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ORIGINAL PAPER

Iron Oxide and Water Paste Rheology and Its Effect on Low Adhesion in the Wheel/Rail Interface

Ben White[1] · Reuben Kempka[1] · Peter Laity[1] · Chris Holland[1] · Klaus Six[2] · Gerald Trummer[2] · Luke Buckley-Johnstone[1] · Roger Lewis[1]

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Abstract
The "wet-rail" phenomenon results in low adhesion between wheel and rail throughout the year, occurring transiently on a slightly wet, or drying railhead. It has been previously proposed that it is caused by a mixture of iron oxides and small amounts of water (from dew or precipitation) on the railhead that form a friction reducing paste. This paper outlines a novel combination of rheology, modelling and experimental work using a twin disc test rig to determine how the rheology of this iron oxide paste affects adhesion. The yield strength of different types of iron oxides, along with solid oxide fraction of the friction reducing paste, was assessed and used as an input into an "adhesion model" for assessing water and oxide suspensions. The rheological and modelling results were compared against very low adhesion recorded in twin disc experimental validation when simulating the wet-rail phenomenon.

Keywords Friction · Rheology · Wheel/rail interface · Iron oxide

1 Introduction

Low adhesion between wheel and rail is a recurrent problem for the rail industry. Low adhesion can lead to wheel slides and slips during acceleration and deceleration, which can cause large amounts of damage to the wheel and rail as well as causing safety and punctuality issues.

Low adhesion has been well-documented throughout the autumn season due to organic contamination [1, 2], but also takes place throughout the year when no visible contamination is seen on the railhead, due to what is known in the UK as the "wet-rail" phenomenon. The wet-rail phenomenon is thought to occur when there are low levels of water on the railhead, formed by dew, mist or light rain, rather than heavy rain. Previous analysis of Network Rail station overruns showed that during the autumn season, no railhead leaf contamination was seen for approximately 50% of incidents [3]. It also showed an increase in low adhesion incidents during morning and evening hours where no precipitation had fallen, likely because of dew formation on the railhead. A graph based on the data from this previous work is shown in Fig. 1 [4]. The data have been normalised by average station stops per hour and shows in increase in overrun per station stops where no precipitation has fallen within 12 h in the early morning and evening hours, possibly due to dew and increased oxide build-up on less frequently used track.

The conditions and mechanisms that cause the phenomenon are not fully understood. It does not occur very often and under what is likely to be a narrow window of transient conditions, where the railhead is at a critical point between wet and dry, which means that it can be difficult to recreate and study. Studies have been carried out to produce low adhesion using iron oxides and water [5], but little work has been carried out to assess the effects of different iron oxide properties.

Beagley [6] initially suggested that the wet-rail phenomenon was due to a paste (formed from a small amount of water and wear debris containing iron oxides) which was present on the railhead and causing low adhesion. Twin disc tests that were run using discs with a layer of wear debris under wet conditions where water application was halted show the friction coefficient was reduced as the contact dried, before rising back up to dry levels as the paste created in the contact was removed. Beagley's twin disc results showing the

✉ Ben White
bwhite2@sheffield.ac.uk

[1] University of Sheffield, Sheffield, UK

[2] Virtual Vehicle Research Center, Graz, Austria

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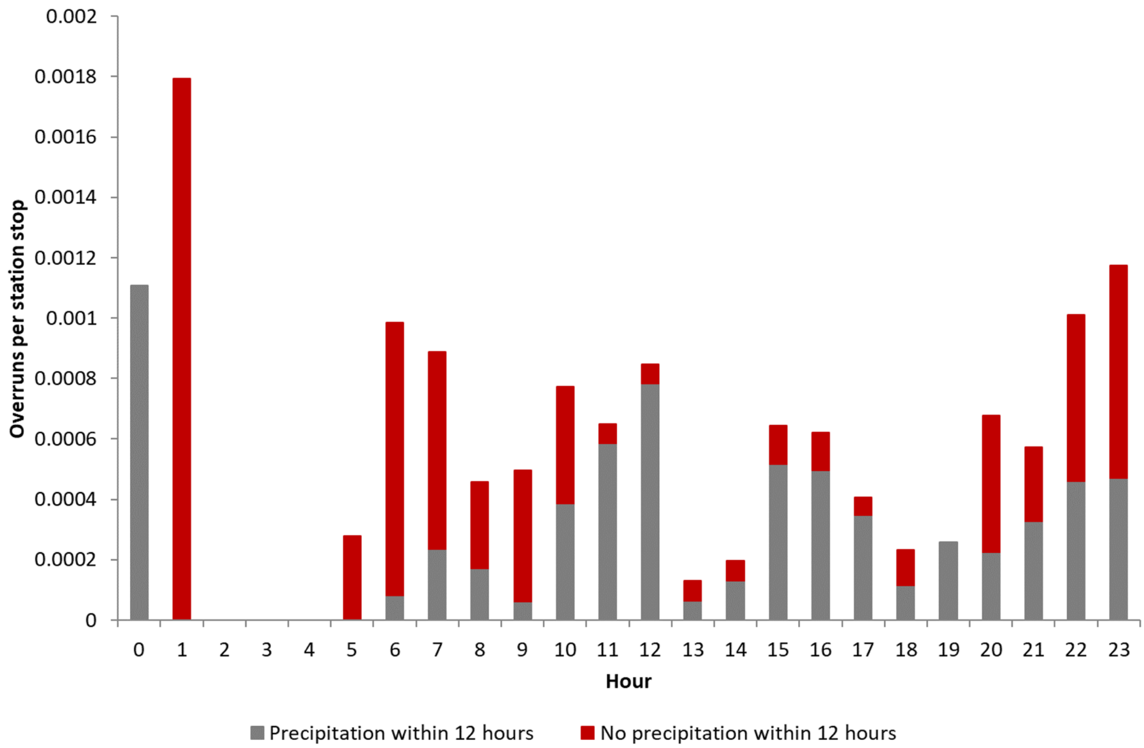


Fig. 1 Number of Network Rail station overruns per station stops where precipitation has fallen within 12 h before the incident and those where no precipitation had fallen, plotted against hour of the day and normalised by average station stops per hour (data collected during previous work but figure re-drawn for the current paper) [4]

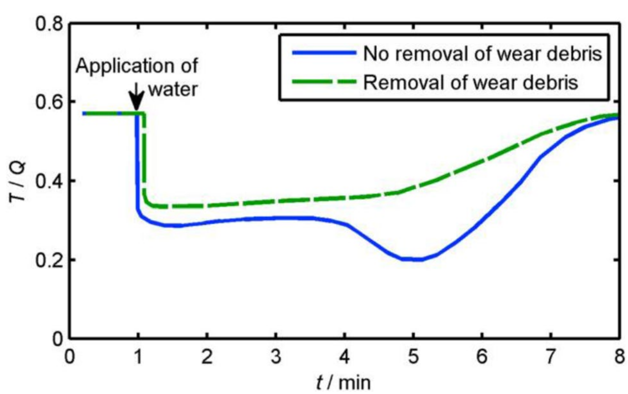


Fig. 2 Twin disc test results, showing lower adhesion when wear debris (including iron oxides) is present in a drying contact [7]

decrease in adhesion have been plotted in modern software and shown in Fig. 2 [7]. Low adhesion due to small amounts of water and an oxidised surface has also been recently replicated on a full scale test rig [8]. Low adhesion has also been reportedly caused by clay and coal contamination [9], which could create a similar paste on the railhead.

