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Simulation and understanding the wet-rail phenomenon using twin disc testing

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Abstract

Low adhesion due to the wet-rail phenomenon is a year round problem for the rail industry. It is thought to occur due to wear debris and iron oxides combined with small amounts of water, often from dew or light rain. It occurs without visible contamination and the transient, low moisture conditions mean that it has previously been difficult to study and has not been simulated in a laboratory, which limits understanding and inhibits the development of mitigation methods. This work simulates the wet-rail phenomenon on a twin disc test rig for the first time and concludes that iron oxide and water alone can form a paste and produce low traction values that are comparable to oil or leaf contamination.

1. Introduction

The wet-rail phenomenon causes low adhesion between wheel and rail throughout the year. It occurs when dew is present on the railhead, or when the railhead is drying after light rain. In the UK, a train generally needs a friction coefficient of 0.09 to brake and 0.2 to accelerate, below this may result in wheel slip or slide which can cause safety and performance issues [1]. Low adhesion costs the UK rail industry an estimated £100 million a year [2] and limits growth as there is demand for higher braking rates, faster trains and more frequent services which all need a predictable friction coefficient.

The conditions and mechanisms that cause the phenomenon are not fully understood. Although the consequences can be severe, low adhesion does not occur very often and under what is likely to be a narrow window of conditions, which means that it can be difficult to recreate and study. It has been shown previously that a build-up of wear debris including iron oxides, mixed with low amounts of water to form a paste, can cause low adhesion and this may be the cause of the wet-rail phenomenon [3][4][5]. The wet-rail phenomenon can be likened to low friction on tarmac roads after a long dry-spell, where a build-up of debris from sources such as tyres, oil and soil can cause dangerously low traction conditions when driving after a small amount of rainfall. Both of these low friction situations do not seem to occur after periods of heavy rain, where any surface debris and contamination is washed away.

Many low adhesion events in the UK are caused by leaf fall and this certainly plays a role in producing low traction conditions, especially in the autumn season. However, analysis of the black, strongly bonded and slippery leaf layer that often causes low adhesion during the autumn season has shown it to be 52-56 % iron oxide [6]. This shows that iron oxides could play a role in low adhesion due to leaf layers, as well as throughout the year due to the wet-rail phenomenon. Previous analysis of Network Rail station overruns showed that during the autumn season, no railhead leaf contamination was seen for approximately 50 % of incidents as seen in Table 1 [7].

Year	Leaf contamination reported	No leaf contamination reported
2010	85	82
2011	20	27
2012	80	67
Total	185	176

Table 1. Incidents where contamination has been reported after an incident [7]

Outside the autumn season, or in situations such as tunnels [8], low adhesion still occurs due to the wet-rail phenomenon so although organic contamination certainly results in low adhesion, there are many more incidents where organic contamination is unlikely to be present.

There are two mechanisms which can form iron oxides on the railhead. The first is oxidation in the contact itself; the high forces and temperatures produced in the wheel-rail contact cause the steel to oxidise The second mechanism is environmental oxidation, where environmental conditions such as condensation, precipitation or high humidity cause the steel surface layer to oxidise [9]. Oxides form both on the bulk steel and on wear particles produced by the wheel-rail contact. The wear particles have a large surface area so quickly oxidise, also either in the heat of the contact itself or later due to environmental conditions after the wheel has passed. These oxide particles can be crushed into smaller fragments with each wheel pass and are compacted by subsequent wheel passes into a glaze on the rail surface [10].

The wet-rail phenomenon is difficult to analyse on a railway because only a thin layer of iron oxide or wear debris is found which is often difficult to see, compared to the black layer often associated with leaf contamination. It is highly transient; water will evaporate and particles can be pushed aside by a wheel passage which means the conditions at the time of incident are unlikely to be the same when the track is inspected afterwards. There are also 5 different types of iron oxides and oxy-hydroxides that have been found on the railway [11], the type and size varies dependent on conditions and they are often found in layers due to an oxygen gradient on the steel surface, which makes field testing very difficult to control.

Small scale testing provides more controllable conditions, but extended time periods of low adhesion due to the wet-rail phenomenon have not previously been recreated in a laboratory. Previous twin disc testing has simulated low adhesion due to leaf and oil contamination [12]. The influence of wear debris and iron oxides has been tested previously using twin disc testing and has produced lower traction than a “clean” specimen, as seen in Figure 2, but has not produced the very low traction seen when low adhesion incidents occur on the railway [4][13]. Low adhesion due to an iron oxide layer has also been recreated using twin disc testing but this was at a low slip value of 0.3 %, which is typical for a rolling wheel but lower than would be seen when braking or accelerating [14]. Other work has created an oxide layer under very similar conditions on a twin disc test rig, the oxide layer is only a few microns thick and shown in Figure 4 [18].

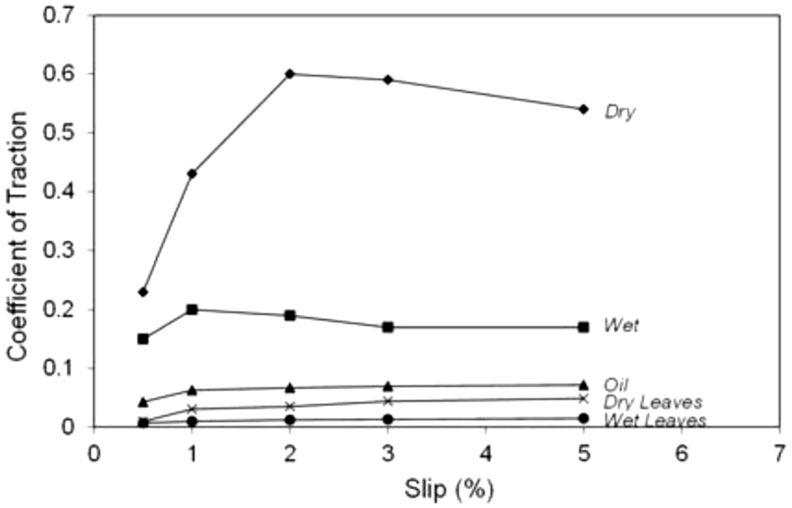


Figure 1. A twin-disc creep curve for different rail contaminants [12]

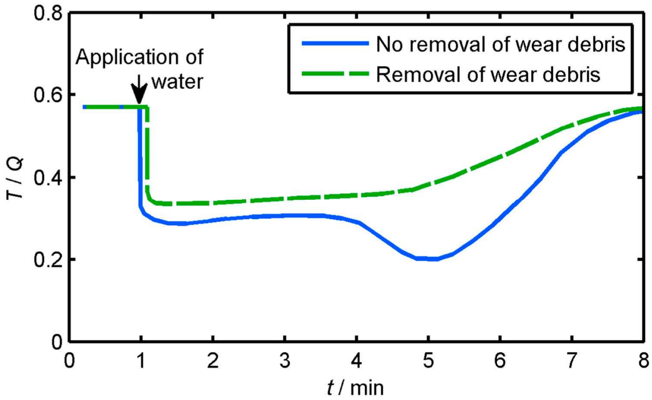


Figure 2. Previous results from twin disc testing, showing the lower adhesion level when wear debris (including iron oxides) is mixed with water to form a paste, compared to water alone (wear debris removed with iron brush). Water was applied for a short time only, afterwards contact dried out. T/Q is the traction coefficient [4] [13]

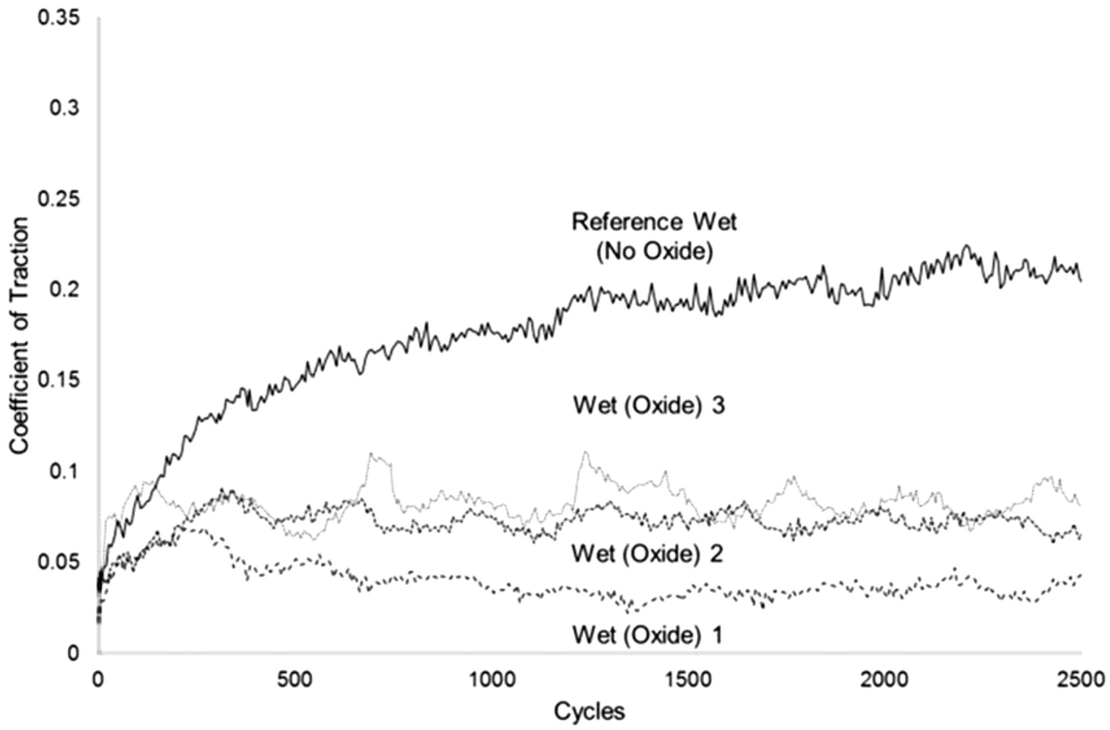


Figure 3. Traction coefficient data for twin disc tests using oxidised specimens [14]

