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The low adhesion problem: the effect of environmental conditions on adhesion in rolling-sliding contact

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Abstract: Low adhesion problem is one of the major problems for railways all over the world because this phenomenon can occur anytime and anywhere. To investigate when poor adhesion conditions can be expected in real operation, a ball-on-disc tribometer with a climate chamber was employed to simulate rolling-sliding contact under various environmental conditions. Clean and contaminated discs with leaf extract were used to simulate different surface conditions. Results indicate that contact operating under rolling-sliding conditions is more prone to the occurrence of low adhesion than found by others for pure sliding contact. Very low adhesion (≤0.05) were identified for contaminated and oxidized specimens operating under humid and wet conditions. For clean surfaces, low adhesion (≤0.15) were found under dew conditions.

Keywords: low adhesion; wheel-rail tribology; environmental conditions; contaminated contact

1. Introduction

Low adhesion between rail head and wheel tread is one of the major problems for railways in many countries all over the world. This phenomenon has a negative impact on cost, performance, and safety. The term "low adhesion" or "poor adhesion" is usually associated with the autumn season when a slippery layer from crushed fallen leaves is formed on the track. Both laboratory **[1-3]** and field research **[4-5]** revealed that this layer can result in the coefficient of adhesion (CoA) lower than 0.15, in some critical cases even lower than 0.05 **[6]**. Although it is a well-known fact that leaf contamination causes serious problems in railways all over the world; it must be emphasized that fallen leaves are not the only cause of low adhesion incidents. Besides fallen leaves, there are other causes of low adhesion which are mainly related to environmental conditions.

Water can be considered as one of the most common contaminants influencing adhesion in the wheel-rail contact. Water in the field can be found in various forms such as morning dew, fog, and light or heavy rain. These different forms may lead to different adhesion levels. In the case of bulk water, CoA can take values between 0.05 to 0.5 **[7-12]** depending on speed, roughness, and other parameters. More significant adhesion drop can be expected for slightly wet conditions, which usually occurs due to dew or light rain. Beagley et al. **[13]** observed that a small amount of water from condensation decreased CoA to 0.22. Even more critical case was found when the rail was not free of solid particles. This combination of a small amount of water and solid particles (such e.g. wear debris) led to the formation of a viscous paste, which provided low (<0.15) **[14]** or even very low CoA (<0.05) **[15]**.

In the case of weather conditions, daytime evolution of relative humidity (RH) and temperature can have a substantial impact on CoA. Beagley et al. **[13]** showed that CoA was reduced from 0.55 to 0.22 with increasing RH, while the effect of temperature was rather negligible during these tests**.** Similar findings were reported by Olofsson et al. **[16]** where the effect of RH on CoA was studied for dry and leaf contaminated contact using the pin-on-disc apparatus. It was found that the coefficient of friction (CoF) was reduced to 0.37 (dry) and 0.27 (leaf) when RH reached 95%. A pin-on-disc device was used also by Zhu et al. **[17, 18]** who investigated the effect of RH and temperature on CoF for clean and rusted specimens. These complex studies showed that rusted discs generally led to lower CoF than found for clean discs; however, the lowest observed adhesion was still 0.4 or higher for both disc types. The lowest values of CoF was observed when RH reached 70%. A subsequent increase in RH did not lead to a further decrease in CoF.

Previous research works have shown that adhesion/friction is very variable depending on contaminants and current weather conditions. It means that low adhesion problem can happen anytime and anywhere. Although a decrease of CoA/CoF was observed in all above-mentioned studies, low CoA or CoF (<0.15) was found predominantly when contact was contaminated with leaves. However, White et al. **[19]** reported that many of low adhesion incidents in a real operation were not associated only with leaf contamination but there were other factors leading to low adhesion incidents. These authors suggested several reasons why these low adhesion incidents happened, such as due to the presence of water, moisture or not detectable leaf layer. The conditions and mechanisms leading to low adhesion phenomenon are not fully understood.

The main objective of this study is to reveal conditions when low adhesion ($\mu \leq 0.15$) and very low adhesion conditions ($\mu \leq 0.05$) can be expected in the wheel-rail contact. Special attention is paid to the effect of RH, temperature and leaf contamination. For this purpose, a ball-on-disc tribometer with a climate chamber is employed. This contact configuration is chosen because it enables to set typical rolling-sliding conditions occurring in the wheel-rail interface. Based on the previous studies, it is assumed that pure sliding configuration, where a pin is in permanent contact with the counterpart, is not sufficiently representative in terms of the formation and action of the third-body layer. The presence of this layer is important to study low adhesion problem.

2. Material and methods

2.1 Test setup and specimens

Adhesion measurements were conducted on the ball-on-disc tribometer (Mini–traction–Machine, PCS Instruments) where a 19.05 mm steel ball and 46 mm diameter flat steel disc was loaded against each other as is depicted in **Fig. 1**. Both these specimens were independently driven, thus a rolling-sliding contact (where the slip was accurately controlled) can be achieved. The slip is defined in **Eq. (1)**, where w_{ball} and w_{disc} are the angular speeds of the ball and the disc respectively and r_{ball} and r_{disc} represent the radii of specimens. CoA was calculated as a ratio between traction and normal forces which were directly measured using embedded sensors.

$$slip = \frac{w_{bal}}{\qquad\qquad} \tag{1}$$

The material of both the ball and the disk was bearing steel AISI 52 100 with the hardness of 800–920 HV (ball) and 720–780 HV (disc). The initial roughness of the ball and the disc was Ra 0.01 μm and Ra 0.02 μm respectively. These specimens were enclosed in a climate chamber where temperature and air humidity were controlled. Heating was ensured by heaters installed in the tribometer body while cooling was provided by an external cooling unit with cooling oil circulating through the tribometer body. Air with controlled RH and ambient temperature was fed to the chamber from external humidity unit. Thanks to the method of cooling, this equipment enables to reach dew point conditions resulting in water condensation on the surface of the disc. Detail parameters of employed sensors are listed in Appendix A.

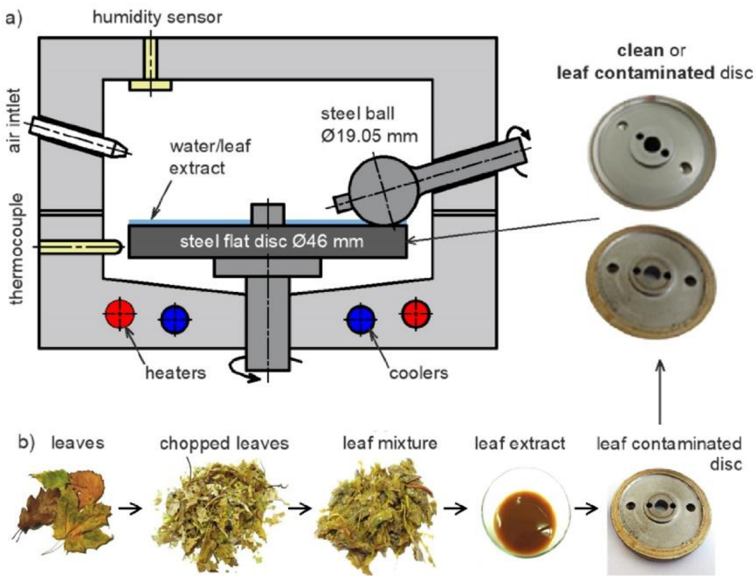

Fig. 1 *(a) Scheme of the ball–on–disc apparatus with a climate chamber, (b) preparation of leaf extract and contaminated disc*

2.2 Experimental conditions and procedure

Several sets of adhesion measurements were conducted under various operating and environmental conditions, see **Tab. 1a**. For all sets, a contact pressure of 750 MPa (a normal force of 17 N) was used to achieve representative light rail system contact conditions. In the beginning, tests under dry and wet (fully-flooded) conditions were run to obtain reference CoA values for dry and wet (heavy rain) conditions. Based on these tests, adhesion characteristics for dry and wet (fully-flooded) conditions were drawn for a speed range of 0.5 to 3 m/s. Each point on adhesion characteristics was evaluated as the average value from a 30-second test. After the completion of these reference tests, other tests were always conducted with a fixed slip value of 5% and a speed of 1 m/s. Test sets No. 3 and 4 were focused on the effect of water (light precipitation) and leaf extract amounts on CoA. Last two test sets (No. 5 and 6) were performed under various temperature (1 – 50 °C) and RH values (6 – 100%) to investigate conditions occurring throughout the day. Moreover, the last test set was conducted with the contaminated disc (described below) to combine the effects of leaf contamination, RH, and temperature on CoA.

Leaf contamination was represented in two ways: as a liquid leaf extract and as a dry friction layer (from the extract) on the disc. The leaf extract was prepared from leaves which were gathered from fallen maple, beech, birch and oak leaves near the railway network in autumn. Subsequently, leaves were chopped into small pieces (approx. 5 μm) and soaked in water for 5 days. After that, excess water was separated and the leaf extract was obtained as shown in **Fig. 1b**. A dry layer from leaf extract was prepared one day before testing. The preparation of the layer proceeded in several steps. At first, 20 μl of leaf extract was applied on the disc and then, several cycles under pure rolling conditions were carried out to create a uniform friction layer around the circumference of the disc. Finally, the disc was left for several hours to ensure that all liquid contained in the friction layer was evaporated. This preparation process of dry leaf layer was needed before each particular measurement. The disc with the layer is further referred to as "contaminated disc".