There are five different types of iron oxides that have been found on the railhead using in situ spectroscopy [10]. These can be split into two groups, the first group are iron oxides known as magnetite (Fe_3O_4) and hematite (Fe_2O_3), the second group are iron oxide–hydroxides which are known as goethite (α-FeOOH), lepidocrocite (γ-FeOOH) and akaganeite (β-FeOOH–Cl). No experimental data are available for the effects on friction of this range of different oxides, with the main focus in previous work being on hematite and magnetite as they have been shown to form within the interface as a result of the temperature and pressure experienced [11]. Iron oxides are also often found as a mixture and with different particle sizes, which will impact the resulting traction coefficient. The presence of different oxides is also likely to vary spatially and temporally along the track due to changing environmental conditions.

Oxide particles on the rail can accumulate due to oxidative wear. Oxidised wear particles from a twin disc rolling-sliding test rig, run under dry and unlubricated conditions, were analysed and found to be in the magnitude of 1 µm, with some larger particles reaching 10 µm. These particles were compacted into a glaze, found to be 20 µm thick [12]. A literature review of iron oxides in wheel/rail tribology is found in [13]. Stable low adhesion, with a friction coefficient below 0.1, using a twin disc test rig has been achieved using a mixture of hematite and water [14]. This simulates the very low adhesion that occurs due to the wet-rail phenomenon and the results of these tests have been plotted alongside modelling results in this paper.

An "adhesion" model, based on squeeze film theory [15], was developed in previous work [7, 16] and uses Beagley's yield shear stress data from a paste composed of hematite and water, made to different solid weight fractions [6]. The model shows how friction varies when the proportion of oxide and water in the paste is changed when tested in a high pressure torsion (HPT) test rig. The HPT rig compresses a sample with a realistic wheel/rail contact pressure and then measures the friction coefficient under torsion.

The model is designed to show the change in adhesion in a qualitative way when a "paste like" mixture of iron oxide and water is used. Originally, the model was limited to a single oxide (hematite) due to the lack of previous experimental data. Validating the model with experimental results and expanding it to multiple different iron oxides and oxide–hydroxides helps understand the conditions that produce this narrow window of conditions and how different paste properties will affect adhesion. This will lead to better understanding, prediction and mitigation of the wet-rail phenomenon to benefit the rail industry.

Further input parameters for the model are paste layer thickness and roughness of the contacting bodies. An adhesion minimum was identified where (dependent on the normal load, the thickness of the paste layer and the surface roughness) ultra-low friction occurred at a specific solid oxide fraction, as seen in Fig. 3. This model is intended to describe the change in adhesion under quasi-static conditions (hydrodynamic effects and influence of shear stresses on paste yielding are not considered yet) in a qualitative way, helping to explain why it has been difficult to achieve low adhesion due to the wet-rail phenomenon in laboratory tests.

This paper describes experiments carried out to gather rheology data, from different iron oxide types and solid oxide fractions, to use as inputs into the adhesion model. Different paste properties and oxide types are analysed and the results are used as inputs into the updated adhesion model. The adhesion model outputs are then compared against previously collected twin disc test results, to assess the validity of the model.

The combination of oxide paste rheology measurements, adhesion modelling and twin disc testing was used to investigate the hypothesis that iron oxide and water alone could cause ultra-low adhesion due to the "wet-rail" phenomenon and assess how the adhesion model outputs may vary with different types of iron oxides.

This paper will assess if iron oxide rheometry results, combined with the adhesion model, can be used to predict the traction coefficient in a simulated, small scale wheel–rail contact by comparing against the wet-rail simulation method shown in previous work [14]. The findings can be used to better predict when and where the wet-rail phenomenon will occur and prevent low adhesion incidents on the railway.

2 Methodology

2.1 Oxide Characterisation

Six different types of iron oxide powder were used in this work. Three different particle sizes of hematite were used, 50 nm, 2 μm and the third particle size known as "100 mesh" (a US size which is equal to approximately 150 μm). The oxide–hydroxides, goethite and lepidocrocite were also

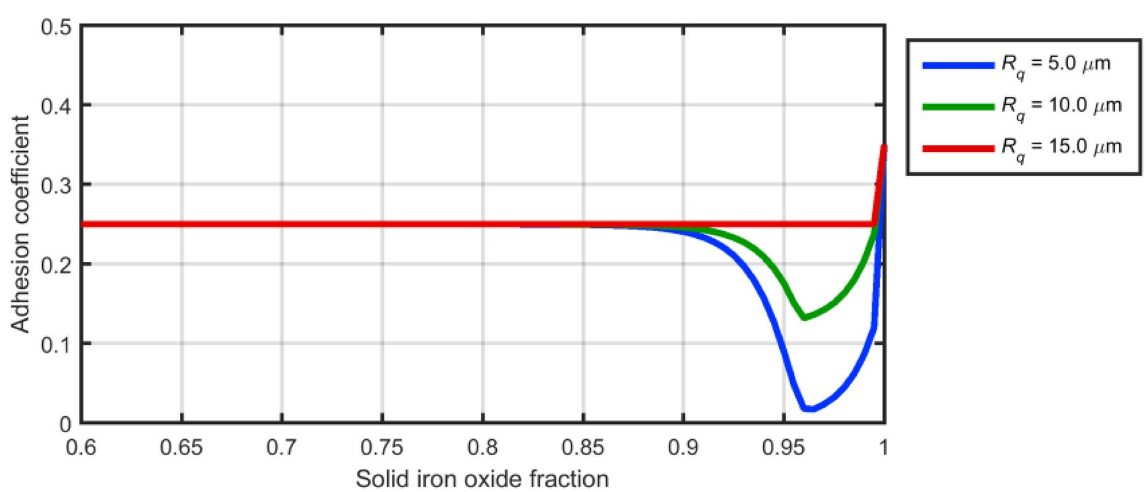


Fig. 3 Previously modelled results for the change in adhesion coefficient for different solid oxide fractions of hematite and water pastes at different surface roughness [7]

tested. The sizes 50 nm and 2 µm were chosen to provide two sizes that were close to that observed in previous work [12, 17], along with the 100 mesh which is larger than has been previously reported to be used as a comparison. The oxides used in this work were first analysed with a scanning electron microscope (SEM), revealing the structures for each powder used.

