approach to top-of-rail friction management is primarily used to reduce noise, wear, and rail head corrugations. In the last 20 years, many scientific investigations have been aimed at verifying the benefits of TOR products (FMs and TOR lubricants) using both laboratory and field experiments. Although the so-far published articles proved the ability of TOR products to provide the above-mentioned benefits, it should be noted that research was almost entirely carried out with one commercial water-based product (FM). It means that only a little is known about the friction behaviour of other TOR products, especially the abilities of TOR lubricants have not been examined in detail yet. Moreover, the so-far published articles have not usually dealt with the influence of applied quantity in spite of the fact that it may be one of the most important factors influencing adhesion in the wheel-rail contact. With respect to the critical analysis of the current state of the art, the main goal of this doctoral thesis was to clarify the friction behaviour of TOR products (FMs and TOR lubricants) in terms of adhesion, wear, and noise reduction, while the main attention was paid to low adhesion issues related to the application of these substances.

The original results of this doctoral thesis are published in three scientific papers. The aim of the first paper was to investigate if TOR lubricants are able to provide the same benefits as FMs (the intermediate level of friction, positive traction curve, and wear reduction). For these purposes, two commercial TOR lubricants with different content of PFM were used in order to investigate how significantly the performance of TOR lubricants varies with regard to a different content of PFM. Apart from this, the influence of TOR lubricant quantity on adhesion was studied to reveal if TOR lubricants can cause traction and braking difficulties. Note that besides the reasonably small quantities, the experiments under fully-flooded conditions were conducted to evaluate the possible worst case when the wheel-rail contact is overdosed with TOR lubricant. At the end of this study, wear and surface damage of specimens were analysed and compared with the results obtained under dry and oil conditions. The most important conclusion was that the over-application can lead to extremely low adhesion values compromising traction and braking performance. Following these findings, the goal of the second paper was to verify the results obtained in the first paper using another experimental device (a twin-disc machine) and field measurements (a light rail system). Furthermore, the ability of TOR lubricant to reduce noise was investigated both under laboratory and field conditions. The last paper was focused on the friction behaviour of FMs with various complexities in order to describe the effect of individual constituents of FMs on adhesion and film formation. As in the case of the first paper, the performance of substances was evaluated for various applied quantities. Moreover, some of these experiments were performed in both liquid and dry form (after base medium evaporation) in order to investigate how the drying effect affects their performance. At the end of this study, the effect of these water-based substances on wear and surface damage was determined.

The current thesis contains the original results extending the knowledge in the area of friction modification within the wheel-rail contact. The results are confronted with the previous studies. A further step should be to expand the knowledge about the interaction of TOR products with common railhead contaminants under various atmospheric conditions. Besides this, the future work should be focused on the differences between the formation of friction layer in the laboratory and real conditions. Based on this, a redistribution model of TOR product could be developed; thus, a better transferability of laboratory results to the real wheel-rail contact can be achieved. The main contribution of the thesis can be summarized as follows:

- The influence of applied quantity was revealed for both TOR lubricants and FMs with various complexity where even the experiments under fully-flooded conditions were carried out in order to evaluate the worst possible scenario (over-application).
- The ability of TOR lubricants to provide the required adhesion level, wear and noise reduction was investigated and verified using both laboratory and field approaches.
- For the first time, the effect of composition of FMs on adhesion and wear was studied for both liquid and dried form of FMs in order to describe the role of particular constituents of FMs and to evaluate how much the drying effect influences adhesion.

Regarding the scientific questions, the obtained knowledge can be summarized in the following concluding remarks:

- Experiments conducted using both a ball-on-disc tribometer and a twin-disc machine proved that the larger is the applied quantity, the longer is the lasting effect of TOR products **(hypothesis H1 was confirmed)**.
- Whereas the shape of friction curve can be advantageously controlled by the applied quantity in the case of TOR lubricants, almost no changes in the shape of friction curve were observed for water-based substances (FMs) with increasing applied quantity **(hypothesis H2 was falsified)**.
- Regarding both the laboratory and field measurements, it seems to be difficult to achieve a significant reduction of noise without the impact on traction and braking capabilities. Even if the beneficial N-shape behaviour of TOR lubricant was identified, some adhesion losses were identified during the first cycles of measurements after the application **(hypothesis H3 was falsified)**.
- The over-application of wheel-rail contact by TOR lubricants caused the critically low adhesion in spite of the fact that PFM enter the contact. These results were subsequently verified by field experiments where the over-application led to the significant extension of braking distance accompanied by complete wheels slide. It means that over-application can lead to braking

and traction issues. Some adhesion risks were also identified for FMs with solid lubricant or with a high content of mineral particles as PFM **(hypothesis H4 was falsified).**

- The field experiments revealed that the most significant extension of braking distance occurred during the second or the third pass after the application of TOR lubricants, while the braking distance closest to baseline conditions was found for the first pass after the application **(hypothesis H5 was falsified)**.
- In the case of complex FMs, zinc oxide particles used as PFM had the dominant effect on friction behaviour of FMs. However, the opposite effect was found for mineral particles as PFM where the friction behaviour was mainly given by the effect of water and binding agent. In this case, the effect of PFM was even rather negative **(hypothesis H6 was falsified)**.
- TOR lubricant with higher content of PFM generally provided the longer or the same lasting effect as TOR lubricant with lower content of PFM. In the case of complex FMs, the different dependencies were identified with respect to type of PFM. When oxide particles were used as PFM, then the lasting effect was shortened with the increasing content of PFM. In contrast, the lasting effect was almost insensitive to the changes in the content of PFM when mineral particles were used **(hypothesis H7 was falsified)**.
- It was found that substances free of PFM can be used as TOR product because they were able to provide beneficial friction behaviour **(hypothesis H8 was falsified)**.
- When the performance of FMs was evaluated in both liquid and dried form, it was revealed that dry substances provided the shorter lasting effect; however, lower wear rate was achieved for these dry substances **(hypothesis H9 was falsified)**.

8 LIST OF PUBLICATIONS

8.1 Papers published in journals with impact factor

GALAS, R., M. OMASTA, I. KRUPKA and M. HARTL. Laboratory investigation of ability of oil-based friction modifiers to control adhesion at wheel-rail interface. *Wear,* 2016, 368–369, 230-238.

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LIST OF SYMBOLS AND ABBREVIATIONS

Λ	1	film thickness parameter
μ	1	adhesion coefficient
τ	Pa	shear stress
τ_c	Pa	critical shear stress
f	1	friction coefficient
F_n	N	normal force
F_t	N	friction force
F_T	N	tangential force
G	Pa	shear elastic modulus
h	m	film thickness
k	Pa	shear plastic modulus
r_{ball}	m	ball radius
r_{disc}	m	disc radius
R_{q1}	m	ball roughness
R_{q2}	m	disc roughness
w_{ball}	s^{-1}	ball angular speed
w_{disc}	s^{-1}	disc angular speed

AoA	Angle of attack
FM	Friction modifier
HPF	High positive friction modifiers
HVF	Heavy haul freight
LCF	Low coefficient friction modifiers
MTM	Mini-Traction-Machine
PFM	Particles for friction modification
PSI	Phase Shifting Interferometry
RCF	Rolling contact fatigue
RH	Relative humidity
SRR	Slide-to-roll-ratio
TORL-A	Top-of-rail lubricant A
TORL-B	Top-of-rail lubricant B
VHPF	Very high positive friction modifiers
VSI	Vertical Scanning Interferometry
VXI	High resolution mode of VSI