***Tab. 1** Experimental conditions of the tests*

<table>
<tr><th>set of tests</th><th>contaminant</th><th>disc</th><th>amount (μl)</th><th>running-in</th><th>mean speed (m/s)</th><th>temp. (°C)</th><th>RH (%)</th><th>Hertz pressure (MPa)</th><th>slip</th><th>correspond Fig. No.</th></tr>
<tr><td>1r*</td><td>none</td><td>clean</td><td>-</td><td rowspan="2">dry</td><td rowspan="3">0.5 – 3</td><td rowspan="5">ambient</td><td rowspan="5">ambient</td><td rowspan="7">750 ± 3</td><td rowspan="3">0 – 8</td><td>2</td></tr>
<tr><td rowspan="2">2r*</td><td rowspan="2">water</td><td>clean</td><td rowspan="2">fully-flooded</td><td>3a</td></tr>
<tr><td>oxidized</td><td>wet</td><td>3a, 3b</td></tr>
<tr><td>3</td><td>water</td><td rowspan="3">clean</td><td>1 – 10</td><td rowspan="3">dry</td><td>1</td><td rowspan="4">5</td><td>4, 5, 8</td></tr>
<tr><td>4</td><td>leaf extract</td><td>1 – 20</td><td></td><td>6, 7, 8</td></tr>
<tr><td>5</td><td>none</td><td>-</td><td></td><td>1 – 50</td><td>8 – 100</td><td>9, 10a, 11a, 12a, 13 a</td></tr>
<tr><td>6</td><td>none</td><td>contam.</td><td>-</td><td>none</td><td></td><td></td><td>6 – 100</td><td>10b, 11b, 12b, 13 b</td></tr>
<tr><td colspan="10">overview of selected results</td><td>16</td></tr>
</table>

* reference tests

Each test in **Tab.1**, except tests with the contaminated disc, was started by a running-in to remove oxides and any other residual layers adhered on contact surfaces. This running-in was stopped when a stable and dry level of adhesion was reached. Experimental conditions of running-in (speed, slip, etc.) were the same as the conditions of the "main" test performed immediately after this running-in. As is evident from **Tab.1**, some tests were carried out with oxidized disc. In this case, the clean disc was run under wet (fully-flooded) conditions to form the oxide layer. This wet running-in was stopped when CoA was dropped (due to the presence of oxides) and stabilized. All liquids were applied to the contact using a micropipette with a dosing accuracy of ±0.04 μl. In the case of fully-flooded conditions, the disc was immersed in water. At the end of each test, both specimens were removed from tribometer and ultrasonically cleaned with acetone. The statistics data of all tests are listed in Appendix B.

To judge the effects of tested contaminants and environmental conditions listed in **Tab. 1**, the following intervals of CoA were considered in this study: *high adhesion* $\mu > 0.4$, *intermediate adhesion* $0.4 \geq \mu > 0.15$, *low adhesion* $0.15 \geq \mu > 0.05$, and *very low adhesion* $0.05 \geq \mu$.

3. Results and Discussion

3.1 Reference tests under dry and wet conditions

To obtain reference values of CoA, adhesion characteristics under dry and wet (fully-flooded) conditions were measured for four different mean speeds (**Fig. 2** and **Fig. 3**). **Fig. 2** shows data from the tests ran in dry conditions where CoA reached the typical values for non-lubricated rolling-sliding contact operating in laboratory conditions **[9, 20]**. The results also indicate that there was almost no significant change in CoA as the speed increased; however, the tested speed range used in this study was rather limited. As was shown in **Tab. 1**, most of the tests were carried out at 5% slip. For this particular slip value, CoA reached approximately 0.6 for all tested speeds. The value of 0.6 is considered as a reference value of CoA for dry conditions in later parts of this study.

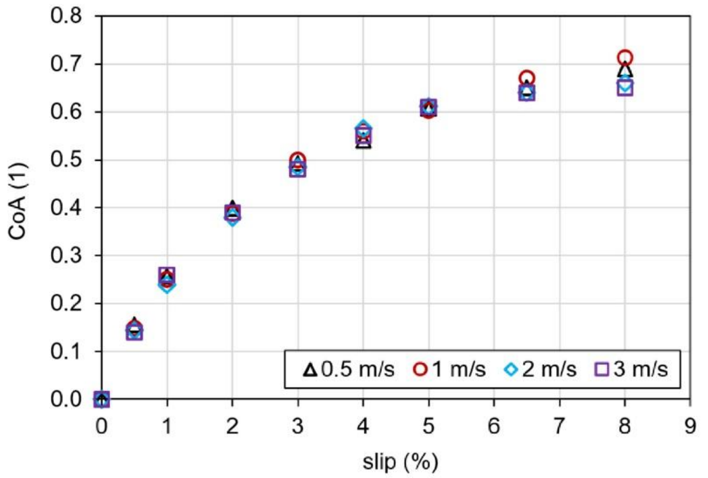

Fig. 2 Adhesion characteristics for different speeds in dry conditions

Besides the value of CoA, the shape of the adhesion characteristic is another important factor influencing a maximum available adhesion in the contact and wear (corrugation formation especially). From the results in **Fig. 2**, it is obvious that a positive slope of the adhesion characteristic was found in all cases even though the negative adhesion characteristic is generally expected for non-lubricated wheel-rail contact as was found in

Ref. **[21]**. The reason for this discrepancy may be the fact that the slip in laboratory research is usually set as a fixed value, while the slip in a real wheel-rail contact can immediately change depending on current operating conditions. This hypothesis is consistent with the findings from previous laboratory research, where the positive adhesion characteristic was also observed under dry conditions **[22,23]**.

When tests under dry conditions were completed, the same set of experiment was conducted again with pure water under fully-flooded conditions, which ensured that the contact did not starve during the test, see the set of tests in **Fig. 3a** marked as "no oxide". The results give evidence that no significant drop of CoA occurred under these conditions. Even at the maximum speed, CoA reached a relatively high value of 0.47 at 5% slip which means that CoA was reduced by 28% compared to dry conditions. The fact that wet conditions did not lead to low adhesion is well correlated with lambda prediction for isoviscous-elastic lubrication regime. For the tested range of speeds (from 0.5 to 3 m/s), the lambda parameter ranged between 0.02 and 0.07 which means that the contact was operating in the boundary lubrication regime. This regime can be supposed for trams and non-high speed trains when rain is heavy and other contaminants are washed away from the rail surface. The similar findings were reported by Chen et al. **[10]** where CoA under wet conditions was measured by the twin-disc machine. Chen's results showed that CoA at low speed (v < 2 m/s) reached high values (μ > 0.4). Moreover, these authors conducted the tests with a lower slip (s = 0.7%) and also the roughness of specimens was approx. half in comparison with the roughness in the present study.

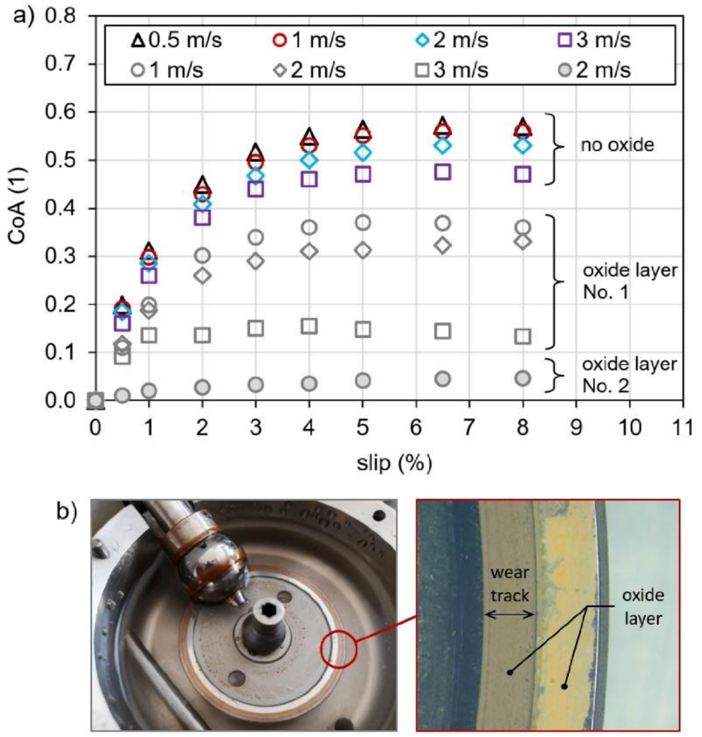

Fig. 3 (a) Adhesion characteristics in wet (fully-flooded) conditions for clean (colour points) and oxidized disc (grey points), (b) the oxide layer No. 1

However, there are some publications **[1, 3, 9]** where the application of water resulted in substantially lower CoA (between 0.17 and 0.28) than found in the present study. There are two things which can explain this important difference. Firstly, other authors used lower slip values leading to lower values of CoA. Note that the slip value of 5% in this study was chosen based on the actual shape of adhesion characteristics in **Fig. 2**. This slip value should ensure that the contact was operating near to the saturation point as is apparent from curves in **Fig. 3a**. The second thing is that in this study the material of specimens was the bearing steel AISI 52 100 which differs from common wheel and rail materials in chemical composition as well as in the hardness. Note that the bearing steel contains Cr (1.3-1.6%) which can affect an oxidation rate. These different properties of specimens could slow down the formation of the oxide body layer between contact surfaces.