The 2 µm hematite particles (Fig. 4) are rounded in comparison to other particles viewed in this section, most particles are approximately 2 µm, but there are larger particles up to 10 µm present. The 100 mesh hematite particles (Fig. 4) are very geometric and crystalline in comparison, with flat faces. The hematite less than 50 nm (Fig. 5) contains clusters of particles.

These rounded clusters, made from an agglomeration of smaller particles, have been observed in the field [17]. The images shown show rounded agglomerations that are similar to the 50 nm and 2 µm particles observed here, rather than the more angular 100 mesh particles. The main difference is that the field data contained a mixture of particles such as different oxides, wear debris, oil contamination and organic compounds [17]. In this previous study the clusters analysed were sub-micron, but this is expected to vary due to the changing environmental and physical conditions of the railhead.

The magnetite particles (Fig. 5) are sub-micron and easily separated compared to other oxides shown here. The goethite and lepidocrocite (Fig. 6) have needle like particles, the lepidocrocite particles have clustered in places.

2.2 Rheometry

In order to determine new inputs for the adhesion model, rheology of the different oxides was studied. Iron oxide

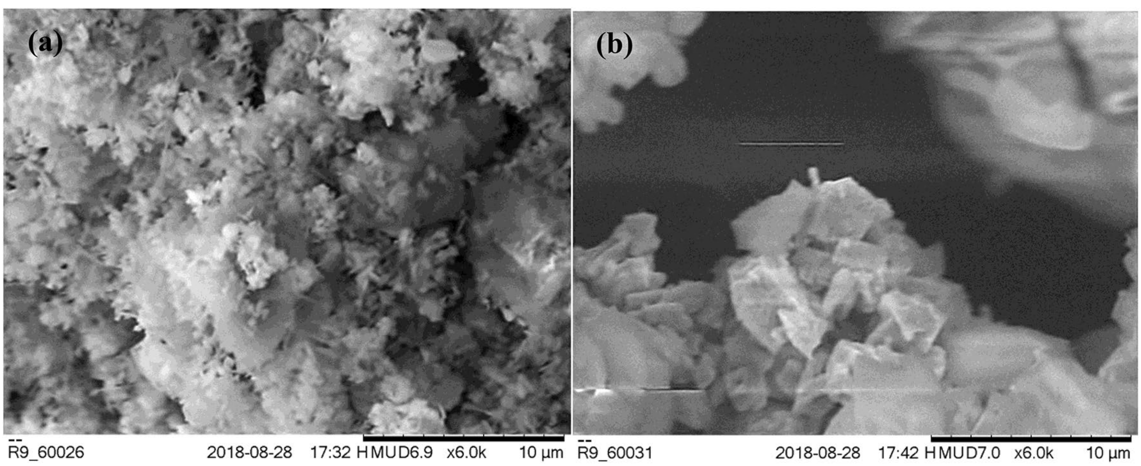


Fig. 4 SEM images of **a** 2 µm hematite and **b** 100 mesh hematite

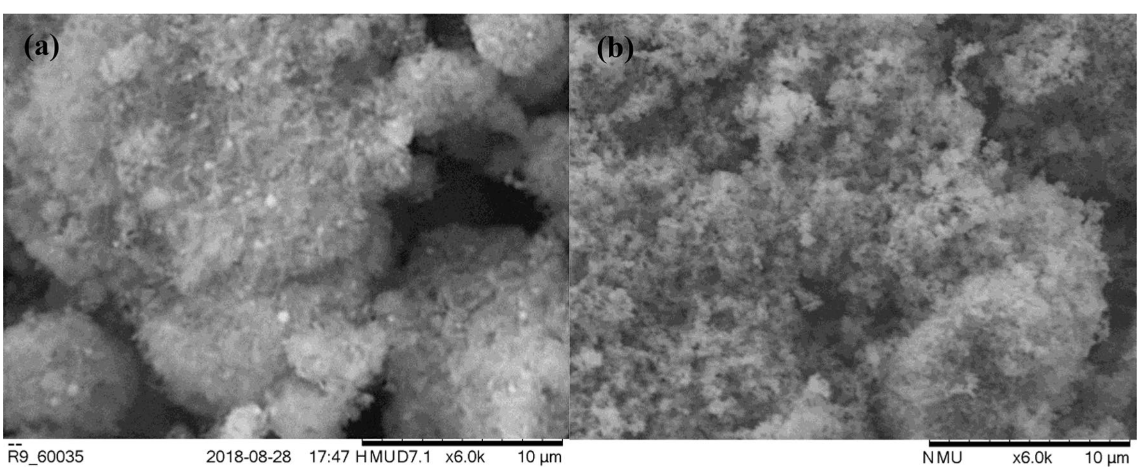


Fig. 5 SEM images of **a** 50 nm hematite and **b** magnetite

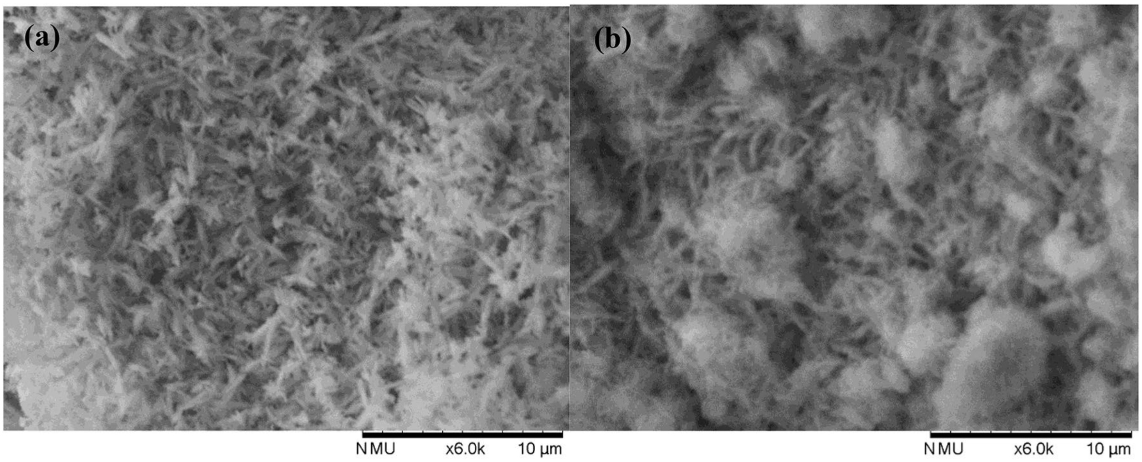


Fig. 6 SEM images of **a** goethite and **b** lepidocrocite

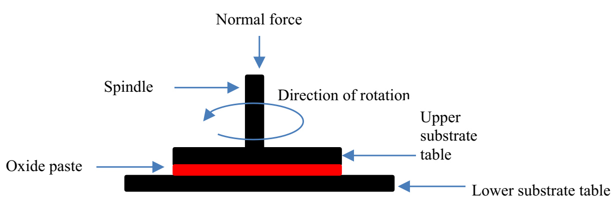


Fig. 7 A schematic diagram of the rheometer set-up used in this work

powders were mixed with water to form pastes of different solid weight percentages (wt%). For instance, 10 ml of a 60 wt% paste was formed from 6 g of oxide powder and 4 g of water. The modelling section of this paper uses solid oxide fraction to keep consistency with previous papers using this model, where a 60 wt% paste would equate to a solid oxide fraction of 0.6. The pastes were shaken thoroughly before addition to the rheometer in each of the following test methods.

A TA Instruments AR2000 rheometer was set-up with a 40 mm parallel plate geometry, a labelled diagram of the rheometer is shown in Fig. 7. Oxide paste was added to the substrate table and the parallel plate lowered to 1 mm above the table surface. The parallel plate was then spun with a ramping shear rate over 10 min until the shear rate reached 100 s^{-1}. The torque, converted to shear stress, needed to spin the parallel plate at each shear rate was recorded, with the yield shear stress being the point at which the parallel plate begins to spin. The rheometer then reduced the shear rate to zero over the next 10 min to produce results for the reducing rate.

2.3 Modelling

A detailed description of the "adhesion" model can be found in [7], but a basic outline will be given here. The model was developed to predict adhesion conditions in a quasi-static HPT experiment, based on squeeze film theory [15]. The model uses yield shear stress, amount of paste entering the contact, surface roughness and the boundary wet and dry friction coefficients as input values to generate a predicted adhesion coefficient for each weight percentage of hematite paste. This work aimed to adapt this model to fit twin disc testing and updates the model with input values that are found from the experimental tests carried out in this work.

The adhesion coefficient, f, can be taken as the tangential force in a contact, divided by the normal force applied. Therefore, in a contact that contains an iron oxide paste between two parallel plates, the coefficient in this model can be taken as the sum of the tangential forces from the plate asperities (T_B) and the iron oxide (T_C), divided by the sum of the normal force upon the asperities (N_B) and iron oxide (N_C).