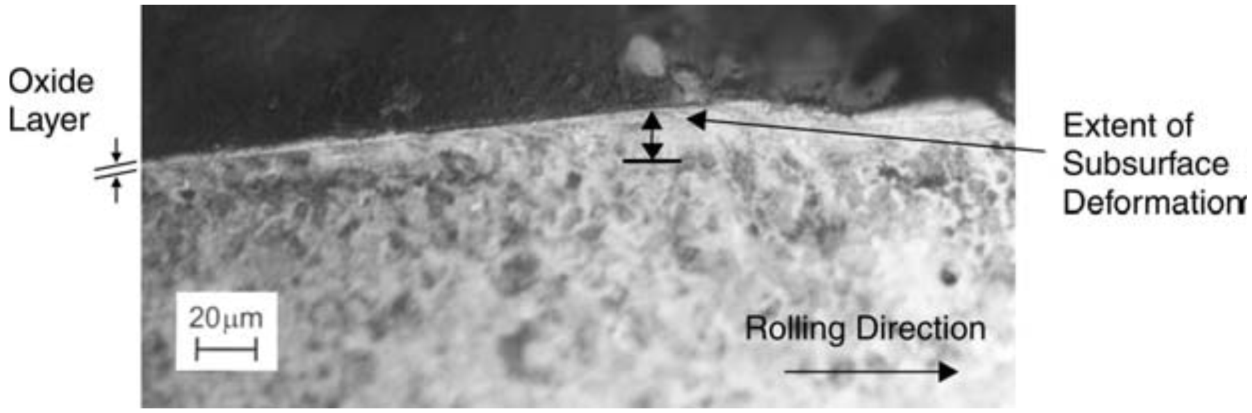


Figure 4 An oxide layer generated in a twin disc test rig at 1500 MPa, 0.2 % slip [19]

Previous work has not successfully produced the very low traction conditions seen in the wet-rail phenomenon and possible reasons for this are described here. Firstly, purely sliding test rigs such as pin-on-disc [15] may not be able to simulate the wet-rail phenomenon because the pin may plough through any oxide on the surface and push it out of the contact, rather than entraining it into the contact as often happens with a wheel rolling over a rail. Rolling/sliding test rigs provide more realistic contact conditions than purely sliding methods so this has been chosen for this work. Any surface layer of oxide or applied oxide paste can be rotated into the contact rather than being pushed aside. The downside to twin disc testing is that material can be "consumed" in the contact and contact conditions change over repeated cycles so that if a critical point that low adhesion occurred in was found, it may only last for a short period of time.

Relatively large water volumes have been used in previous tests. If the wet-rail phenomenon can be caused by dew on the railhead, very low water volumes must be required. Large volumes of water addition may have either diluted the oxide too much or simply washed it away from the contact so low adhesion did not occur. Recent full scale testing has shown that a lower amount of water can produce much lower traction coefficients [16] and twin disc testing, coupled with the syringe plunger used in this work, allows the simple application of very small amounts of water, as well as other third body materials.

Finally, the critical conditions that lead to the wet-rail phenomenon may have been missed simply because this form of low adhesion only occurs in a narrow window of conditions, so a large range of test conditions were used in this work. A previous study used a similar method but focussed on much longer test durations [17]. The oxide layer may have caused low adhesion at the beginning of the test but the effect of this was hidden due to the large number of cycles.

This work aims to recreate the wet-rail phenomenon on a small scale, twin disc test rig and show the effects that iron oxides can have on the traction coefficient. The two methods described in this paper can be used in future to better understand the wet rail phenomenon, predicting where it may occur and help develop mitigation methods.

2. Test methodologies

2.1 SUROS set-up

This work tested the effect of iron oxides and water on the Sheffield university rolling/sliding test rig, SUROS, to attempt to understand the wet-rail phenomenon. The SUROS twin disc test rig uses two counter-rotating discs, made of wheel and rail steel, with a normal load applied to simulate a wheel-rail contact. The slip (creep) in the contact can be adjusted using independently controlled disc velocities. A schematic of the SUROS rig is shown in Figure 5 and further information can be found in [20].

This work involved two different methods in order to test the range of conditions needed, but the initial set-up procedure remained constant and is described in this section. Firstly, clean (non-oxidised and ground by the manufacturer) discs were ultrasonically cleaned in acetone to remove any oil-based residue and mounted to the rig. The wheel disc was mounted to the lower motor and rail disc to the upper, care was taken to avoid touching the disc surfaces to ensure no contamination occurred.

The motors were then turned on to begin disc rotation and the hydraulic arm turned on to apply load and enable disc contact. Iron oxides and water were added as required and the load, slip and traction coefficient were logged throughout the test before the discs were separated and the rig shut down.

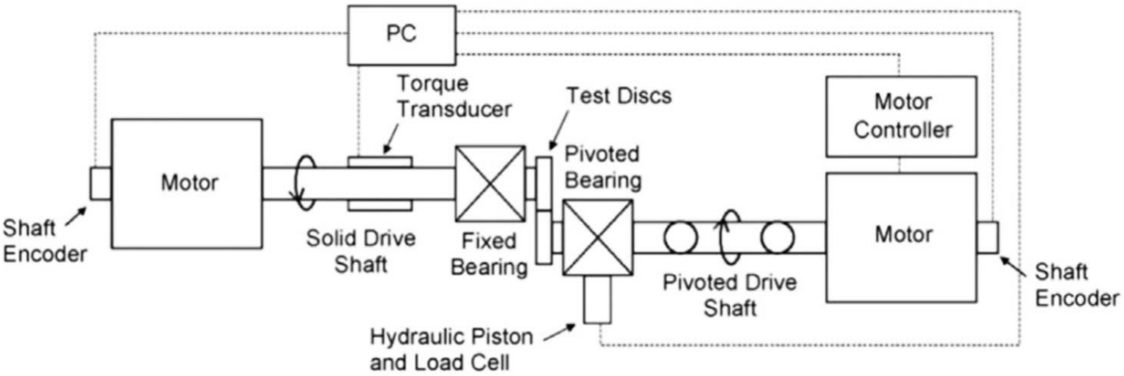


Figure 5. A schematic of the SUROS test rig [20]

2.2 Generated oxide tests

Pre-oxidation was carried out on rail discs in some tests to simulate an oxide coated rail. The tests that simulate low adhesion due to mechanically oxidised test specimens will be known as “generated” oxide tests in this work.

For pre-oxidation, rail discs were run together at 0.2 % slip, 1500 MPa and 400 RPM for 4000 cycles under dry conditions, this will be known as the “pre-oxidation” step and has been used in previous work [14]. An oxide layer was generated on the discs using this method and the discs changed from a reflective bare metal to a duller brown colour, this discolouration started at approximately 1000 cycles and continued to grow over time. The oxide layer was light brown and appeared to be thin and tightly bonded to the metal substrate. For the purposes of this work, discs that have not been pre-oxidised will be known as “non-oxidised”.

The SUROS rig was set-up with a pre-oxidised rail disc and a non-oxidised wheel disc. A syringe plunger was set-up to ensure an accurate and variable volume of water could be added to the discs. SUROS was programmed to ramp from 0.2 to 1 % creep so that a partial creep curve could be analysed.

A list of tests undertaken in this section is shown in Table 2. One dry baseline test was carried out and then four water application rates were used; 2.5 µl/s, 4 µl/s, 15 µl/s, 25 µl/s and 100 µl/s. Test 5 used the same conditions as test 4, but a non-oxidised rail disc was used instead of a pre-oxidised specimen. Tests were carried out at 900 MPa to simulate typical wheel-rail contact conditions.

Test No.	Paste Application	Water Application
1	pre-oxidised rail, non-oxidised wheel	N/A
2	pre-oxidised rail, non-oxidised wheel	2.5 µl/s
3	pre-oxidised rail, non-oxidised wheel	4 µl/s
4	pre-oxidised rail, non-oxidised wheel	25 µl/s
5	non-oxidised rail, non-oxidised wheel	25 µl/s
6	pre-oxidised rail, non-oxidised wheel	100 µl/s

Table 2. Generated oxide tests

2.3 Applied oxide tests

The wet-rail phenomenon was also simulated without pre-oxidation, by adding suspensions of oxide powder and water. The tests that simulate low adhesion using this method will be known as "applied" oxide tests in this work.

SUROS was set-up as described previously. Iron oxide powder was mixed with water to form pastes of different weight percentages (wt %). For instance, 10 ml of a 60 wt % hematite paste was formed from 6 g of hematite powder and 4 g of water.

Hematite pastes were first used at different weight percentages and two different application rates. Hematite powder with an approximate particle size of 2 µm was used, as the oxidised wear debris on a railhead has been found in previous work to be approximately 1-10 µm [10]. Tests were carried out at 1500 MPa. A list of tests undertaken in this section is shown in Table 3.

The paste was mixed before application to minimise any separation. The paste was applied using a 20 ml syringe before and throughout disc contact at different application rates, droplets of paste were added to the contact every 20 seconds. The syringe was used in a position that meant the droplets of oxide paste would fall on the upper disc and would be rotated into the contact, as used in the water application.

Magnetite pastes were then tested at 50, 60 and 70 wt % at 2 ml/min and 2 % slip to compare between the two types of iron oxide. Finally, a test was run using a 6 wt % suspension of bentonite clay at 2 ml/min and 2 % slip. Bentonite clay and water produce a suspension of small particles, similar to the hematite suspensions. Testing this would explain whether it was a chemical characteristic of oxides alone that caused low adhesion, or whether different types of particle suspensions could also cause issues. Hematite and magnetite were chosen because they are common oxidation products and have been previously found on the railhead [11]. Tests were carried out at 1500 MPa. A list of tests is shown in Table 4.