Consequently, the second set of tests under wet conditions were conducted. In that case, each test was started by running-in under wet (fully-flooded) conditions to oxidize the disc. This wet run-in period of the test took approx. 30 minutes until a visible oxide layer has been formed on both contact surfaces, see **Fig. 3b**. After that, CoA was evaluated for the same experimental conditions as before, see the set of tests in **Fig. 3a** marked as "oxide layer No. 1". Subsequently, the same test with wet run-in period was conducted again for the speed of 2 m/s, but the duration of wet running-in was doubled compared to the previous test. This longer wet run-in period ensured that a different level of surface oxidation was reached, see the test in **Fig. 3a** marked as "oxide layer No. 2". By comparing the results in **Fig. 3a**, it can be concluded that the presence of an oxide layer under wet conditions can cause a significant adhesion decrease. At 2 m/s and 5% slip, CoA was reduced to 0.37 and 0.041 depending on the level of surface oxidation. These results imply that heavy rain does not generally cause poor adhesion conditions itself but CoA can be significantly impacted by heavy rain when contact surfaces are covered by an oxide layer. These findings are consistent with the findings in Ref. **[24]** where the presence of an oxide layer under wet conditions caused that CoA was reduced by up to 75% compared to a reference wet test without oxide layer.

3.2 Effect of a small amount of water on CoA

To imitate light rain, the effect of small amounts of water on CoA over time was investigated, see **Fig. 4a**. These friction curves show that a drop of CoA occurred immediately after water application; however, poor adhesion conditions were not observed in any of the tests. On the other hand, small amounts of water reduced CoA significantly more than found under fully-flooded conditions, see **Fig. 4b**. Comparing to dry (0.6) and wet fully-flooded conditions (0.55), CoA was reduced up to by 35 and 20%

respectively when small amounts of water were applied into the contact. The results show that the larger the amount of water, the less significant decrease in CoA (the average value in the middle part of friction curve) and the longer drop time of CoA "*t*" (from 5 to 39 s).

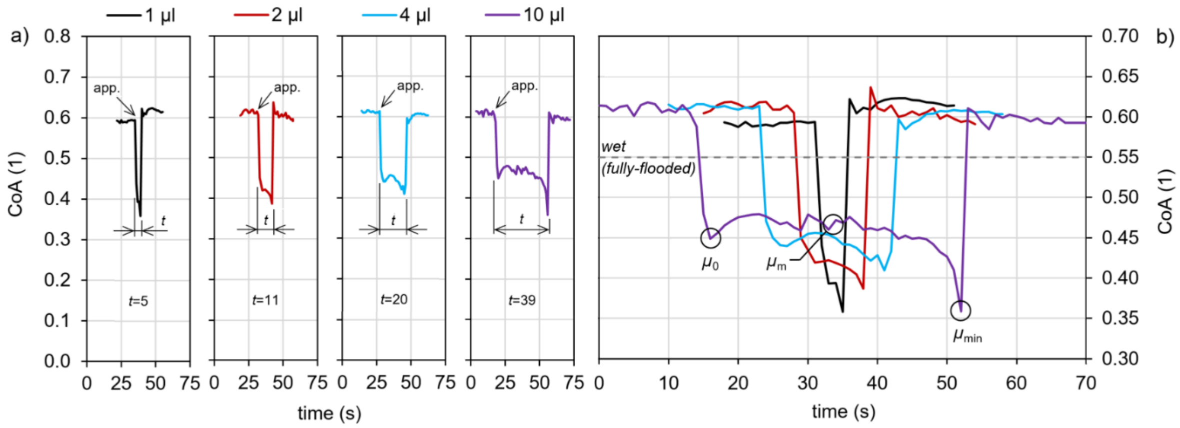

Fig. 4 (a) Friction curves for contact contaminated with a small amount of water, (b) detailed comparison of these curves

Friction curves in **Fig. 4a** are compared to each other in detail in **Fig. 4b**. This figure shows that friction curves can be described by three followings points: μ_0, μ_m, μ_{min}. The first point μ_0 represents the drop of CoA occurring immediately after the application of water; so this point describes the transition between dry and wet conditions. After that, CoA usually slightly increases and CoA is more or less stable because a friction boundary layer is formed. This "middle" part of the friction curve can be described by the second point μ_m. The last point μ_{min} describes the transition between wet and dry conditions. This phenomenon is usually accompanied by a significant decrease in adhesion as can be seen in **Fig. 4b** for 10 µl. This is in line with Ref. **[25]** where a similar trend of friction curve was found for the case when water was applied continuously and then water was stopped and hot air drier was started. Note that in that study the second adhesion drop μ_{min} was observed after several cycles since stopping the water.

The data from this and the following subchapter are summarized in **Fig. 6**. As was mentioned above, no poor adhesion conditions were found for contact contaminated with a small amount of water. The lowest observed CoA during all tests was 0.36. Nevertheless, considering the results in the previous chapter, it can be reasonably expected that the combination of a small amount of water and oxides or other solid contaminants can lead to very low CoA. In that case, a small amount of water and solid particles can form non-Newtonian viscous mixture/paste **[13]** resulting in low or even very low CoA, e.g. μ=0.14 in Ref. **[23]**, and 0.05 in Ref. **[26]**.

3.3 Effect of leaf contamination on CoA

To investigate the conditions typical for autumn months, friction tests with different amounts of leaf extract were carried out, see **Fig. 5a**. It was found that all tested amounts of leaf extract caused a rapid drop in CoA leading to low adhesion conditions ($\mu \leq 0.15$), see **Fig. 5b**. These results are in good agreement with previous laboratory studies where CoA was lower than 0.1 for both leaves **[2]** and leaf extract contamination **[27]**.

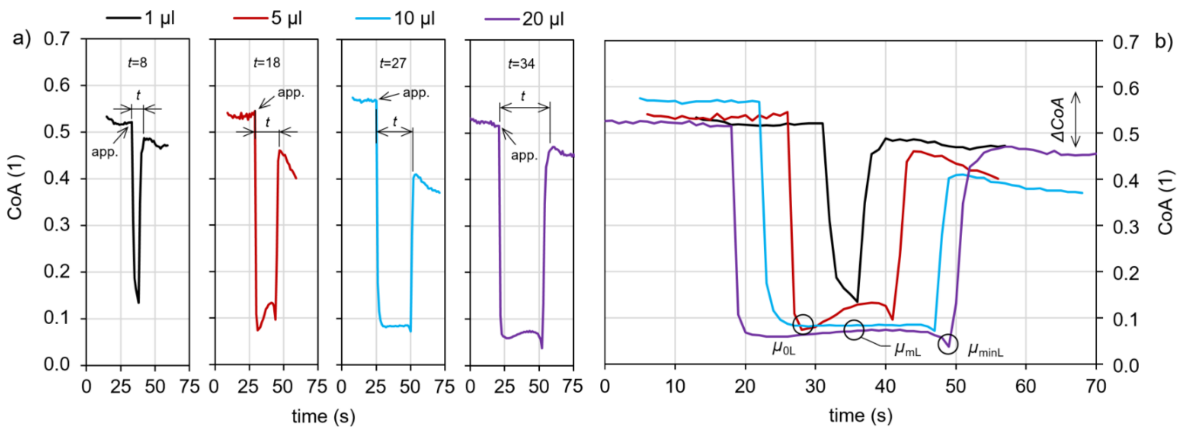

Fig. 5 (a) Friction curves for contact contaminated with different amount of leaf extract, (b) detailed comparison of these curves

As can be seen from the comparison of **Fig. 4b** and **Fig. 5b**, there are similarities between friction curves for a small amount of water and leaf extract. For both of these tests, the same following stages of friction curves can be identified: (1) a rapid decrease of CoA occurring after the application (μ_0, μ_{0L}), (2) relatively stable middle part of CoA (μ_m, μ_{mL}), (3) the second drop in CoA related to the transition between wet and dry conditions (μ_{min}, μ_{minL}), and (4) the final rapid increase of CoA. The only exceptions are the tests with the smallest applied amount of water/leaf extract because these amounts seem to be insufficient for forming of a lubrication film around the circumference of the ball and the disc; thus, the contact quickly starved and CoA increased rapidly. Besides this, it should be emphasized that in case of tests with leaf extract, CoA was stabilized at values less than the reference value for dry adhesion, see *ΔCoA* in **Fig. 5b**. This difference in CoA may be due to the changes in surface conditions of specimens that occurred during the test. Furthermore, CoA may be also affected by the presence of residual components from leaf extract, which remained in the wear track.