$$f = \frac{T_B + T_C}{N_B + N_C}. \quad (1)$$

The relationship between the yield shear stress and percentage solid of an oxide paste was used as a key initial input into the adhesion model and influences surface separation.

Friction is metal–metal asperity dominated at low yield stress of iron oxide paste, which results in the adhesion coefficient being equal to the upper boundary friction coefficient. As the yield stress increases, the iron oxide paste is able to support more of the normal force and therefore influences the adhesion coefficient.

The adhesion coefficient of a wet contact, without oxide addition, is used as an initial upper boundary friction coefficient; a value of 0.25 is used in Fig. 3. The low viscosity of water will not support the parallel plate load so the boundary friction is used to provide a friction coefficient which is entirely metal-to-metal. Increasing the wt% of iron oxide will reduce the amount of metal-to-metal contact between the plates because of the increased shear stress and reduce the adhesion coefficient, which occurs at a sold weight percentage of 0.9 in Fig. 3. When the contact becomes too dry at very high weight percentages, the adhesion coefficient will increase rapidly. The friction coefficient of dry oxide powder, with a solid oxide fraction of 1, limits the maximum friction coefficient.

2.4 Experimental Verification

Previously collected results from the SUROS twin disc test rig were used in this work to verify the model outcomes. The SUROS test rig is able to log the traction coefficient of two counter-rotating steel discs, manufactured from R260 rail steel and R8T wheel steel material and ground to surface roughness of R_a 1 µm (typical for a worn wheel/rail contact [18]). Contact conditions of 400 revolutions per minute (equivalent to 0.1 m/s), 1500 MPa (representative of a real wheel/rail contact) and 2% slip were used. These contact conditions were used because they had been used for previous low adhesion studies on the SUROS rig involving iron oxides, so the results were comparable [19]. A detailed description of the test rig is found in [20] and a schematic diagram is shown in Fig. 8 [21].

The 2 µm hematite powder was used for these tests because it has a particle size that was closest to that found in previous work [12]. It also agglomerated into rounded clusters that were observed in previous field work [17]. 30, 40, 50, 60 and 70 wt% hematite and water pastes were added to the rotating discs at a rate of 2 ml/min via a syringe pump, able to accurately and continuously dispense the required volume of paste, and the traction coefficient logged. Water alone and dry 2 µm hematite powder were added to represent 0 and 100 wt% hematite. The paste was added drop-wise to the upper disc so that it was rotated into the contact. 30, 40, 50 and 60 wt% hematite pastes were run for 400 cycles each, but difficulties were encountered when adding the 70% hematite paste due to the high viscosity, the paste appeared to "bounce" off the rotating discs rather than sticking and being pulled into the contact as seen in the less viscous pastes. Because of this, the 70 wt% test was only run for 200 cycles before the oxide applicator became clogged and unusable.

Specimens were analysed after testing using an Alicona InfiniteFocus SL3D roughness profilometer, which was able to generate roughness and approximate layer thickness data without deforming the oxide layer due to physical contact.

3 Results

3.1 Rheology

The yield shear stress of each solid oxide fraction of hematite paste with an approximate particle size of 2 µm is shown in Fig. 9. A temperature of 10 °C was used, to simulate the cooler morning and evening conditions where the wet-rail phenomenon occurs. Two results were taken for each solid wt% and have been plotted with Beagley's previous data [6]. As expected, the yield shear stress increases with increasing wt% of hematite paste, but the new results show a higher yield stress for each weight percentage than the previous data.