Test No.	Paste Application	Water Application
7	N/A	2 ml/min
8	30 % hematite paste, 2 ml/min	N/A
9	40 % hematite paste, 2 ml/min	N/A
10	50 % hematite paste, 2 ml/min	N/A
11	60 % hematite paste, 2 ml/min	N/A
12	60 % hematite paste, 6 ml/min	N/A
13	70 % hematite paste, 2 ml/min	N/A
14	Hematite powder, 2 g/min	N/A

Table 3. Hematite paste tests carried out in this work

Test No.	Paste Application	Water Application
15	50 % magnetite paste, 2 ml/min	2 ml/min
16	60 % magnetite paste, 2 ml/min	N/A
17	70 % magnetite paste, 2 ml/min	N/A
18	7.5 % clay suspension, 2 ml/min	N/A

Table 4. Magnetite and clay paste tests carried out in this work

SUROS specimens were analysed using an Alicona InfiniteFocus SL 3D roughness profilometer. The optical profilometer had the benefit of being able to generate a profile of a sample without needing physical contact with the specimen, which may have broken any oxide layer on the test specimens. Roughness analysis was carried out on specimens at different traction coefficients to assess how the surfaces may be different between a sample causing a very low traction coefficient and one with a higher traction coefficient after paste addition. 3 repeats from different areas of the specimen were taken for each measurement and the average shown in this work.

The specimens will continue to oxidise after testing and the morphology of the oxides may change over time. To minimise any changes, the specimen was put in a vacuum jar containing silica gel packets immediately after testing and taken out shortly before analysis. Roughness has been split into longitudinal and lateral roughness so that the two directions can be compared; a schematic of the two roughness profiles in relation to a SUROS specimen is shown in Figure 6.

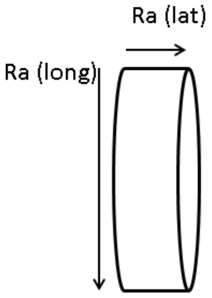


Figure 6. Lateral and longitudinal roughness of a SUROS specimen

3. Results

3.1 Generated oxides

Water application rates of 0, 2.5, 4, 25 and 100 µl/s were tested on pre-oxidised discs under creep ramp conditions, from 0.3-1 % slip. Results for these tests are shown in Figure 7. The results start at very low traction coefficients and begin to rise up as the oxide layer wears away. Dry values are reached after approximately 2000 cycles for the low volumes of water after the oxide layers have worn away, which shows that it is the oxide layers that are causing very low traction. The traction coefficient in the 2.5 µl/s rises faster than the results with higher water application rates, presumably because this very low amount of water is not enough to protect the oxide layer from wear, but the test drops back down to 0.1 after approximately 3000 cycles. By this point a brown paste is visible on the disc surfaces.

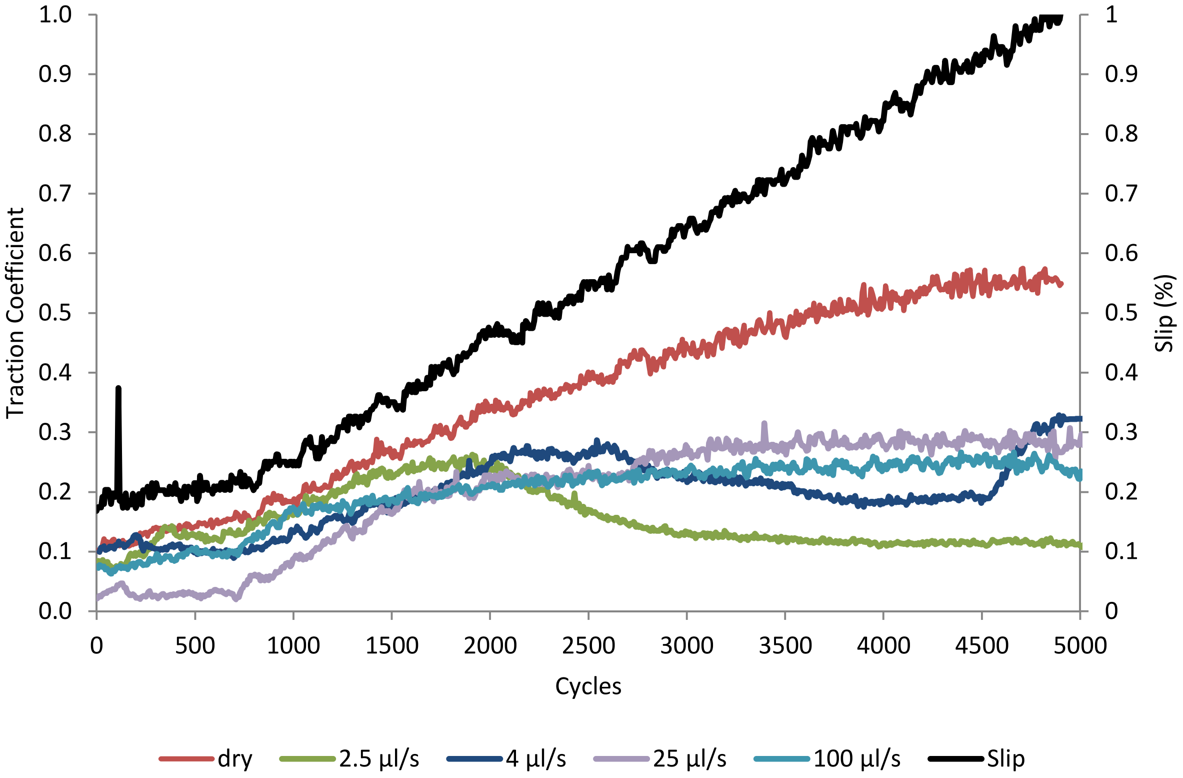


Figure 7. Water application rates of 0, 2.5, 4, 25 and 100 µl/s, using pre-oxidised rail discs and a creep ramp of 0.2-1 % at 900 MPa

To assess the effect of pre-oxidation, a test were run using a non-oxidised wheel and rail specimen with a 25 µl/s water application. This was compared against a pre-oxidised rail and a non-oxidised rail, also with a 25 µl/s water application. The results are shown in Figure 8. As expected, both tests with water addition produce a lower traction coefficient than the dry value. The pre-oxidised test starts of at a lower traction coefficient, approximately 0.03 rather than 0.08 and remains lower for approximately 1500 cycles. At this point both tests return to a value of 0.28.

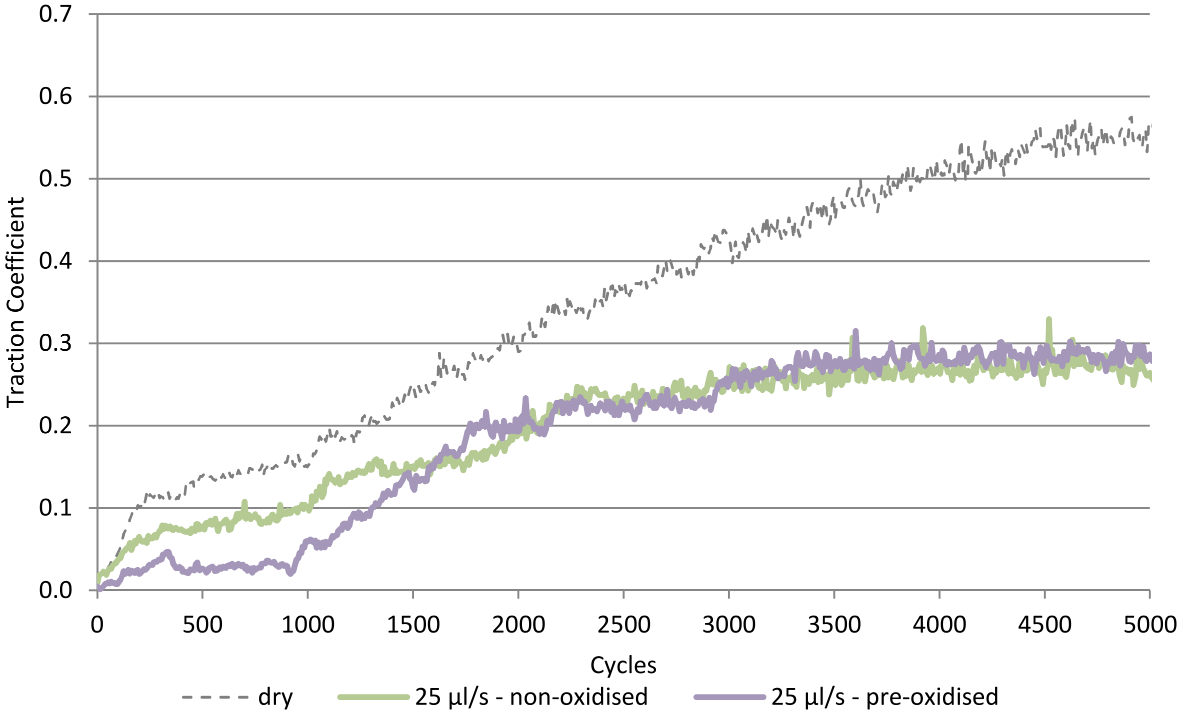


Figure 8 A comparison of non-oxidised and pre-oxidised rail specimens, with 25 µl/s water application at 900 MPa and 0.3-1 % slip

3.2 Applied oxides

0, 30, 40, 50, 60, 70 and 100 wt % hematite suspensions were tested at 2 % slip and shown in Figure 9. 2 ml/min water was used as 0 % and hematite powder, with no added water, was used as 100 %. Minimum, mean and maximum traction coefficients for each test are shown in Figure 10. There is a clear trend of an increased wt % hematite causing a lower traction coefficient up to a certain point. The 70 wt % hematite was difficult to add to the SUROS contact, causing a short test length and fluctuating results, however it produced a very low traction coefficient of 0.02 when it entered the contact.