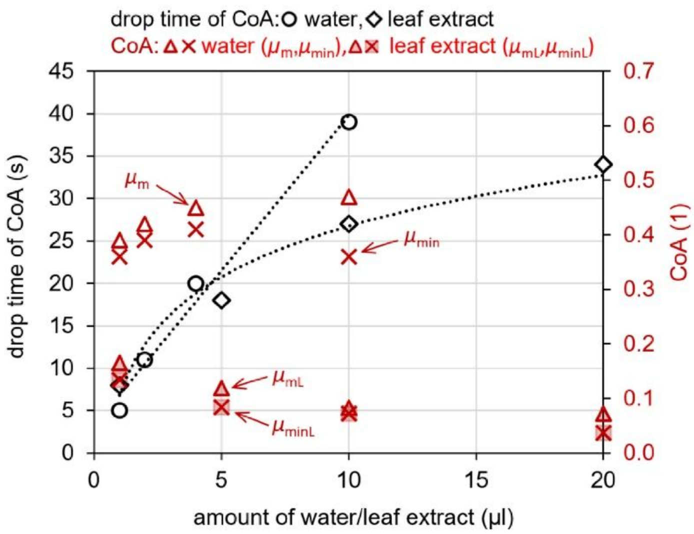

__Fig. 6__ The effect of the amount of water/leaf extract on drop time of CoA and on the level of "CoA"

As mentioned in Chapter 2, a leaf extract is a mixture of water and a liquid lubricant released from the chopped leaf pieces. This composition may explain the similarity of a shape of friction curves under wet and leaf extract conditions. Moreover, this composition explains why CoA was even lower than 0.05, see **Fig. 6**. It is a well-known fact that a mixture of water and oil leads to very low CoA, even lower than for pure oil **[28]**. **Fig. 6** also shows that there is an opposite dependence between the applied amount of leaf extract and CoA than was observed for different (small) amounts of water.

3.4 Effect of humidity and temperature on CoA

The influence of humidity and temperature on CoA was studied for the clean and contaminated disc, see **Fig. 1**. **Fig. 7** shows an example of friction tests with a clean disc where the effect of various RH on CoA was investigated at a constant air temperature of 1 °C. The same set of tests were carried out, for both clean and contaminated disc, for various temperatures according to **Tab. 1**. Based on the data from the last 30 seconds of each measurement, the average CoA was calculated and **Fig. 8 and Fig. 10**, which describe the relationship between CoA and RH for various air temperatures, was plotted.

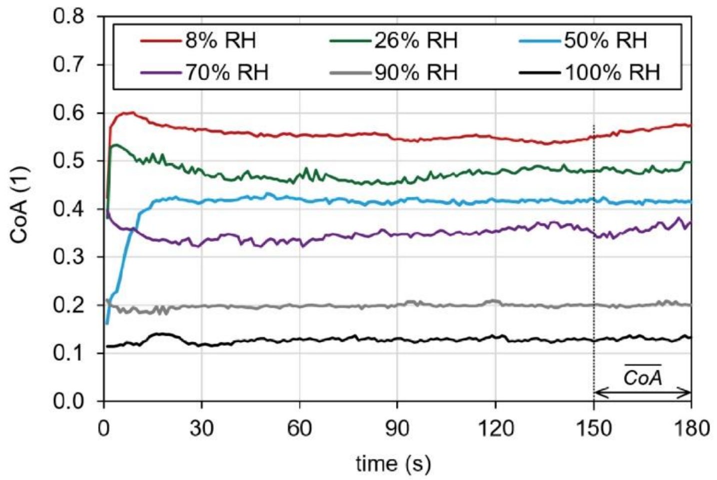

Fig. 7 *Effect of RH on CoA for the clean disc at air temperature 1 °C*

The results in **Fig. 8** show that an increasing RH reduces CoA for all tested conditions and the trend is nearly linear. For the clean disc (**Fig. 8a**), it was investigated that CoA is almost insensitive to changes in RH for temperature higher than approximately 30° C. In contrast, the effect of RH on CoA becomes substantial when the temperature drops to or below 24 °C. The combination of low temperature and high RH led to the condensation resulting in a rapid decrease of CoA, see the condensation area in **Fig. 8a** and **Fig. 9a**. Under these undesirable conditions, low adhesion conditions occurred ($\mu \leq 0.15$) when the air was fully-saturated with water (RH = 100%).

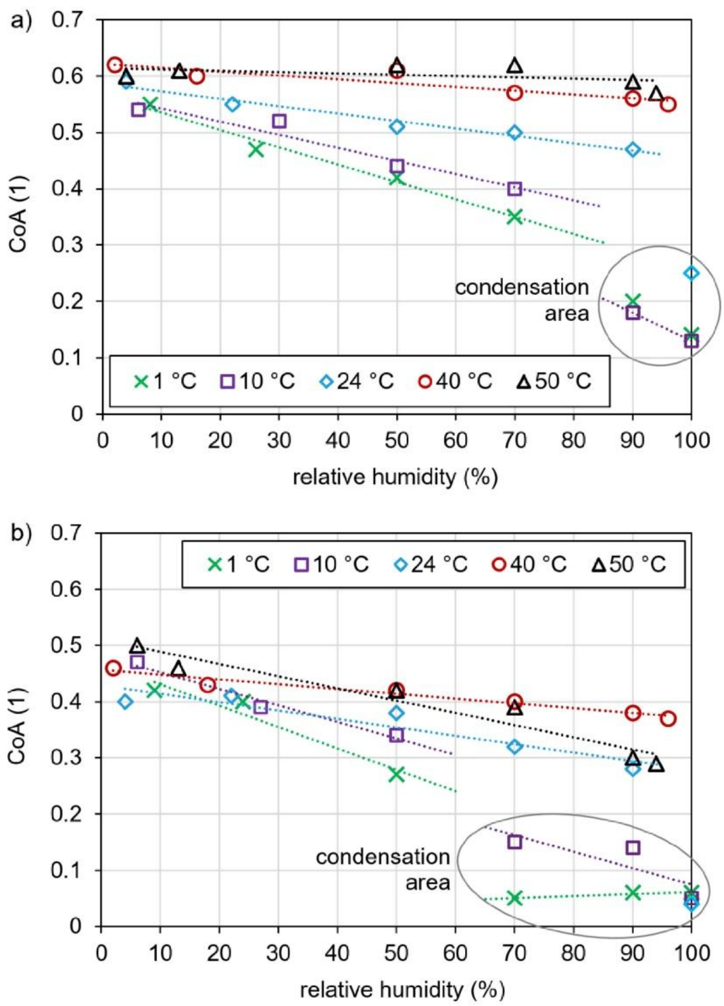

Fig. 8 Effect of RH and temperature on CoA for clean disc (a) and contaminated disc (b)

An even more significant decrease in CoA was found for the tests with the contaminated disc. The results in **Fig. 8b**. revealed that for RH values below 10% the presence of the leaf layer on the disc decreases CoA by only 0.1 (compared to the tests with the clean disc). Once RH starts to rise, CoA falls more dramatically than for the clean disc. Unlike tests with the clean disk, a significant decrease of CoA was observed even for high temperatures. A substantial decrease of CoA was found for lower temperatures (1 and 10 °C) when RH value was higher than 60%. As expected, the lowest CoA was found when a dew point occurred, see the condensation area in **Fig. 8b** and **Fig. 9b**. Under these conditions, CoA was lower than 0.1 and at some points even lower than 0.05; so very low adhesion conditions were found. This abrupt fall of CoA could occur as a result of the softening of the leaf layer with a small amount of condensation water. This softening could lead to a decrease in the shear strength of the leaf layer; thus, the maximum achievable CoA in the contact was reduced.

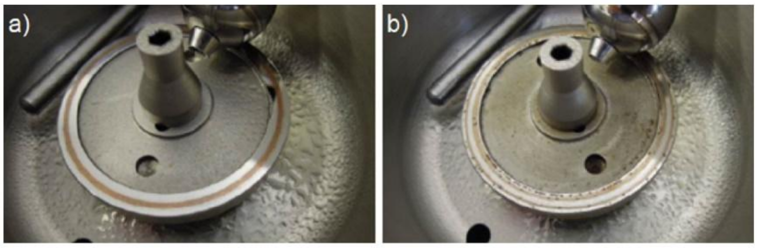

Fig. 9 *Condensation during tests with the clean disc (a) and contaminated disc (b)*

The results above revealed that CoA decreases with increasing value of RH. The most considerable adhesion drop was observed for the temperature to be 24 °C and lower, once the condensation occurred. Under these conditions, CoA was reduced to 0.13 and 0.04 for clean and contaminated disc respectively. These results are well correlated with Ref. **[14, 16-18]** where a gradual decrease of CoA with increasing RH was also observed. However, it must be noted that the lowest observed CoA in these studies was 0.22 **[14]**, 0.28 **[16]**, 0.41 **[17]**, and 0.40 **[18],** even though the tests were performed with leaves **[16]**, with the rusted disc **[17, 18]**, and with the heavily rusted disc **[17]**. In the case of Ref. **[14]**, a twin-disc Amsler machine was employed and the temperature range during tests was from 20 to 40 °C. Results in Ref. **[14]** showed the friction coefficient was almost independent of temperature; however, the tested temperature range was very limited. As was shown in the present study, the greatest decrease in CoA was found for the temperatures lower than 20 °C. In the case of Ref. **[16-18]**, tests were conducted using a pin-on-disc tribometer operating under pure sliding conditions. Generally, these conditions can lead to a higher contact temperature and can cause severe removal of oxide layers formed on surfaces, whereby the occurrence of low adhesion associated with high RH value, or even with condensation, can be suppressed.