Shear stress was plotted against shear rate for these tests and shown in Fig. 10, an alternative plot of viscosity against shear rate is shown in Fig. 11. As expected, the shear stress generally increased with increasing oxide weight percentage. Shear thinning behaviour was observed where the viscosity was seen to decrease overall with increased shear rate over the 10-min test. Hysteresis effects were seen, where the viscosity on a decreasing rate (down) did not follow that of the increasing rate (up). When testing the 55 and 60 wt% pastes, a sudden decrease, followed by an increase in viscosity was seen at a shear rate of approximately 7 s^{-1}.

In a railway situation there may be multiple different particle sizes and types of iron oxide so the following

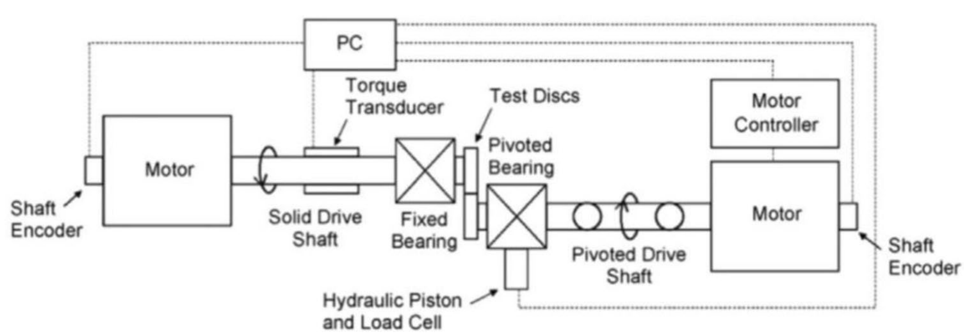


Fig. 8 A schematic diagram of the twin disc SUROS rig [21]

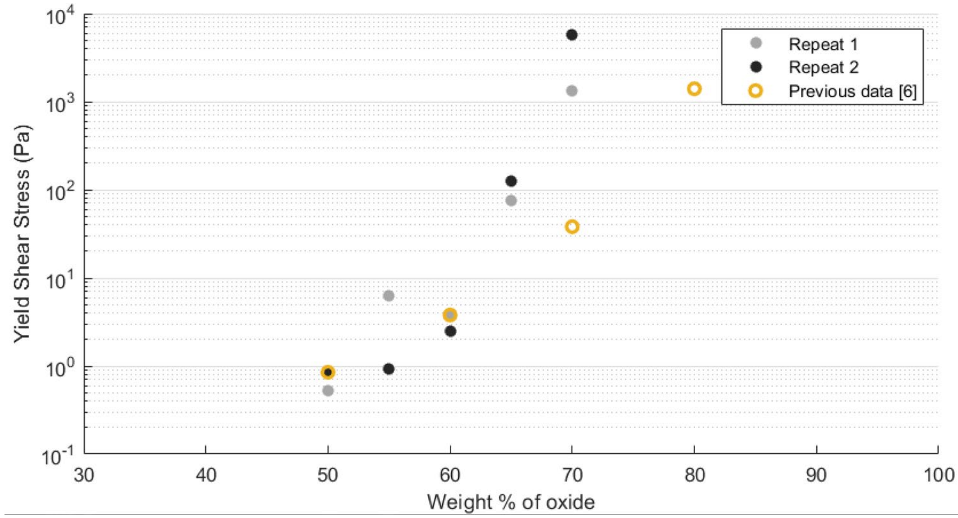


Fig. 9 Yield shear stress for different wt% of hematite 2 µm particles, 10 °C

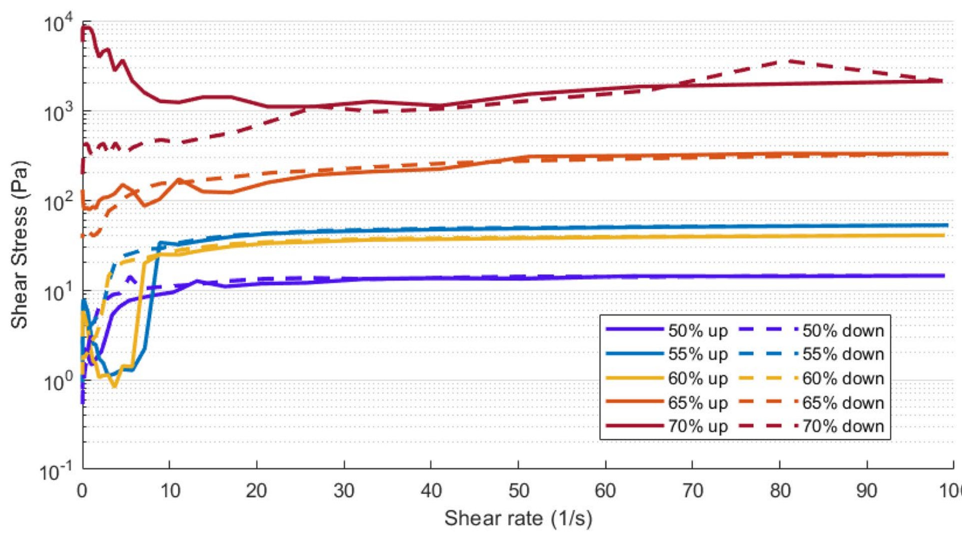


Fig. 10 Shear stress plotted against shear rate for different wt% of 2 µm hematite particles, 10 °C

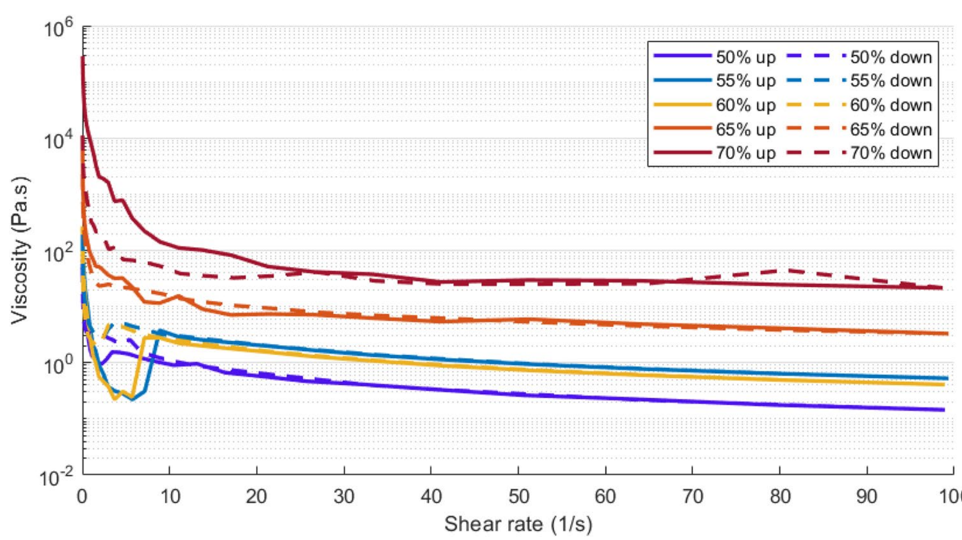


Fig. 11 Viscosity plotted against shear rate for different wt% of 2 µm hematite particles, 10 °C