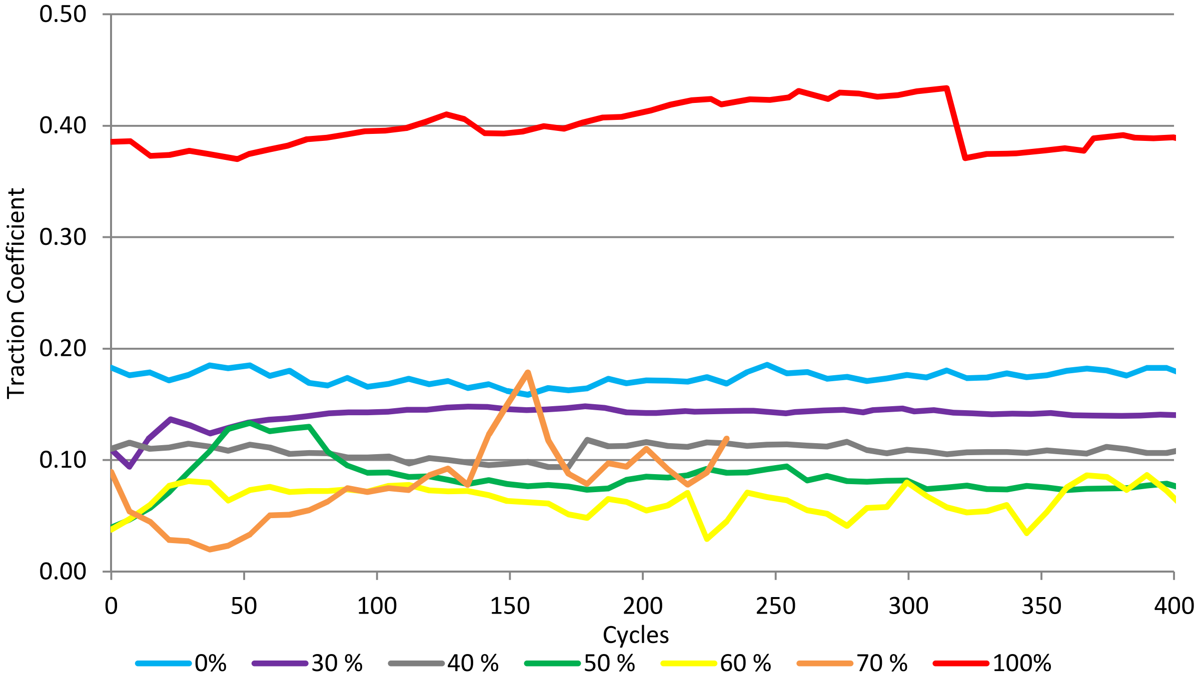


Figure 9. Raw results for 0-100 wt % hematite suspensions at 1500 MPa and 2 % slip

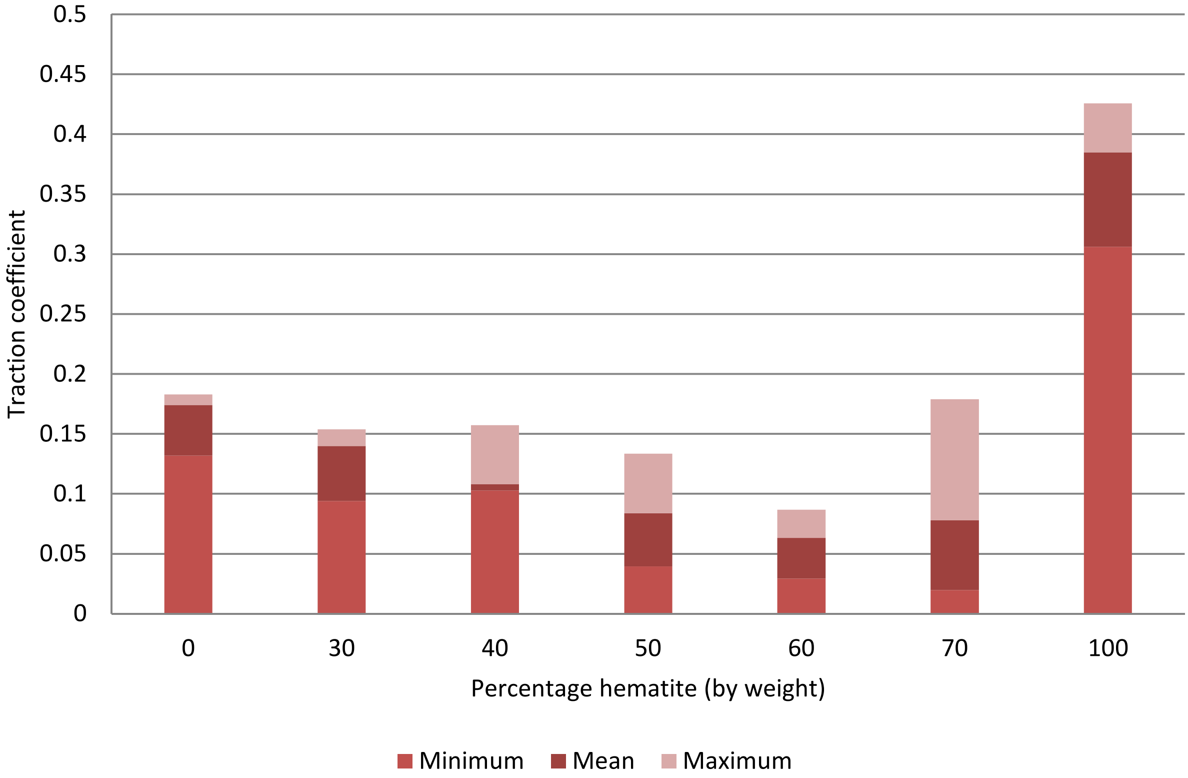


Figure 10. Minimum, mean and maximum traction coefficients for 0-100 wt % hematite suspensions at 1500 MPa and 2 % slip

Two different rates of hematite application were then tested, 2 ml/min and 6 ml/min at 60 wt %. The SUROS creep was ramped up over time to produce a partial creep curve in the region of 0.3-1 % slip and shown in Figure 11. The "noise" in the slip value is due to the control system that ramps up the SUROS creep value. Hematite paste added at 2 ml/min produces a lower but less consistent traction coefficient than 6 ml/min, due to the contact drying between paste applications.

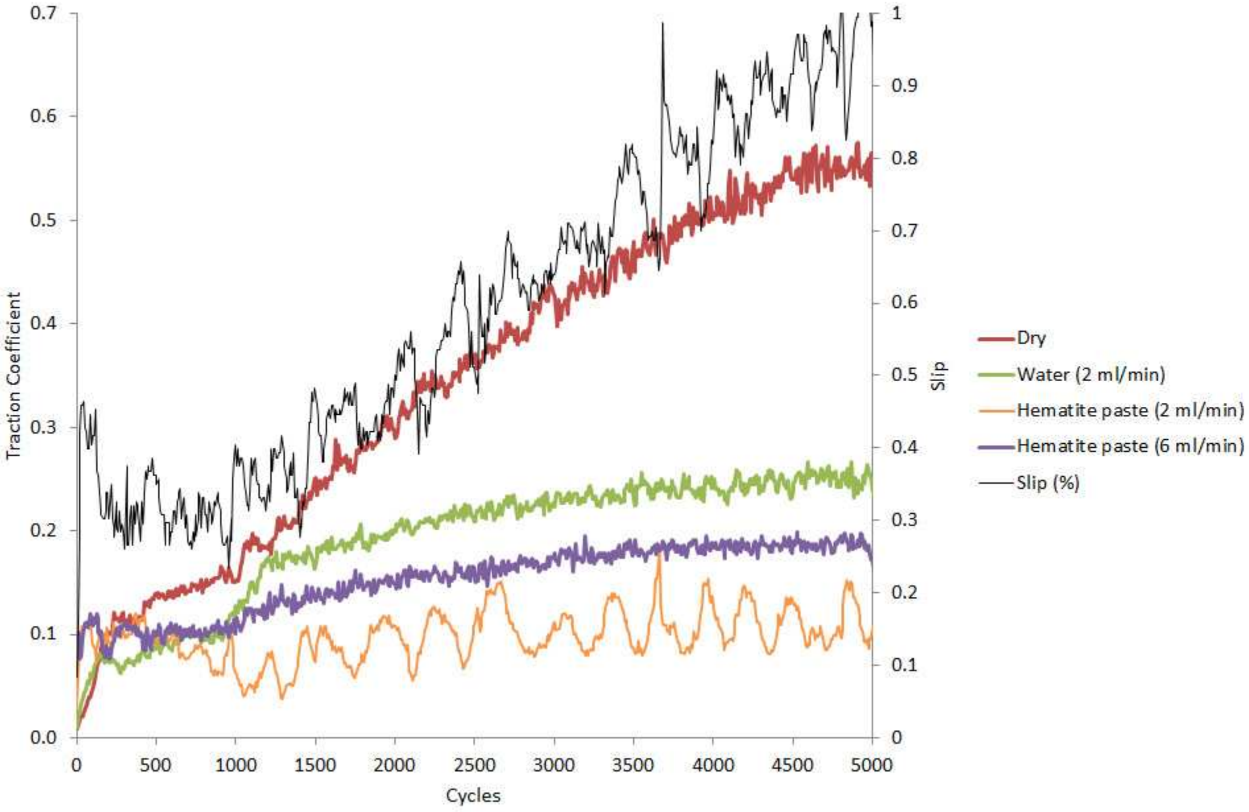


Figure 11. 60 % hematite application rates of 2 ml/min and 6 ml/min, 0.3-1 % slip at 1500 MPa

Magnetite was tested at 50, 60 and 70 wt % with an application rate of 2 ml/min; minimum, mean and maximum results are shown in Figure 12.