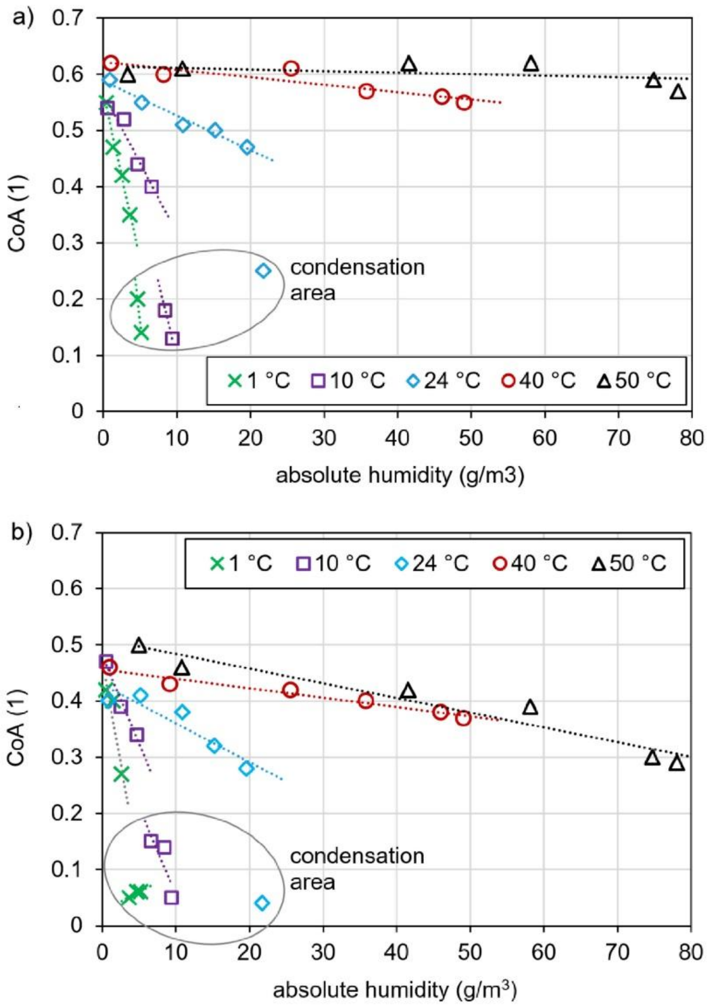

Fig. 10 Effect of AH and temperature on CoA for the clean disc (a) and contaminated disc (b)

Finally, the data from **Fig. 8** were recalculated to the absolute humidity (AH) in g/m3 with the following equation using Bolton's approximation for the saturation vapour pressure of water **[29]**:

$$AH = \frac{6.112 \cdot e}{} \tag{2}$$

where T is a temperature in °C and RH is the relative humidity in %RH. The results in **Fig. 10** show that the trend is nearly linear for each temperature; however, the data in the condensation area do not follow the trend for the specific temperature without condensation.

3.5 Analytical model for prediction of CoA

The results of CoA measurements for various temperatures and various RH values are summarized for both clean and contaminated conditions in the contour plot in **Fig. 11**. It should be noted that the data when condensation occurred are not included in these graphs. The experimental data were fitted to the following regression equations:

(3)

(4)

where T is a temperature in °C and RH is the relative humidity in %RH. In the model, the dependence of CoA on temperature is a quadratic polynomial for clean conditions while for leaf-contaminated conditions is linear. The dependency on RH is linear in for both cases. This regression model leads to a very good determination coefficient of 0.962 for clean conditions and fairly good value of 0.725 for contaminated conditions. Generally, CoA for contaminated conditions is in average 25% lower than that under clean conditions. The difference is very low for the lowest adhesion that starts at app. 0.25 because the contaminated data are not included. The area of occurrence of relatively low or intermediate adhesion is larger for contaminated conditions. Larger differences can be observed for higher adhesion values where the maximum CoA 0.65 and 0.45 for clean and contaminated conditions respectively.

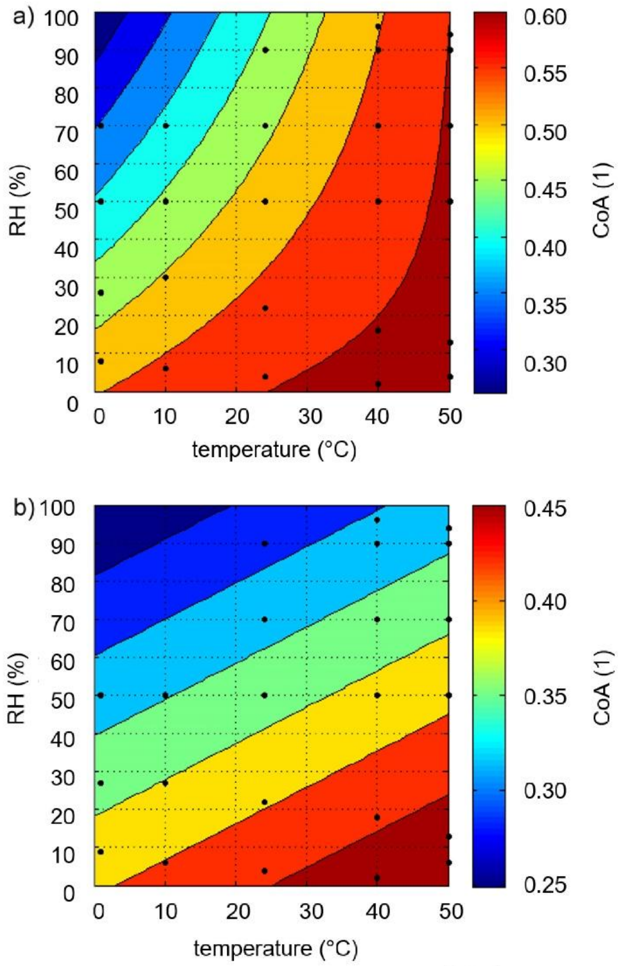

Fig. 11 Contour plot of the regression model of the effect of RH and temperature on CoA for clean conditions (a) and contaminated conditions (b)

The analytical model for the clean disc, created as an approximation of measured data, predicts the effect of RH on CoA as a linear function with a very good determination coefficient. However, previously published studies **[17, 18, 30-34]** have reported an uneven trend. Some of them **[30-32]** point to a more significant drop in friction accompanied by an abrupt change in wear mechanism, although the transition level of RH varies across the studies between 15 % **[30]**, 45 to 55 % **[31]** and 50 a 60% RH **[33]**. Other studies predict the trend as bilinear, wherein the change in behaviour occurring at 65% RH is explained by counterbalancing the effect of the boundary layer formed by the water molecules and hematite film formation at higher RH **[17, 18, 33]**. This difference in the trend can be explained by two following facts.

Firstly, the data in the present work represents CoA determined in rolling-sliding contact at a slip of 5%, whereas most of the previous studies utilized a pure sliding friction approach to measure CoF. As apparent in **Fig. 2** and **Fig. 3a**, this slip was still before the saturation point in the ball-on-disc configuration, so the difference between CoA and CoF was substantial. The second difference is associated with the formation and retention of oxide layers between pure sliding and rolling-sliding tests. In real wheel-rail contact (rolling-sliding contact), the oxide layer usually consists of two types of oxides, magnetite (Fe3O4) and hematite (a-Fe2O3) **[33, 35, 36]**. Magnetite, known as "black oxide", decreases friction while hematite has generally a tendency to increase friction **[35]**. Some hypotheses consider that under higher humidity normal atmospheric oxidation is inhibited because of the effect of water molecules in the surrounding air **[37]**. This could explain decreasing friction with RH when considering slowed down the formation of hematite. However, the process of oxide layer formation under pure sliding conditions can vary greatly. A pin operating under pure sliding conditions is in permanent contact with a counterpart that generally leads to higher flash temperature and heat dissipation can cause higher pin bulk temperature. Moreover, the formation of oxide layers on the pin/disc surface is prevented, as well as the access of water molecules to the wear track **[38]**. This is in contrast to rolling-sliding contact which provides a time for the environment to act on both surfaces during each cycle and it does not cause such an intensive removal of the formed layer.