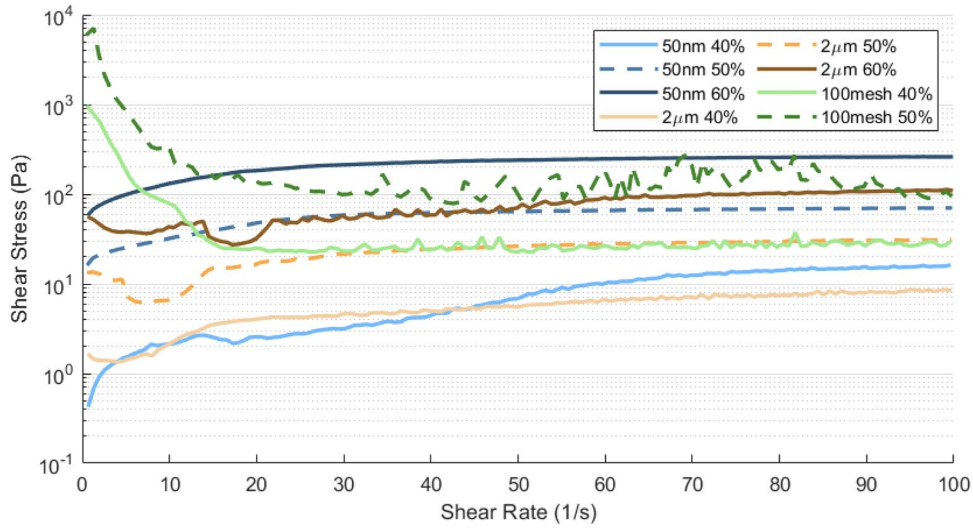


Fig. 12 Shear stress plotted against shear rate for 50 nm, 2 μm and 100 mesh particle sizes of hematite, 25 °C

work shows how the paste rheology can vary for different particle sizes of hematite, as well as data for other types of oxide including magnetite, goethite, and lepidocrocite.

Shear stress was also plotted against shear rate for different weight percentages of 50 nm, 2 μm and 100 mesh particle sizes of hematite at 25 °C and shown in Fig. 12. An alternative plot of viscosity against shear rate is shown in Fig. 13. The results show that the larger and more angular 100 mesh particles produce a higher initial yield shear stress for each weight percentage. The overall trend remains the same, with shear thinning behaviour, but these second set of results do not show the decrease before a rapid rise in shear stress that is seen in Fig. 10.

The yield shear stress a key input into the adhesion model so this was plotted for 50 nm, 2 μm and 100 mesh particle sizes of hematite and shown in Fig. 14. It can be seen that the larger 100 mesh particles have a far higher yield shear stress, whilst the 50 nm and 2 μm results have very similar values.

The yield stress for different types of iron oxide; hematite, lepidocrocite, goethite and magnetite is shown in Fig. 15. The oxide–hydroxides (goethite and lepidocrocite) have a higher yield shear stress than the oxides, hematite and magnetite. This may be due to the different interactions with water; a stronger interaction will produce a higher yield shear stress. The rheometer was not able to measure the very viscous suspensions so a maximum of 70 wt% hematite was measured for 2 μm hematite, which was lower for other types of oxide.

3.2 Modelling

The adhesion model was modified to fit the smaller contact area of the SUROS specimens rather than the HPT rig it was originally based on, estimated as two cylinders using

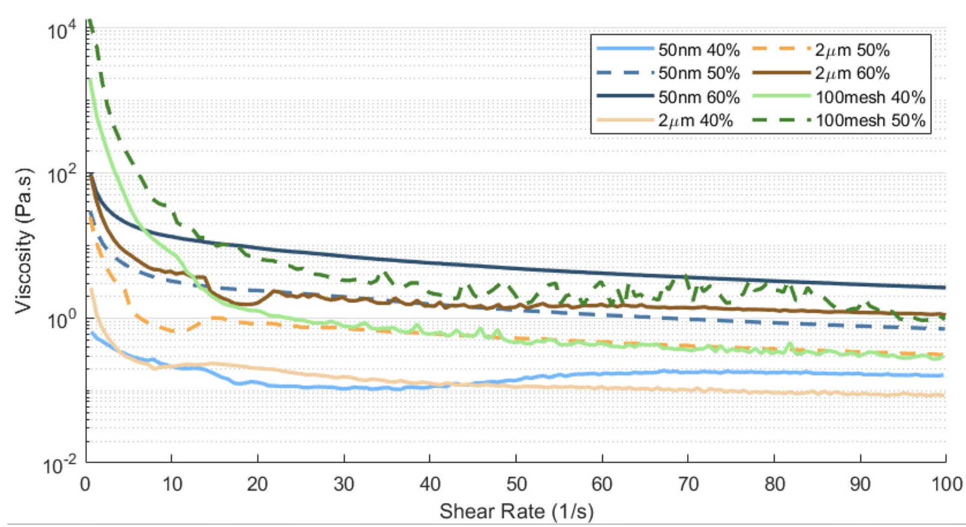


Fig. 13 Viscosity plotted against shear rate for 50 nm, 2 μm and 100 mesh particle sizes of hematite, 25 °C

Fig. 14 Yield shear stress plotted against oxide wt%, for 50 nm, 2 µm and 100 mesh hematite particles, 25 °C