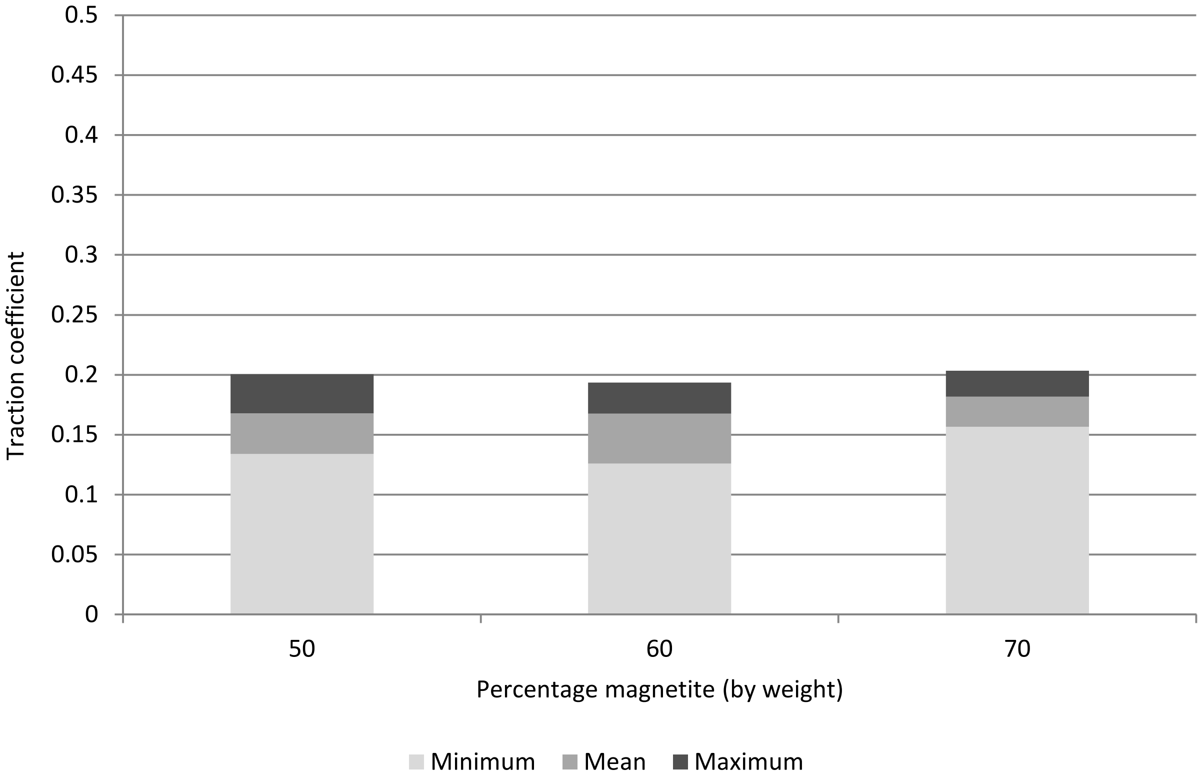


Figure 12. Minimum, mean and maximum traction coefficients for 50, 60 and 70 wt % magnetite suspensions at 1500 MPa and 2 % slip

Figure 13 shows raw results for the bentonite clay suspension in test 18, plotted against tests 7, 10 and 11 for comparison. The clay suspension gives a low traction coefficient similar to that seen in the hematite suspensions, with a traction coefficient starting lower than the 50 % and 60 % oxides at 0.05, before rising slightly.

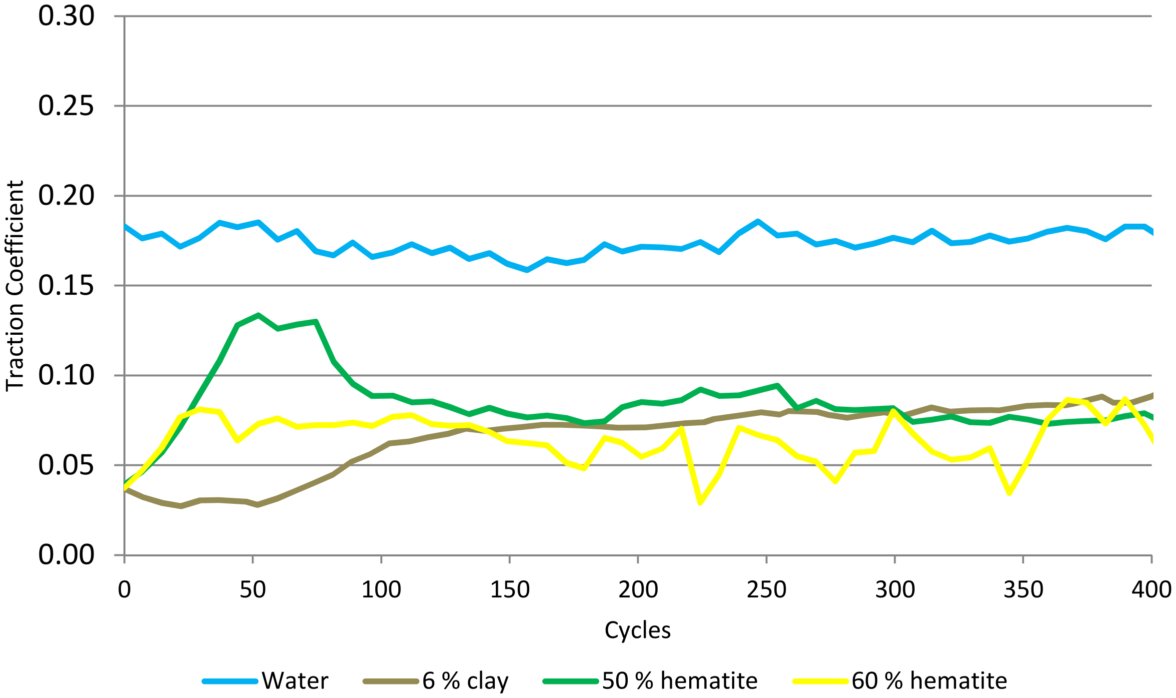


Figure 13. Raw results for the 6 % clay suspension at 1500 MPa and 2 % slip

Two separate tests were run using 60 wt % hematite paste at 2 ml/min, 1.3-3 % slip and 1500 MPa. Images of specimen discs before the test, during low traction at 300 cycles, 1.3 % slip and after the low traction period at 3000 cycles, 3 %

slip are shown in Figure 14. Images through an Alicona optical microscope are shown in Figure 15. Average combined roughness for each set of wheel and rail discs is shown in Figure 16.

As the slip value increased, a brown layer built up on the specimens, which became pitted at 3 % slip. An example profile of one of the pits seen in Figure 15, areas of bare steel where the oxide layer has been removed, found on the rail discs after 3000 cycles is shown in Figure 17. This shows an estimated dry layer thickness of 12 µm.

XPS analysis was carried out on the specimen "after" low adhesion. The layer was removed with a metal spatula and place in a Kratos Supra with a monochromatic aluminium source, two points of each sample were analysed and a low resolution "sweep" was carried out before obtaining high resolution spectra for each element present. A low resolution survey scan was performed to determine which elements were present and then high resolution scans were taken for each element. A scan of the hematite powder, before testing is shown in Figure 18. A scan of the surface layer, removed from the test specimen, after 3000 cycles is shown in Figure 19. Hematite is seen in the first scan and a mixture of hematite and an oxyhydroxide is seen in the second, showing that some of the oxide may have been transformed in the contact, or produced separately by the oxidation of steel.

Figure 14. Images of the SUROS rail specimens before, during and after a period of low adhesion

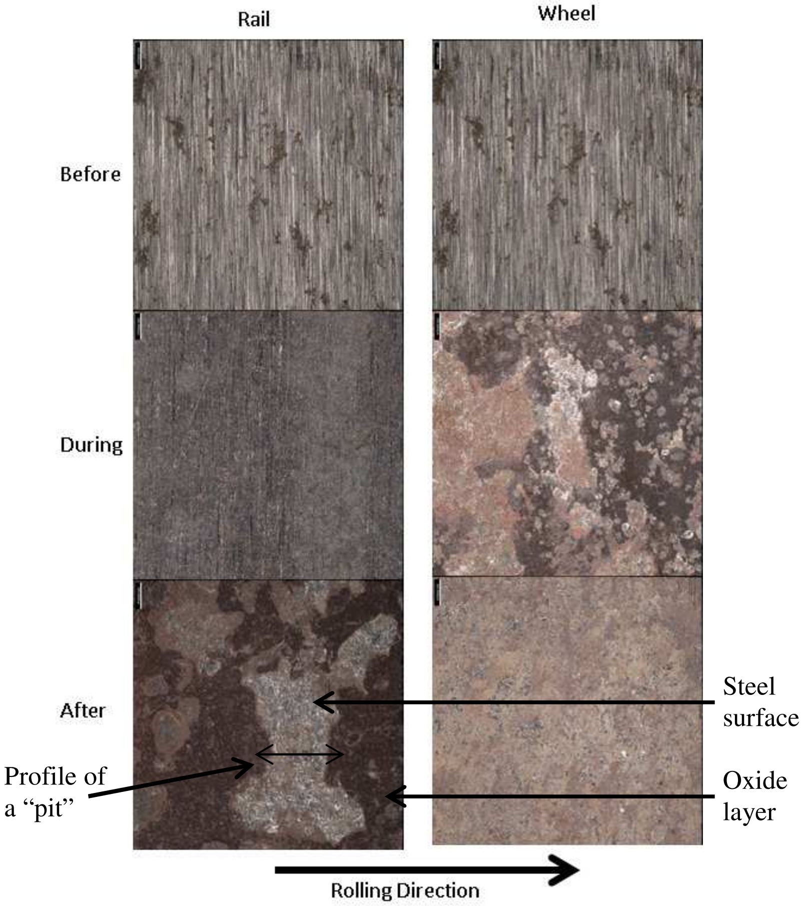


Figure 15. Microscope images of SUROS specimens before, during and after a period of low adhesion

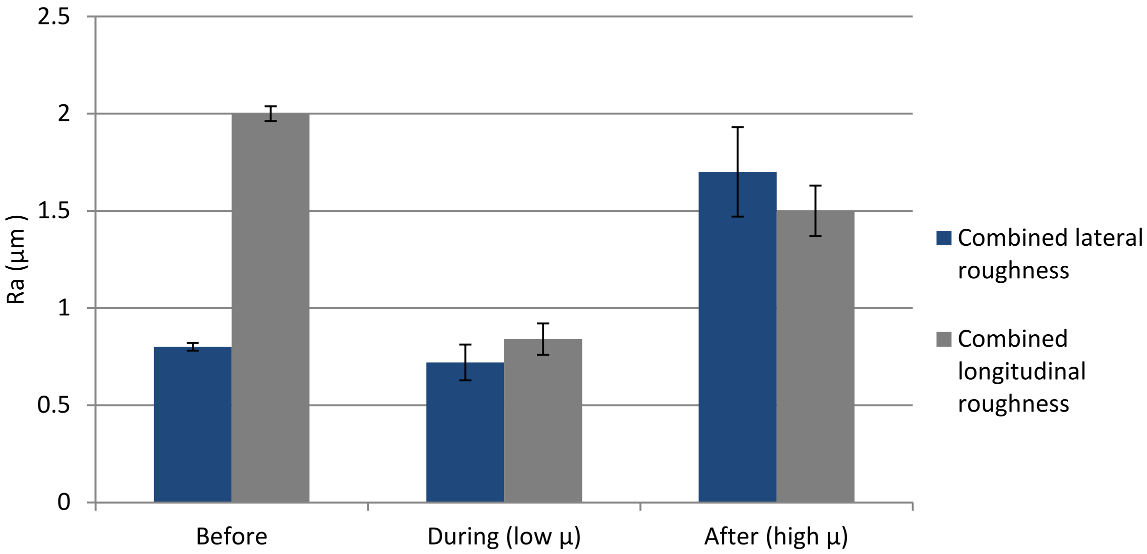


Figure 16 Combined roughness of the rail and wheel specimens shown in Fig. 14 and 15