Note that there is also a question about the effect of sample material. From this perspective, the most representative studies are those using a real rail and wheel steels

[17, 18, 32, 36, 38]. Nevertheless, a fundamental discussion on the effect of relative humidity on friction and wear comes from studies using more general materials such as carbon steels **[31]**, austenitic stainless steel **[33, 39]** and bearing steel **[30, 40]** and the trends are qualitatively similar. It is believed that the effect of the material is not as significant as the effect of the testing configuration.

3.7 General discussion: possible occurrence of low adhesion

The summary of the selected results is depicted in **Fig. 12** where the results are categorized into different adhesion intervals. This figure gives evidence that neither heavy nor light rain does not lead to low adhesion conditions when contact surfaces are clean (free of debris). However, clean surfaces in operation can be expected very rarely such as after heavy rain when contaminants are washed away. Otherwise, rail and wheel surfaces are contaminated with dust, wear debris, their oxides, etc. These solid contaminants affect adhesion even under dry conditions; however, their impact on CoA can be much more substantial under wet conditions as was observed for oxidized surfaces operating under fully-flooded conditions, see **Fig. 12**. Under these conditions, even very low adhesion conditions were found when the contact was run-in under wet conditions before the test; thus, the tick and uniform oxide layer has been formed on the surfaces. With respect to these findings, it can be reasonably expected that more significant adhesion drops may occur even for light precipitation when contact surfaces are covered by the oxide layer or contaminated with free solid particles, as was observed in **[13, 15, 23, 26]**.

Besides water, leaves are common natural contaminants causing an annual problem for rail transportation. To study the effect of leaves on adhesion, two approaches were used in this study. In the former case, a liquid leaf extract was used as a lubricant which was applied directly into the contact, while in the latter case, a solid friction layer was prepared from the leaf extract on the disc surface. For a liquid leaf extract, low adhesion was found for all tested amounts. These results indicate that not only thick black leaf film can lead to poor adhesion conditions, as was observed before **[4],** but poor adhesion conditions can also occur due to the release of natural lubricant from the crushed leaves, such as pectin gel **[41]**. These results are in a line with Ref. **[19]** where a large number of low adhesion incidents have been reported for "non-contaminated" surfaces. Authors in **[19]** proposed these incidents can be caused by not detectable leaf layer. As was shown in the present study, the leaf extract can cause traction/braking difficulties and it can be difficult to detect this almost invisible layer on the rail surfaces.

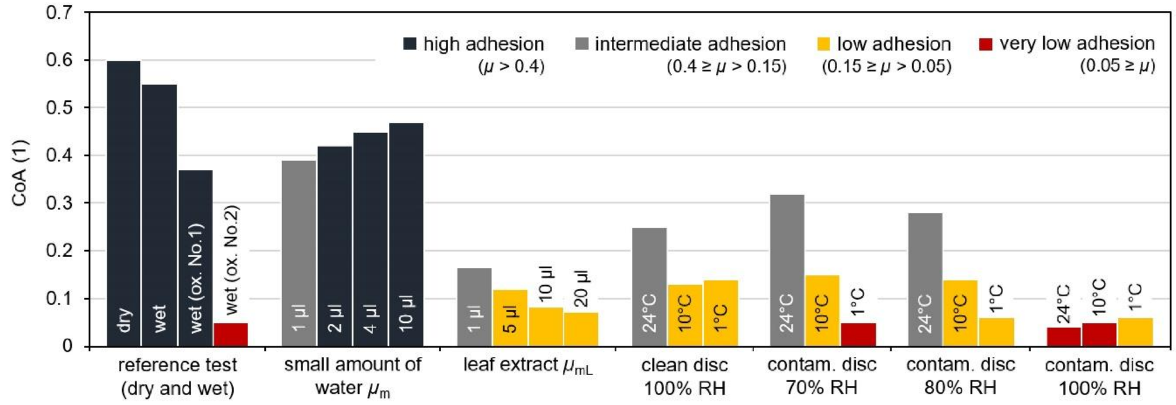

Fig. 12 Overview of selected results

In the last part of this study, the influence of RH and temperature on CoA was studied for the clean and contaminated disc. These results show that low adhesion can be expected especially during cold mornings and evenings when low temperature and very high RH usually occur **[19, 41]**, see **Fig. 12**.

An even more critical case may occur in the autumn months when a leaf layer is formed on rail heads, see tests with the contaminated disc in **Fig. 12**. Under these conditions, low adhesion incidents can be anticipated more often for two reasons. First, CoA reaches critically low values when a leaf layer on the rail is wetted by a small amount of water from condensation. In such a situation, CoA can be even lower than 0.05. Second, the presence of leaf layer on the rail causes that very high RH is not needed for a rapid adhesion decrease because an adhesion drop may even occur at RH of 70% when the temperature is low (<10 °C). It means that adhesion problems can be observed even the dew point has not been reached yet.

This study showed that the most substantial adhesion drop occurs when contact is contaminated with water from condensation. This adhesion drop is much more serious than in tests with small amounts of water, see **Fig. 12**. Although it is difficult to quantify the amount of condensed water in the wear track, it can be assumed that the amount was similar to amounts applied during the set of tests No. 3 (1 – 10 μl). It means that this difference in adhesion drops is likely not attributed only to different amounts of water in the wear track, but can be the result of another phenomenon. The specimens used in sets of test No. 5 and 6 were exposed to high RH before starting the test because it was necessary to wait for RH and temperature to stabilize. It is hypothesised that the contact surfaces exposed to high RH for longer time are covered with a thin oxide layer. If RH is subsequently high enough for condensation, then a small amount of condensed water between oxidized surfaces results in low adhesion conditions. This hypothesis is contradictory to several studies that have noted that the pre-created oxides have a little effect since they are easily removed due to the contact conditions in pin-on-disc **[17, 18]** as well as twin-disc **[36]** tests. So the hypothesis will be tested in the future study in detail.

4. Conclusions

In this work, the ball-on-disc tribometer with the climate chamber was used to identify conditions when low adhesion incidents can be expected in operation due to weather and season changes. The performed tests investigated the effect of several factors influencing adhesion. Unlike previously published articles dealing with the effect of environmental conditions on adhesion, the low and even very low adhesion conditions have been found for several contact conditions. These low and very low adhesion conditions were mostly associated with a high value of RH leading to the formation of oxide layer between surfaces. Based on this, the authors recommend studying "low adhesion phenomenon" under rolling-sliding conditions. This experimental approach seems to be more suitable than tests under pure sliding conditions where an oxide layer is quickly removed; thus CoA is almost unaffected by this layer. With regard to a possible occurrence of low adhesion incidents, the main conclusions of this study are as follows:

- The lowest value of CoA was found when the contaminated disc (by leaf extract) was run at RH of 70% or higher. Under these conditions, CoA fell even below 0.05. In real operation, this undesirable situation can occur especially during autumn mornings even though no visible leaf layer may be detectable on the rails.
- For leaf extract contamination, low adhesion conditions were observed for all tested amounts of extract but very low adhesion conditions did not occur.
- If contact surfaces are clean, very low adhesion conditions were not found for any tests; however, low adhesion incidents may occur under dew conditions.

- In the case of water as the most common natural contaminant, no important adhesion drops were observed for clean surfaces but very low adhesion was found when an oxide layer was formed on the surfaces.

Future work should be focused on the effect of condensate water on adhesion for various surface conditions of specimens occurring due to surface oxidation. Besides this, an interaction of condensed water and leaf residuals should be investigated to explore if these conditions may be responsible for unexpected low adhesion incidents during the autumn season.

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Appendix A – Parameters of employed sensors

sensor	**range**	**accuracy**	**nonlinearity**
load cell for normal force	2 to 75 N	±0.3 N	±1% of full scale
load cell for friction force	-20 to +20 N	±0.3 N	±2% of full scale
servodrives	-4 to +4 m/s	±1mm/s or 0.1% of speed, whichever is larger	not applicable
temperature sensor	0 to 150°C	±0.5 °C	±1% of full scale
relative humidity sensor	0 to 100% RH (for temperature between -20 and +60°C)	2% RH	< 1% RH