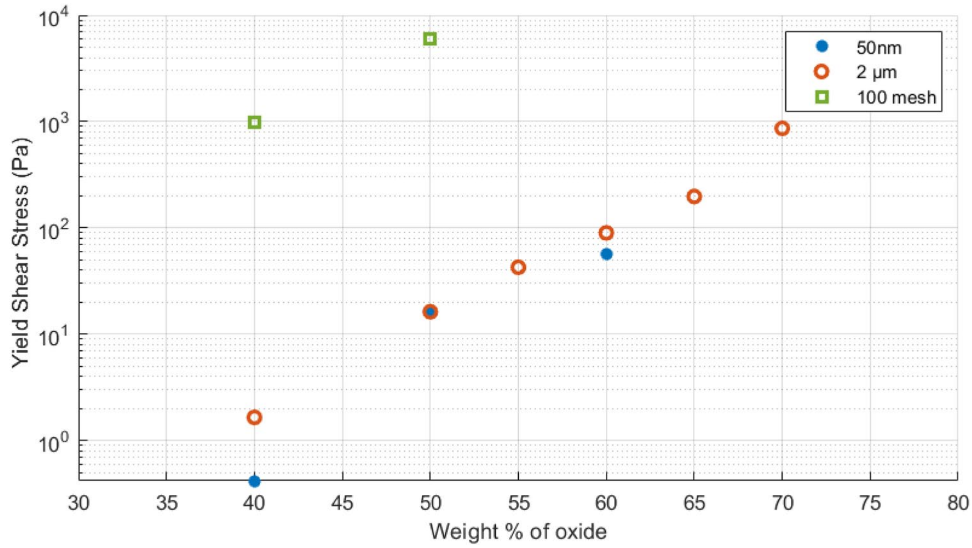


Fig. 15 Yield shear stress plotted against oxide wt%, for hematite (2 µm), lepidocrocite, magnetite and goethite, 25 °C

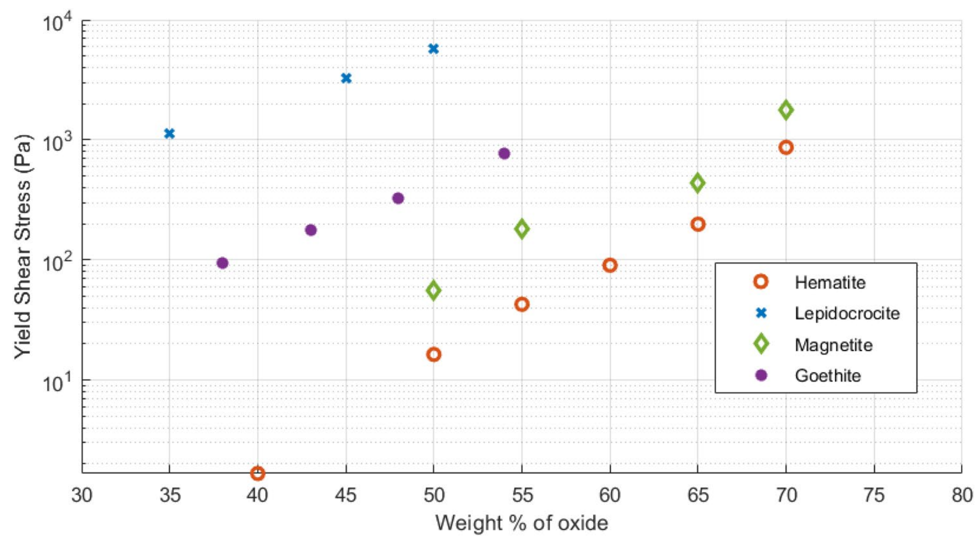
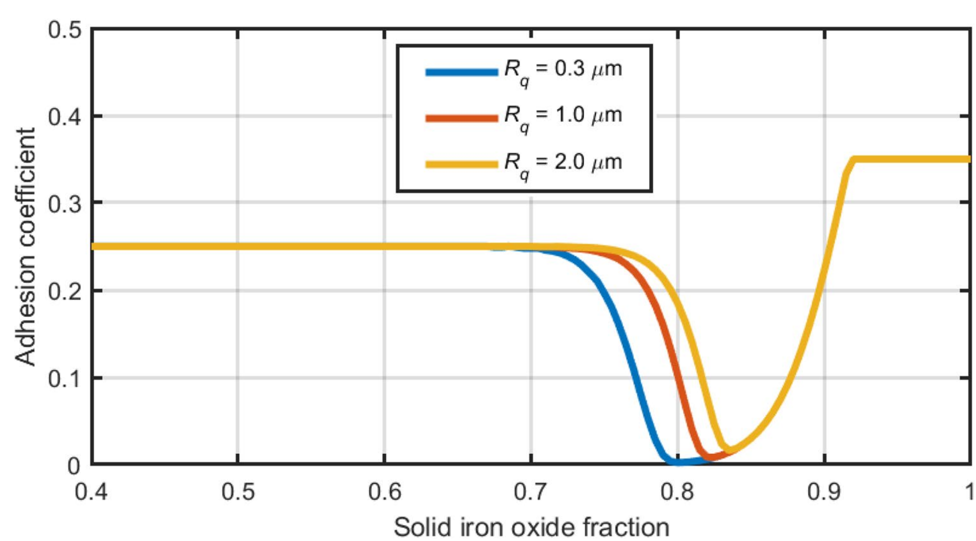


Fig. 16 Modelling results using extrapolations of the data presented in Fig. 9, at different roughness values



Hertzian contact. The roughness and specimen separation inputs were modified to those that had been obtained in the experimental validation, as described in the next section.

The model was also updated with new predicted yield stress curves, created by extrapolating the results shown in Fig. 9. Results for the updated model outputs at R_q 0.3, 1 and 2 μm are shown in Fig. 16. The model retained a similar shape to the original shown in Fig. 3, but there was a shift in the predicted results so that the reduction in traction coefficient occurred at lower percentage weights, the traction minimum was now located at approximately 80 wt% (solid iron oxide fraction 0.8) rather than the original 97 wt% (solid iron oxide fraction 0.97).

Predicted yield shear stress curves for different oxide types were used as model inputs, created by extrapolating the results shown in Fig. 15 to assess how different types of oxides may affect the adhesion coefficient. The model outputs are shown in Fig. 17. The higher yield shear stress of the oxide–hydroxides in particular create an extended adhesion minimum. This supports data found in a previous paper, which identified high concentrations of goethite and lepidocrocite at railway sites which suffered from low adhesion issues [10, 22].

3.3 Experimental Verification

Hematite (2 μm particle size) and water pastes with solid oxide fractions from 0.3 to 0.7 were tested at 2% slip at 400 rpm and 1500 MPa, results are shown in Fig. 18 [14]. A box plot of average results, plotted against the modelling output for the results shown in Fig. 9, is shown in Fig. 19. Higher solid oxide fractions of hematite paste, up to 0.6 produced a lower traction coefficient. A solid oxide fraction of 0.7 produced a large spread of results due to difficulties in applying the viscous paste, but very low minimum traction coefficient values of 0.02 were seen when the paste entered the twin disc contact.