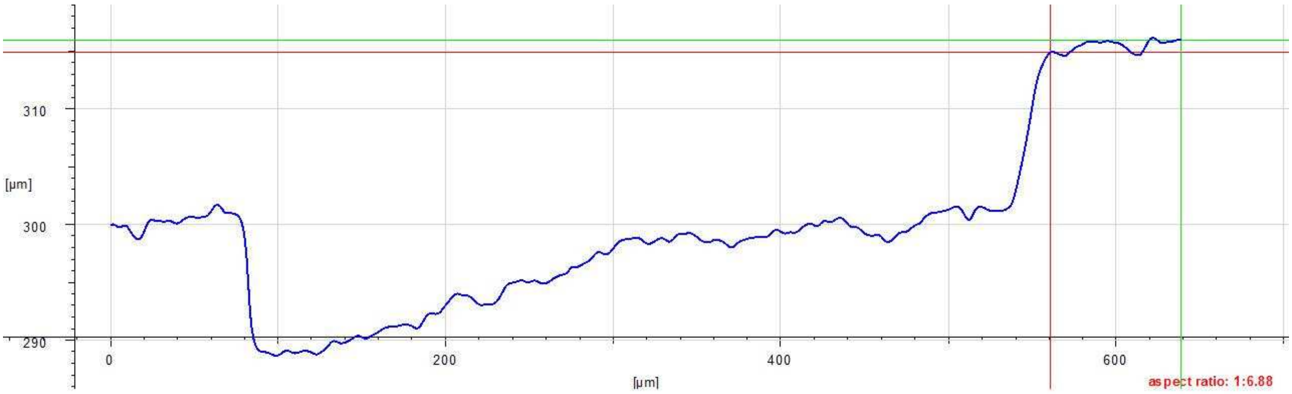
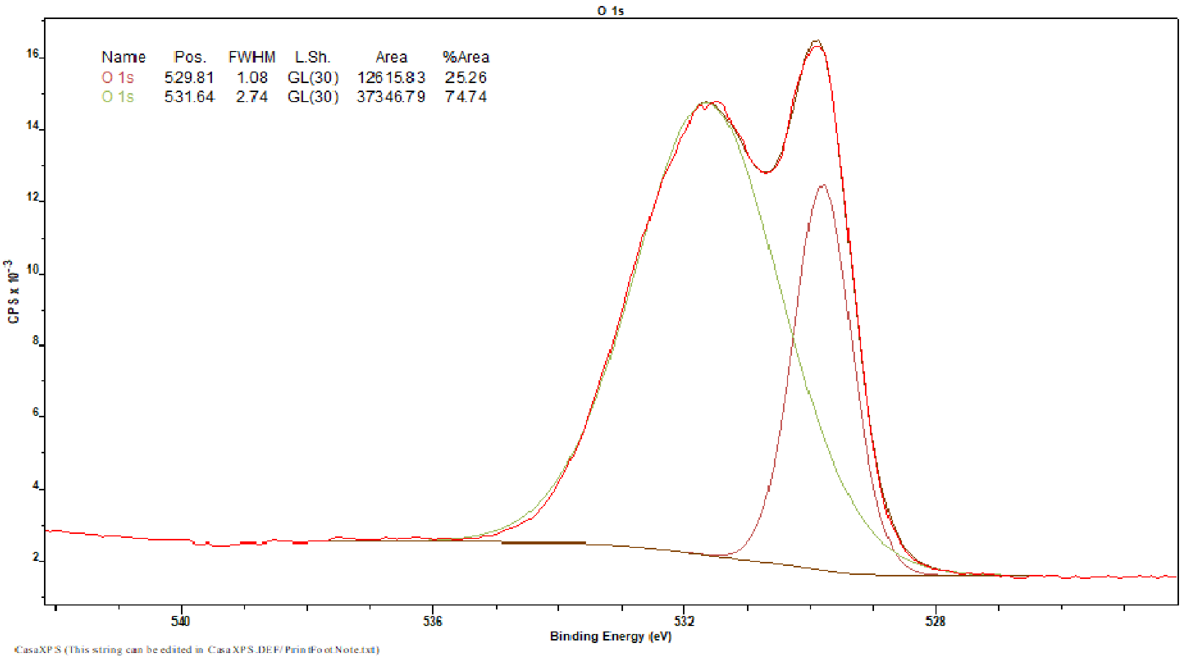
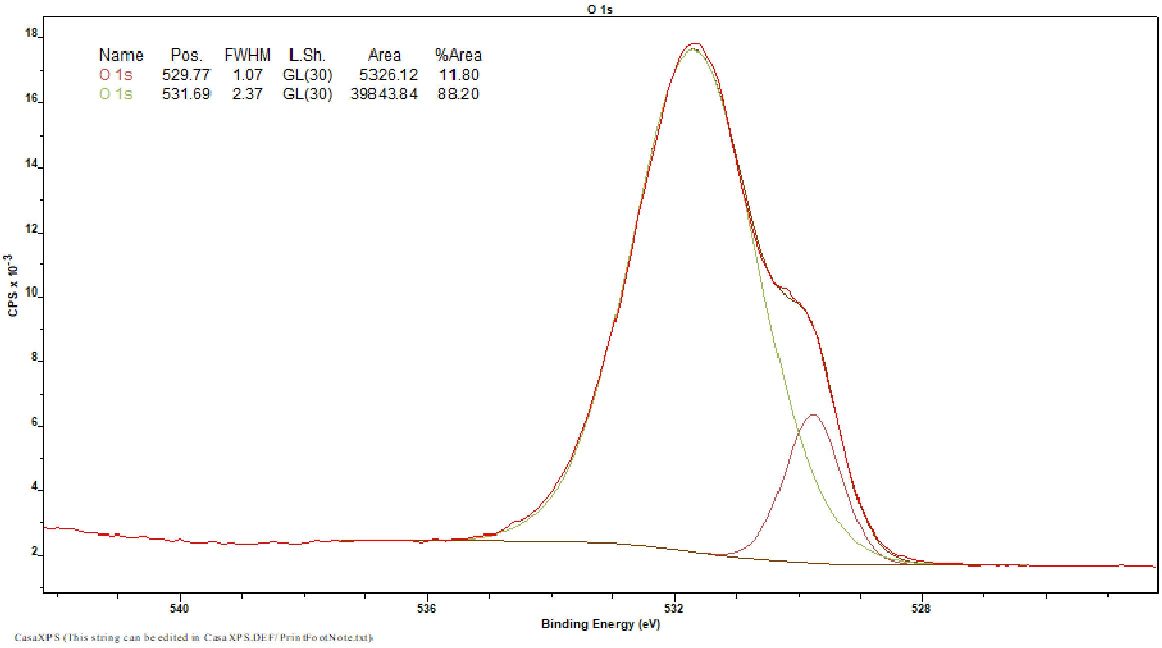


Figure 17. A pit in the oxide layer after a period of low adhesion, profile taken from Fig. 14



Name	Pos.	FWHM	L.Sh.	Area	%Area
O 1s	529.81	1.08	GL(30)	12615.83	25.26
O 1s	531.64	2.74	GL(30)	37346.79	74.74

Figure 18. XPS scan of the hematite powder, before testing



Name	Pos.	FWHM	L.Sh.	Area	%Area
O 1s	529.77	1.07	GL(30)	5326.12	11.80
O 1s	531.69	2.37	GL(30)	39843.84	88.20

Figure 19. XPS scan of the surface layer of the SUROS specimen, after 3000 cycles

4. Discussion

4.1 Generated oxides

Very low and sustained traction coefficients have been produced on the SUROS rig using a pre-oxidised specimen and water at low slip values. The traction coefficient during these tests varied greatly depending on how much water was added. The change in traction coefficient over the creep curve tests with a generated oxide shown in Figure 7 can be split into 4 regions, shown in Figure 20. Region 1 is the initial lubrication due to the oxide layer on the rail disc. This occurs during low, linear slip and the traction coefficient starts low, below 0.1. The tightly bonded oxide layer will remain intact at first due to the low slip, but will eventually wear and become present on the previously bare wheel disc; both discs are coated with a brown paste at this point. Region 1 continues if slip ramp is not used and creep values remain low. The period of time that region 1 occurs for varies between tests, depending on contact conditions, water application and the amount of previous oxidation. Sufficient water application is needed to protect the oxide layer from wear, the higher water applications stay in region 1 for longer.