Appendix B – Mean standard deviations for sets of tests listed in Tab.1

set No. 1	**adhesion characteristics under dry conditions**										
	stats	surface	0.5%	1%	2%	3%	4%	5%	6.5%	8%	n*
0.5 m/s	mean	clean	0.14	0.26	0.39	0.48	0.55	0.61	0.64	0.65	20
	Std Dev		0.005	0.002	0.003	0.004	0.004	0.005	0.006	0.005	20
1 m/s	mean		0.15	0.25	0.39	0.50	0.56	0.60	0.67	0.71	20
	Std Dev		0.002	0.003	0.003	0.006	0.005	0.004	0.004	0.005	20
2 m/s	mean		0.14	0.23	0.38	0.48	0.57	0.61	0.64	0.66	20
	Std Dev		0.001	0.003	0.002	0.001	0.002	0.001	0.003	0.003	20
3 m/s	mean		0.14	0.26	0.39	0.48	0.55	0.61	0.64	0.65	20
	Std Dev		0.002	0.002	0.006	0.004	0.004	0.003	0.002	0.003	20
set No. 2	**adhesion characteristics in wet conditions for different speeds and surface conditions**										
	stats	surface	0.5%	1%	2%	3%	4%	5%	6.5%	8%	n*
0.5 m/s	mean	clean	0.20	0.31	0.45	0.52	0.55	0.56	0.57	0.57	20
	Std Dev		0.006	0.005	0.002	0.002	0.001	0.001	0.001	0.003	20
1 m/s	mean		0.19	0.30	0.43	0.50	0.53	0.55	0.56	0.56	20
	Std Dev		0.003	0.003	0.003	0.001	0.001	0.004	0.002	0.001	20
2 m/s	mean		0.18	0.29	0.41	0.47	0.50	0.52	0.53	0.53	20
	Std Dev		0.003	0.002	0.003	0.002	0.001	0.002	0.003	0.002	20
3 m/s	mean		0.16	0.26	0.38	0.44	0.46	0.47	0.47	0.47	20
	Std Dev		0.005	0.006	0.003	0.002	0.002	0.004	0.008	0.002	20
1 m/s	mean	ox. layer No. 1	0.11	0.20	0.30	0.34	0.36	0.37	0.37	0.36	20
	Std Dev		0.003	0.002	0.004	0.02	0.02	0.003	0.004	0.002	20
2 m/s	mean		0.12	0.19	0.26	0.29	0.31	0.31	0.32	0.33	20
	Std Dev		0.004	0.02	0.001	0.003	0.002	0.002	0.005	0.002	20
3 m/s	mean		0.09	0.14	0.14	0.15	0.16	0.15	0.14	0.13	20
	Std Dev		0.002	0.004	0.003	0.002	0.005	0.001	0.003	0.003	20
2 m/s	mean	ox. layer No. 2	0.01	0.02	0.03	0.03	0.04	0.04	0.05	0.05	20
	Std Dev		0.003	0.001	0.003	0.001	0.003	0.004	0.002	0.003	20

set No. 3	**small amount of water**			
	stats	1 µl	2 µl	4 µl	10 µl
μ_m	mean	0.39	0.42	0.45	0.47
	Std Dev	0.029	0.012	0.006	0.006
	n*	4	6	10	10

set No. 4	**leaf extract**			
	1 µl	5 µl	10 µl	20 µl
μ_{mL}	0.17	0.12	0.08	0.07
	0.012	0.012	0.001	0.002
	3	7	10	10

set No. 5	clean disc					
	stats	**8% RH**	**26% RH**	**50% RH**	**70% RH**	**90% RH**	**100% RH**
1 °C	mean	0.56	0.48	0.43	0.36	0.23	0.15
	Std Dev	0.008	0.006	0.015	0.011	0.025	0.002
	n*	30	30	30	30	30	30
RH		**6%**	**27%**	**50%**	**70%**	**90%**	**100%**
10 °C	mean	0.57	0.52	0.46	0.40	0.18	0.14
	Std Dev	0.006	0.007	0.011	0.016	0.012	0.005
	n*	30	30	30	30	30	30
RH		**4%**	**22%**	**50%**	**70%**	**90%**	**100%**
24 °C	mean	0.60	0.55	0.52	0.51	0.48	0.27
	Std Dev	0.001	0.002	0.003	0.002	0.011	0.005
	n*	30	30	30	30	30	30
RH		**2%**	**16%**	**50%**	**70%**	**90%**	**96%**
40 °C	mean	0.62	0.60	0.60	0.57	0.56	0.55
	Std Dev	0.002	0.008	0.003	0.003	0.004	0.005
	n*	30	30	30	30	30	30
RH		**6%**	**13%**	**50%**	**70%**	**90%**	**94%**
50 °C	mean	0.60	0.61	0.61	0.61	0.58	0.57
	Std Dev	0.005	0.004	0.002	0.003	0.004	0.003
	n*	30	30	30	30	30	30

set No. 6	contaminated disc						
	stats	**9% RH**	**24% RH**	**50% RH**	**70% RH**	**90% RH**	**100% RH**
1 °C	mean	0.42	0.38	0.28	0.06	0.06	0.06
	Std Dev	0.003	0.038	0.013	0.004	0.003	0.001
	n*	30	30	30	30	30	30
RH		**6%**	**27%**	**50%**	**70%**	**90%**	**100%**
10 °C	mean	0.48	0.38	0.35	0.14	0.17	0.06
	Std Dev	0.007	0.003	0.005	0.006	0.005	0.001
	n*	30	30	30	30	30	30
RH		**4%**	**22%**	**50%**	**70%**	**90%**	**100%**
24 °C	mean	0.41	0.38	0.38	0.33	0.28	0.04
	Std Dev	0.004	0.004	0.004	0.007	0.009	0.004
	n*	30	30	30	30	30	30
RH		**2%**	**18%**	**50%**	**70%**	**90%**	**100%**
40 °C	mean	0.45	0.43	0.43	0.40	0.38	0.35
	Std Dev	0.004	0.004	0.003	0.002	0.004	0.009
	n*	30	30	30	30	30	30
RH		**6%**	**13%**	**50%**	**70%**	**90%**	**94%**
50 °C	mean	0.50	0.46	0.42	0.39	0.32	0.29
	Std Dev	0.002	0.002	0.003	0.002	0.009	0.037
	n*	30	30	30	30	30	30

*n – sample size

References

1. Wang WJ, Liu TF, Wang HY, Liu QY, Zhu MH, Jin XS. Influence of friction modifiers on improving adhesion and surface damage of wheel/rail under low adhesion conditions. Tribology International 2014;75:16-23. https://doi.org/10.1016/j.triboint.2014.03.008.

2. Shi LB, Wang C, Ding HH, Kvarda D, Galas R, Omasta M, et al. Laboratory investigation on the particle-size effects in railway sanding: Comparisons between standard sand and its micro fragments. Tribology International 2020;146:62-70. https://doi.org/10.1016/j.triboint.2020.106259.

3. Cann PM, Olofsson U, Persson K. The "leaves on the line" problem—a study of leaf residue film formation and lubricity under laboratory test conditions. Tribology Letters 2006;24:151-158. https://doi.org/10.1007/s11249-006-9152-2.

4. Chen H, Furuya T, Fukagai S, Saga S, Ikoma J, Kimura K, et al. Wheel slip/Slide and low adhesion caused by fallen leaves. Wear 2020;446-447. https://doi.org/10.1016/j.wear.2020.203187.

5. Zhu Y, Olofsson U, Nilsson R. A field test study of leaf contamination on railhead surfaces. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2013;228:71-84. https://doi.org/10.1177/0954409712464860.

6. Arias-Cuevas O, Li Z. Field investigations into the adhesion recovery in leaf-contaminated wheel–rail contacts with locomotive sanders. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2011;225:443-456. https://doi.org/10.1177/2041301710394921.

7. Broster M, Pritchard C, Smith DA. Wheel/rail adhesion: its relation to rail contamination on british railways. Wear 1974;29:309-321. https://doi.org/10.1016/0043-1648(74)90017-9.

8. Nagase K, Pritchard C, Smith DA. A Study of Adhesion Between the Rails and Running Wheels on Main Lines: Results of Investigations by Slipping Adhesion Test Bogie. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2016;203:33-43. https://doi.org/10.1243/PIME_PROC_1989_203_206_02.

9. Gallardo-Hernandez EA, Lewis R. Twin disc assessment of wheel/rail adhesion. Wear 2008;265:1309-1316. https://doi.org/10.1016/j.wear.2008.03.020.

10. Chen H, Ishida M, Namura A, Baek K-S, Nakahara T, Leban B, et al. Estimation of wheel/rail adhesion coefficient under wet condition with measured boundary friction coefficient and real contact area. Wear 2011;271:32-39. https://doi.org/10.1016/j.wear.2010.10.022.

11. Lewis SR, Lewis R, Olofsson U. An alternative method for the assessment of railhead traction. Wear 2011;271:62-70. https://doi.org/10.1016/j.wear.2010.10.035.

12. Shi LB, Li Q, Kvarda D, Galas R, Omasta M, Wang WJ, et al. Study on the wheel/rail adhesion restoration and damage evolution in the single application of alumina particles. Wear 2019;426-427:1807-1819. https://doi.org/10.1016/j.wear.2019.01.021.

13. Beagley TM, Pritchard C. Wheel/rail adhesion — the overriding influence of water. Wear 1975;35:299-313. https://doi.org/10.1016/0043-1648(75)90078-2.

14. Beagley TM, McEwen IJ, Pritchard C. Wheel/rail adhesion — the influence of railhead debris. Wear 1975;33:141-152. https://doi.org/10.1016/0043-1648(75)90230-6.

15. White B, Lewis R. Simulation and understanding the wet-rail phenomenon using twin disc testing. Tribology International 2019;136:475-486. https://doi.org/10.1016/j.triboint.2019.03.067.

16. Olofsson U, Sundvall K. Influence of leaf, humidity and applied lubrication on friction in the wheel-rail contact: Pin-on-disc experiments. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2005;218:235-242. https://doi.org/10.1243/0954409042389364.

17. Zhu Y, Olofsson U, Chen H. Friction Between Wheel and Rail: A Pin-On-Disc Study of Environmental Conditions and Iron Oxides. Tribology Letters 2013;52:327-339. https://doi.org/10.1007/s11249-013-0220-0.

18. Zhu Y, Lyu Y, Olofsson U. Mapping the friction between railway wheels and rails focusing on environmental conditions. Wear 2015;324-325:122-128. https://doi.org/10.1016/j.wear.2014.12.028.

19. White BT, Nilsson R, Olofsson U, Arnall AD, Evans MD, Armitage T, et al. Effect of the presence of moisture at the wheel–rail interface during dew and damp conditions. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2017;232:979-989. https://doi.org/10.1177/0954409717706251.

20. Arias-Cuevas O, Li Z, Lewis R, Gallardo-Hernández EA. Rolling–sliding laboratory tests of friction modifiers in dry and wet wheel–rail contacts. Wear 2010;268:543-551. https://doi.org/10.1016/j.wear.2009.09.015.

21. Voltr P, Lata M. Transient wheel–rail adhesion characteristics under the cleaning effect of sliding. Vehicle System Dynamics 2015;53:605-618. https://doi.org/10.1080/00423114.2014.961488.

22. Galas R, Omasta M, Krupka I, Hartl M. Laboratory investigation of ability of oil-based friction modifiers to control adhesion at wheel-rail interface. Wear.

23. Shi LB, Ma L, Guo J, Liu QY, Zhou ZR, Wang WJ. Influence of low temperature environment on the adhesion characteristics of wheel-rail contact. Tribology International 2018;127:59-68. https://doi.org/10.1016/j.triboint.2018.05.037.

24. Hardwick C, Lewis R, Olofsson U. Low adhesion due to oxide formation in the presence of salt. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2013;228:887-897. https://doi.org/10.1177/0954409713495666.

25. Lewis R, Gallardo-Hernandez EA, Hilton T, Armitage T. Effect of oil and water mixtures on adhesion in the wheel/rail contact. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2009;223:275-283. https://doi.org/10.1243/09544097JRRT248.

26. Galas R, Kvarda D, Omasta M, Krupka I, Hartl M. The role of constituents contained in water–based friction modifiers for top–of–rail application. Tribology International 2018;117:87-97. https://doi.org/10.1016/j.triboint.2017.08.019.

27. Omasta M, Machatka M, Smejkal D, Hartl M, Křupka I. Influence of sanding parameters on adhesion recovery in contaminated wheel–rail contact. Wear 2015;322-323:218-225. https://doi.org/10.1016/j.wear.2014.11.017.

28. Wang WJ, Shen P, Song JH, Guo J, Liu QY, Jin XS. Experimental study on adhesion behavior of wheel/rail under dry and water conditions. Wear 2011;271:2699-2705. https://doi.org/10.1016/j.wear.2011.01.070.

29. Bolton D. The Computation of Equivalent Potential Temperature. Monthly Weather Review 1980;108(7):1046-1053. https://doi.org/10.1175/1520-0493(1980)108<1046:TCOEPT>2.0.CO;2.

30. Klaffke D. On the repeatability of friction and wear results and on the influence of humidity in oscillating sliding tests of steel-steel pairings. Wear 1995;189:117-121. https://doi.org/10.1016/0043-1648(95)06672-1.

31. Oh H-K, Yeon K-H, Yun Kim H. The influence of atmospheric humidity on the friction and wear of carbon steels. Journal Of Materials Processing Technology 1999;95:10-16. https://doi.org/10.1016/S0924-0136(99)00259-9.

32. Liew WYH. Effect of relative humidity on the unlubricated wear of metals. Wear 2006;260:720-727. https://doi.org/10.1016/j.wear.2005.04.011.

33. Zhu Y. The influence of iron oxides on wheel–rail contact: A literature review. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2017;232:734-743. https://doi.org/10.1177/0954409716689187.

34. Chen Z, He X, Xiao C, Kim S. Effect of Humidity on Friction and Wear—A Critical Review. Lubricants 2018;6. https://doi.org/10.3390/lubricants6030074.

35. Godfrey D. Iron oxides and rust (hydrated iron oxides) in tribology. Tribology & Lubrication Technology 1999;55(2):33-37.

36. Zhu Y, Chen X, Wang W, Yang H. A study on iron oxides and surface roughness in dry and wet wheel−rail contacts: A literature review. Wear 2015;328-329:241-248. https://doi.org/10.1016/j.wear.2015.02.025.

37. Leheup ER, Pendlebury RE. Unlubricated reciprocating wear of stainless steel with an interfacial air flow. Wear 1991;142:351-372. https://doi.org/10.1016/0043-1648(91)90174-S.

38. Zhu Y, Yang H, Wang W. Twin-disc tests of iron oxides in dry and wet wheel–rail contacts. Proceedings Of The Institution Of Mechanical Engineers, Part F: Journal Of Rail And Rapid Transit 2015;230:1066-1076. https://doi.org/10.1177/0954409715575093.

39. Bregliozzi G, Di Schino A, Kenny JM, Haefke H. The influence of atmospheric humidity and grain size on the friction and wear of AISI 304 austenitic stainless steel. Materials Letters 2003;57:4505-4508. https://doi.org/10.1016/S0167-577X(03)00351-3.

40. de Baets P, Kalacska G, Strijckmans K, Van de Velde F, Van Peteghem AP. Experimental study by means of thin layer activation of the humidity influence on the fretting wear of steel surfaces. Wear 1998;216:131-137. https://doi.org/10.1016/S0043-1648(97)00189-0.

41. Ishizaka K, Lewis SR, Lewis R. The low adhesion problem due to leaf contamination in the wheel/rail contact: Bonding and low adhesion mechanisms. Wear 2017;378-379:183-197. https://doi.org/10.1016/j.wear.2017.02.044

set No. 5	clean disc					
	stats	**8% RH**	**26% RH**	**50% RH**	**70% RH**	**90% RH**	**100% RH**
1 °C	mean	0.56	0.48	0.43	0.36	0.23	0.15
	Std Dev	0.008	0.006	0.015	0.011	0.025	0.002
	n*	30	30	30	30	30	30
RH		**6%**	**27%**	**50%**	**70%**	**90%**	**100%**
10 °C	mean	0.57	0.52	0.46	0.40	0.18	0.14
	Std Dev	0.006	0.007	0.011	0.016	0.012	0.005
	n*	30	30	30	30	30	30
RH		**4%**	**22%**	**50%**	**70%**	**90%**	**100%**
24 °C	mean	0.60	0.55	0.52	0.51	0.48	0.27
	Std Dev	0.001	0.002	0.003	0.002	0.011	0.005
	n*	30	30	30	30	30	30
RH		**2%**	**16%**	**50%**	**70%**	**90%**	**96%**
40 °C	mean	0.62	0.60	0.60	0.57	0.56	0.55
	Std Dev	0.002	0.008	0.003	0.003	0.004	0.005
	n*	30	30	30	30	30	30
RH		**6%**	**13%**	**50%**	**70%**	**90%**	**94%**
50 °C	mean	0.60	0.61	0.61	0.61	0.58	0.57
	Std Dev	0.005	0.004	0.002	0.003	0.004	0.003
	n*	30	30	30	30	30	30

set No. 6	contaminated disc					
	stats	**9% RH**	**24% RH**	**50% RH**	**70% RH**	**90% RH**	**100% RH**
1 °C	mean	0.42	0.38	0.28	0.06	0.06	0.06
	Std Dev	0.003	0.038	0.013	0.004	0.003	0.001
	n*	30	30	30	30	30	30
RH		**6%**	**27%**	**50%**	**70%**	**90%**	**100%**
10 °C	mean	0.48	0.38	0.35	0.14	0.17	0.06
	Std Dev	0.007	0.003	0.005	0.006	0.005	0.001
	n*	30	30	30	30	30	30
RH		**4%**	**22%**	**50%**	**70%**	**90%**	**100%**
24 °C	mean	0.41	0.38	0.38	0.33	0.28	0.04
	Std Dev	0.004	0.004	0.004	0.007	0.009	0.004
	n*	30	30	30	30	30	30
RH		**2%**	**18%**	**50%**	**70%**	**90%**	**100%**
40 °C	mean	0.45	0.43	0.43	0.40	0.38	0.35
	Std Dev	0.004	0.004	0.003	0.002	0.004	0.009
	n*	30	30	30	30	30	30
RH		**6%**	**13%**	**50%**	**70%**	**90%**	**94%**
50 °C	mean	0.50	0.46	0.42	0.39	0.32	0.29
	Std Dev	0.002	0.002	0.003	0.002	0.009	0.037
	n*	30	30	30	30	30	30

*n – sample size