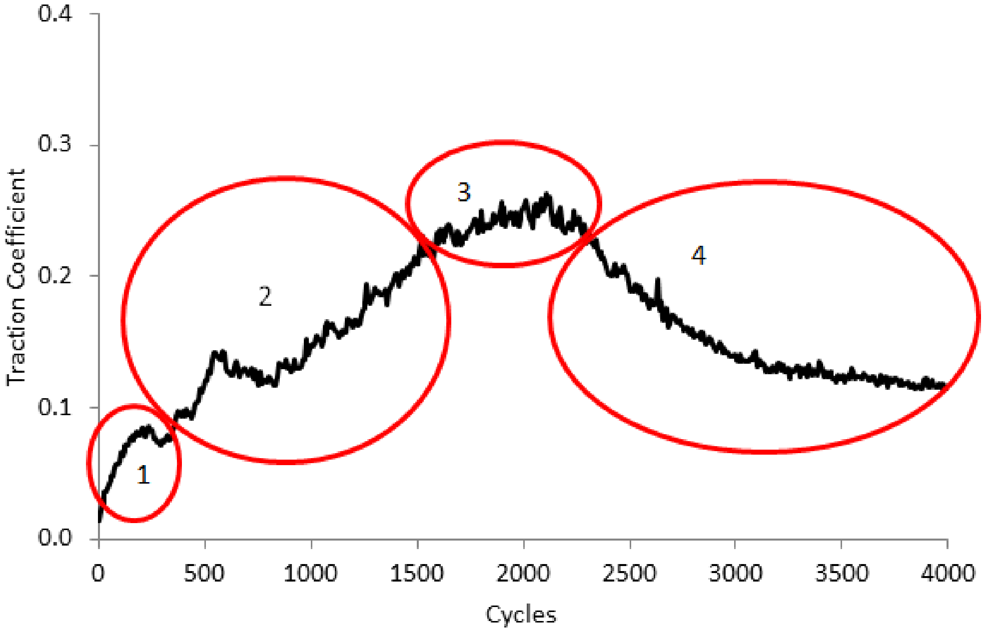
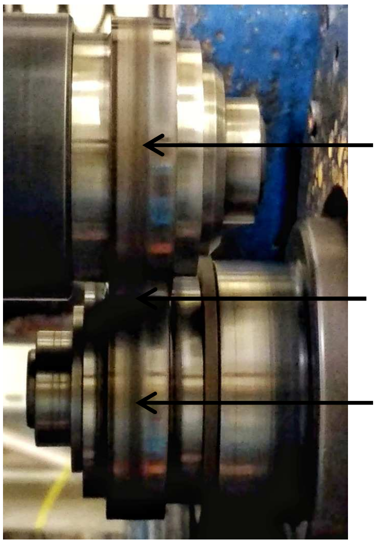


Figure 20. Changes in traction coefficient during a twin disc test

It is impossible to keep conditions constant during the pre-oxidation step and a visible difference in oxidation is seen, the oxide is noticeably thicker and more coloured in some tests than others. Factors that could affect the growth of the oxide layer include humidity, temperature and small changes in load and slip. These could affect rate, type and morphology of oxide growth so there may be chemical differences as well as physical differences such as thickness and roughness.

This brown oxide layer is removed and the discs return to their bare metallic appearance during region 2, where the traction coefficient rises to a value of about 0.2. The time taken to reach this value varies between tests, depending on the slip value, rate of water addition and amount of previous oxidation. The traction coefficient stays largely constant in region 3 and provides a similar traction coefficient to wet baseline tests where the rail has not been pre-oxidised. This is similar to the wet and non-oxidised baseline value so it is hypothesised that the initial oxide coating has no effect on this region. During SUROS tests involving water, there is a pocket of water where the two discs meet and stays due to water tension. The water that is contained in the contact becomes progressively darker as the oxide particles wear away are suspended in it, which likely increases the viscosity. Region 3 seems to occur for most samples at around 1000-2000 cycles which is 0.4 % slip. Both discs have a bare metallic appearance. Some tests will stay in region 3 until water application stops, but other tests enter traction region 4.

The traction coefficient will start to decrease in region 4; this is accompanied by an audible and visual change from the SUROS rig. The traction coefficient decreases and a brown band becomes visible in the centre of the contact, as seen in Figure 21. The traction coefficient drops to a lower value and seems to remain low as long as conditions remain constant. This is possibly because the brown band is picked up from the increasingly viscous pool of liquid in the contact patch and adheres to the discs to produce a traction lowering layer, which can be seen coating the discs in Figure 21, whilst in region 3 the pool of liquid is not viscous enough to be picked up and cause low traction. The brown band seen in these tests looks similar to previous larger scale tests, using a different test rig, which produced a short period of low traction when small amounts of water were added to a contact patch as seen in Figure 22. A schematic of the changes in colour of the 4 regions is shown in Figure 23.



Brown band visible on the rail disc

Dark brown liquid trapped between discs (likely to be oxides and water)

Brown band visible on the wheel disc

Figure 21. The brown band visible on the SUROS discs during the decreasing traction coefficient in region 4

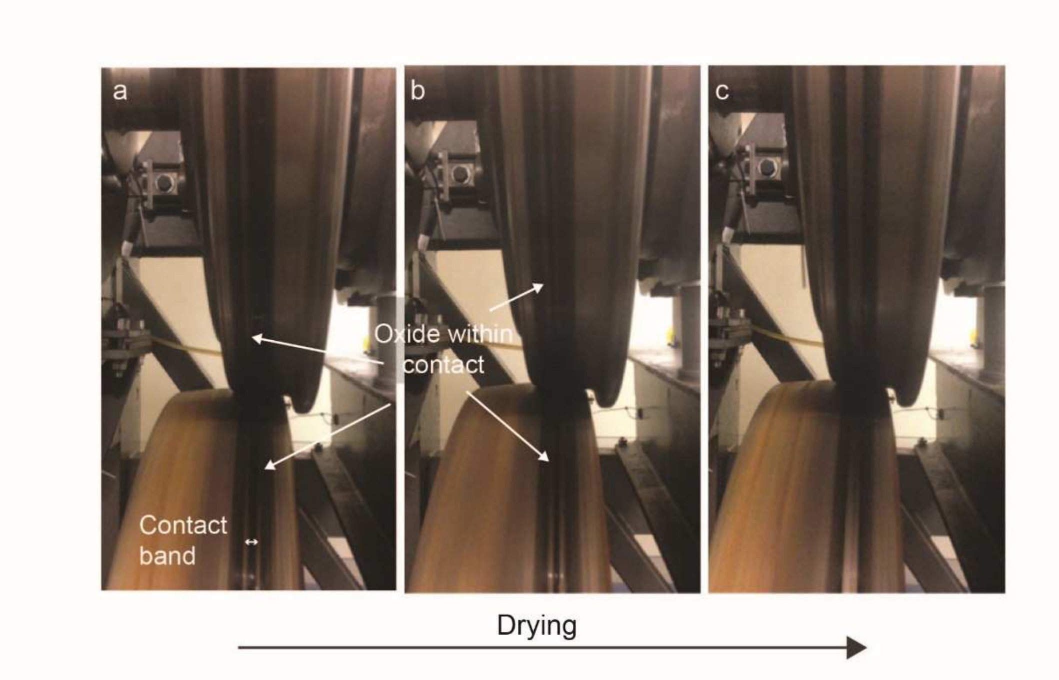


Figure 22 A brown band of iron oxide visible during low traction on another test rig [16]

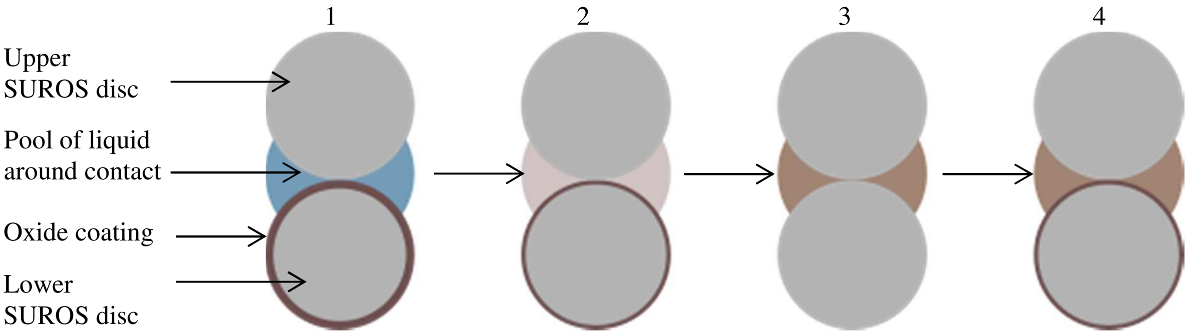


Figure 23. A schematic of traction regions 1, 2, 3 and 4 (left to right)

The initial traction coefficient of the oxidised rail disc in Figure 8 was significantly lower than the non-oxidised rail disc, approximately 0.02 rather than 0.06 and stayed lower for a longer period of time. Both traction coefficients increased to 0.2 at 2000 cycles, the surface oxide layer had been visibly removed by this point. The traction coefficient then stayed at a similar level for the remainder of the test, presumably the initial oxide layer had been removed and therefore the traction coefficient became similar to that of a non-oxidised wet baseline test.

Pre-oxidation seemed to have two effects on the traction coefficient. It firstly reduced the traction coefficient during region one, with the oxide protected from wear by the water. Secondly, no tests without pre-oxidation have been seen to enter region 4 where traction is once again reduced. This could be due to the wear particles from the initial oxide layer building up and remaining on the disc. They could mix with the water, but only reduce the traction coefficient under certain conditions such as the correct viscosity, as seen when testing with hematite powders. The oxide seen in these tests could be entirely due to the pre-oxidised layer or due to oxide being formed in the contact. This is similar to the railway scenario where the oxide in the contact patch could either be due to oxide already found on the railhead or oxide generated in the contact itself due to wear particles, heat and pressure. Future work should be carried out to assess these two options.

4.2 Applied oxides

The artificial hematite pastes seemed to decrease the traction coefficient to levels similar to those seen during the "natural test"; the contact needed regular applications of paste suspension to remain low rather than the "generated" oxides which only required water addition. This could be due to differences in either chemical or physical oxide properties or because the oxide paste is more easily pushed out whilst the natural layer remained in the contact. The results show that both the quantity and viscosity of paste have a large impact on the traction coefficient.

The hematite pastes showed a substantial drop in traction coefficient at higher weight percentages, seen in Figure 10. 30 wt % at 2 % slip gives an average traction coefficient of approximately 0.14, lowering the traction coefficient slightly from a wet value of 0.17. The traction coefficient drops to approximately 0.06 at 60 wt %.

The lower wt % pastes could be easily applied to the SUROS discs, but the 60 and 70 wt % pastes became much more viscous which made application difficult, especially when trying to achieve a steady rate. 70 wt % hematite gave an extremely low minimum traction coefficient of 0.02 at 2 % slip when it was able to enter the contact, as seen in Figure 9. However it could not be applied at a steady rate, the highly viscous consistency meant that it was difficult to apply to the discs consistently for an extended period of time so the test had to be stopped and the traction coefficient fluctuated due to the varying amount of paste in the contact.

As described in the methodology, the oxide pastes were applied to the upper disc and pastes up to 60 wt % stuck to the upper disc and were pulled into the contact. 70 wt % hematite behaved differently and often "bounced" off the upper disc and fell out of the contact area rather than sticking to it and being pulled into the contact so the contact was often dry with no paste in it. The traction coefficient dropped to a minimum whenever any paste stuck to the disc and was able to be pulled into the contact. In a real contact the paste on a rail running band would be trapped between wheel and rail and would not have to rotate into the contact, so higher viscosities may cause low adhesion in a real railway situation, but are unable to when using the SUROS rig.

An oxide application rate of 2 ml/min appears to be the quantity that produces the lowest traction coefficient because upon oxide addition the traction coefficient rose to a maximum value then dropped to a minimum and rose slightly again before more hematite was added to repeat the cycle, creating an oscillating traction coefficient. A closer view of the 2 ml/min application of hematite paste at 60 wt % with labelled points at which the hematite paste is added is shown in Figure 24.

The 2 ml/min of paste application had a more fluctuating traction coefficient than 6 ml/min, possibly because of the large difference in conditions as the contact dries out. The larger quantity of 6 ml/min may have been enough to prevent the contact drying out and therefore generating a stable traction coefficient, but it was the point at which the contact starts to dry that seemed to produce very low traction conditions. This supports the theory that the wet-rail phenomenon tends to occur when the track has very small amounts of moisture and that the critical conditions that result in low adhesion may be when the track is drying out. It also means that low quantities of oxides and wear debris may cause low adhesion rather than a thick layer of contamination.

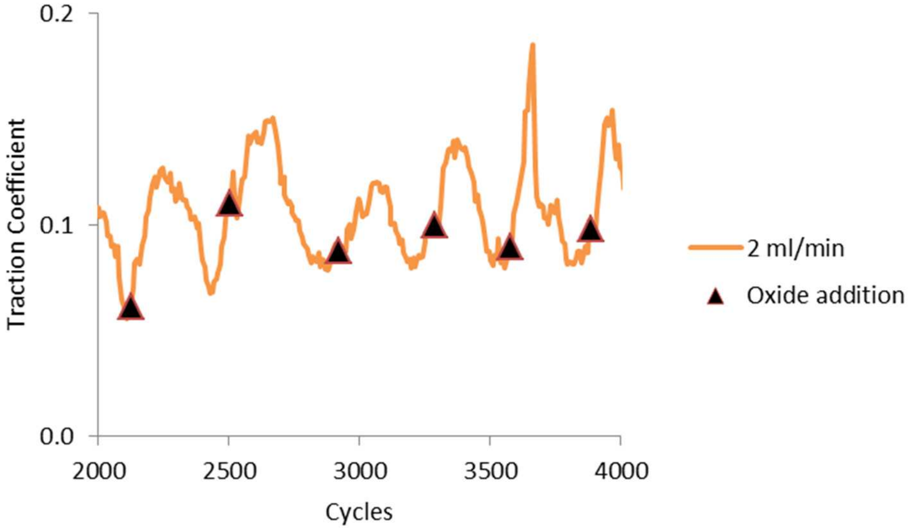


Figure 24. 2 ml/min, 60 % hematite application points plotted alongside traction coefficient

As seen in Figure 24, the initial paste application caused an increase in traction coefficient at 2 ml/min and 60 wt % oxide pastes and low traction was not observed until a period of time after paste addition where the paste layer appeared to become thinner and less visible on the disc. The paste could be either not viscous enough or the quantity could be too high, upon addition of paste it took a period of time to either be removed, spread out or for water to be squeezed out of it before it reduces the traction coefficient. Alternatively the oxide particles may need to be crushed smaller over a number of rotations or crushed into the steel surface to reduce the traction. Time may also be needed to build up a layer of oxide paste on the disc surfaces, producing a layer as seen in Figure 14.

The Alicona profilometer was able to measure the roughness of a compacted iron oxide layer, as well as the steel substrate. The discs visibly changed colour throughout the test due to the build-up of iron oxide on the contact surface which remained on the specimens when the tests were stopped. The oxide layer visible in Figure 14 is strongly bonded and difficult to remove. It can be seen that even after 400 cycles a layer was built up on the wheel disc. At 3000 cycles this layer was much thicker but has transferred to the rail disc, with only a thin layer present on the wheel disc.

The roughness seemed to be lowered substantially during low adhesion, especially the rail disc. This could either be due to mild wear of the steel or the build-up of a solid oxide layer may have created a smoother surface on top of the steel. The low combined roughness, below 1 µm, has been recorded on railway lines previously [21].

The build-up of the oxide layer suggests that the water was squeezed out of at least some of the iron oxide paste in the contact, leaving the dry powder behind to become compressed and build up the layer seen on the test specimens. The darkening colour of the layer throughout the test was likely to be caused by the mixing of hematite powder with steel wear particles, which likely became oxidised themselves in the contact [10].

Figure 18 shows a high resolution O 1s XPS spectrum of the hematite powder before it was made into a paste, whilst Figure 19 shows the O 1s spectrum of powder taken from the surface of a SUROS disc after testing with a 60 weight % hematite paste at 2 % slip. The survey scan of the hematite samples show that the oxide has remained in the same oxidation state, but these high resolution scans show an increase in the oxygen peak at 531.7 eV, which is likely because some of the hematite has been converted to an oxyhydroxide in the contact patch.

This layer appears to have been flaked off in sections to leave holes which expose the bare metal underneath. The profile of the pits, Figure 17, shows that the layer is approximately 12 µm thick in places. The third body layer on a railhead was found to be 15-20 µm so this is representative of real railhead conditions [10], this is thicker than the combined roughness of the wheel and rail steel discs so leads to the suggestion that under certain conditions, the wheel disc could be entirely contacting the third body oxide layer on the rail disc, rather than the steel disc. The remaining oxide layer on the steel specimens was very tightly bonded to the steel and was difficult to remove after testing so it is likely that this layer could prevent wheel and rail contact on the railhead, at least at lower creep values.

Magnetite did not produce low traction when pastes are added to the contact, with average values of approximately 0.17, similar to that seen in tests using water alone. This is likely due to the magnetite and water suspension being far less stable than hematite and water, magnetite particles quickly settled to the bottom of the beaker unlike the hematite particles which created a stable suspension. It is currently unclear whether a different size of magnetite particles would create a stable suspension and cause low adhesion, this should be investigated in future.

The SUROS test that produced low adhesion with a clay suspension showed that low adhesion was likely to be due to the rheological paste properties. Low adhesion has been previously reported on a railway due to coal or clay industrial contamination [22] which supports these findings and could include any other contaminant that forms a viscous paste.

In both sets of testing, repeatability will always be an issue. The results show that a small difference in paste viscosity will cause different resulting traction coefficients and difficulties in both producing and applying these oxides will result in experimental scatter. However, although the exact traction coefficients may differ the results of the applied oxide tests are repeatedly under 0.1 which is a large step forward in simulating and understanding the wet-rail phenomenon.

5. Conclusions

Iron oxides and water alone can produce very low traction conditions. The lowest traction coefficients seen in this work, below 0.02, are comparable to those seen in oil and grease contamination. Low amounts of water, combined with a pre-oxidised rail specimen, are able to produce very low traction conditions on the SUROS test rig. This seems to be due to a combination of an initial oxide layer and then a build-up of oxide wear particles, mixing with water to form a paste. Small differences in conditions and pre-oxidation give large differences in results which explains the narrow window of conditions that seem to cause the wet-rail phenomenon.

Both hematite and clay suspensions were able to decrease the traction coefficient to levels that would be classed as low adhesion when added to the SUROS twin disc test rig. If both oxide and clay pastes can cause low adhesion year round, it is likely that the organic components and other third body particles found on the railhead will also mix with these and add to the problem.

The “applied” test method is a repeatable single-step process unlike the “generated” oxide tests, which vary greatly depending on conditions. The higher wt % hematite pastes produced a lower traction coefficient; this trend is likely to occur until the paste is completely saturated by hematite. Hematite powder, without any water addition, produces the same traction as a dry test with no contaminants. On a real track, a small amount of water could mix with iron oxide and wear debris to form a thick paste and produce the very low adhesion conditions seen in the laboratory during this paper. Magnetite suspensions did not cause low adhesion, which could be due to magnetite forming a less stable suspension in this case, although a more stable magnetite paste could possibly be formed using a different particle size.

The solid particles that form the pastes that caused low adhesion during this work would likely build up on the railhead due to oxidative wear, environmental oxidation and contamination from outside sources such as road crossings and industrial pollution. The work shows that the traction reducing properties of these pastes are strongly affected by the viscosity of paste and therefore the amount of moisture on the railhead plays a large role in low adhesion.

This explains why low adhesion due to the wet-rail phenomenon is often linked to dew, light rain and drizzle, where the small amount of water creates a viscous paste while a larger amount would dilute the suspension too much and possible cause the particles to be washed away. It also explains why the conditions that cause this form of low adhesion are so difficult to replicate and study on a real railway; water will evaporate so the conditions will be constantly changing. A station overrun may be caused by a paste on the railhead and then wiped clean during the wheel-slide, or evaporate to leave only a thin layer of debris before the track is inspected after an incident.

The twin disc test rig was able to simulate these low traction conditions in a laboratory for a significant amount of time. This has not been achieved previously using iron oxides and water alone and the methods shown in this work can be used as a platform to test mitigation methods. The two methods shown in this work to produce low traction may be used to test different types of products; the “generated” oxides could be used to test methods to suppress oxide growth while the more repeatable “applied” oxide tests could be used to test products such as sand or traction gels which may be used in low adhesion hotspots. The author hopes that a more extensive study of the wet-rail phenomenon, using the provided methods, can be carried out in future.

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