A layer of compressed hematite was present on the specimen surface after testing in sections, leaving the exposed metal layer underneath. These "pits" in the layer were

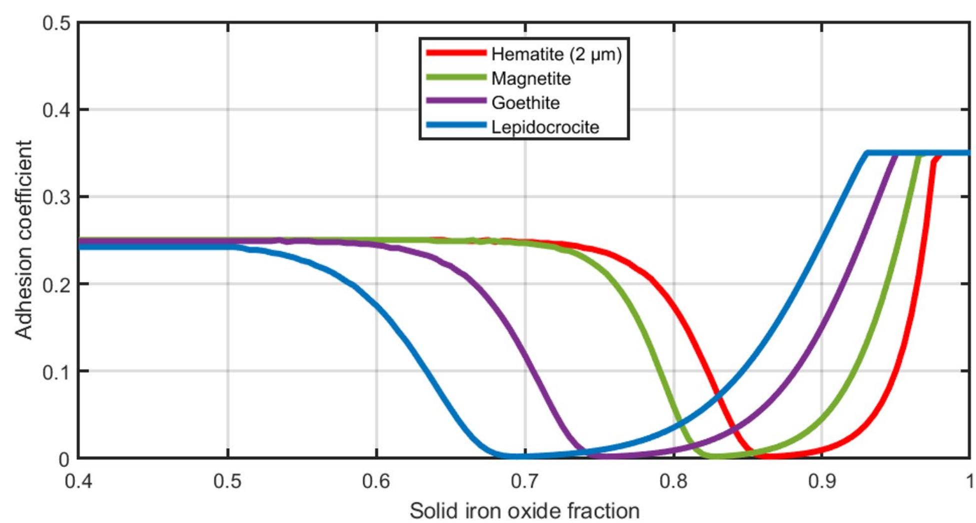


Fig. 17 Modelling results for different oxide types using extrapolations of the results presented in Fig. 15 at R_a 0.3 μm

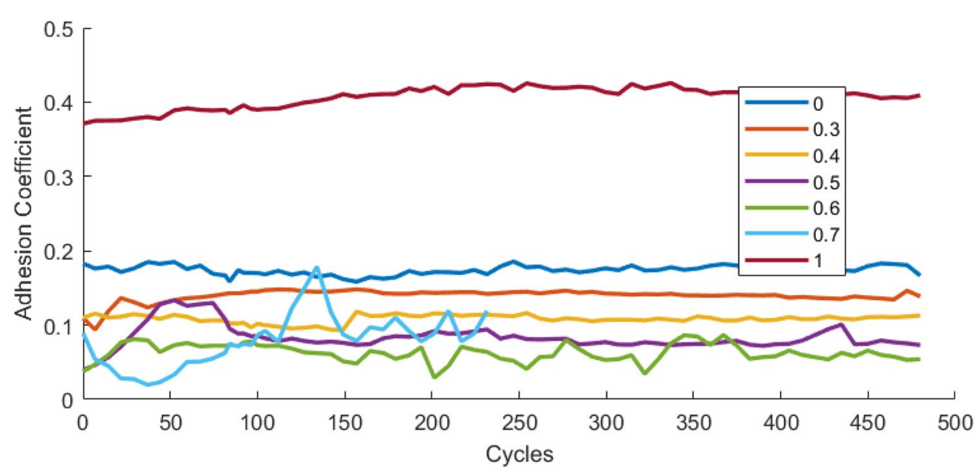


Fig. 18 Raw results for twin disc testing for different solid oxide fractions of hematite, from the results shown in [14]

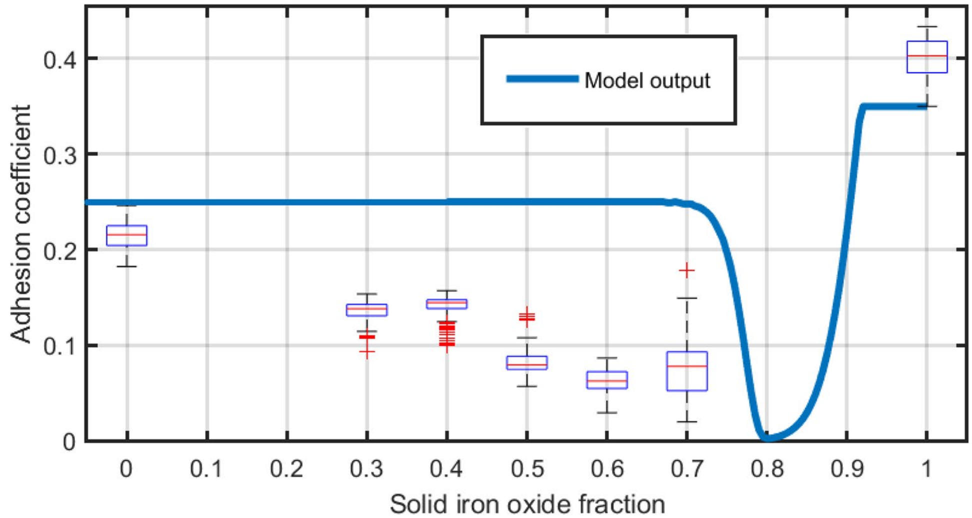


Fig. 19 A box plot showing experimental results from Fig. 18, plotted against the modelling output for R_a 0.3 µm presented in Fig. 9

analysed using the Alicona 3D profilometer and found to be 12 ± 0.05 µm deep which may provide an indication of the paste thickness during these tests. The roughness of the specimen discs became lower throughout the test, with an initial combined wheel and rail roughness (R_a) of 0.8 µm for the lateral direction (perpendicular to rotation direction) and 2 µm for the longitudinal direction (parallel to rotation direction). This is comparable to a run-in rail sample from a previous study [18]. When specimen discs for the 0.6 solid fraction hematite paste were stopped after 400 cycles they were found to have a lower combined roughness of 0.7 µm in the lateral direction and 0.8 µm in the longitudinal direction, averaged over 5 locations in the sample.

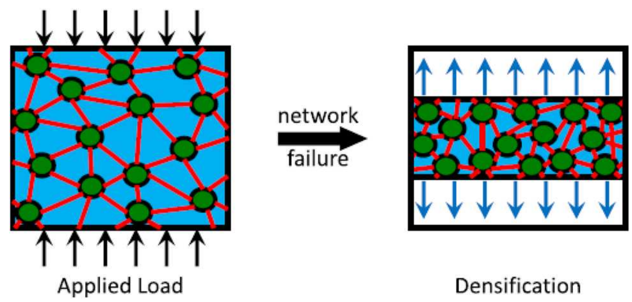


Fig. 20 The de-watering process after network failure [23]

4 Discussion

4.1 Rheometry

The biggest difference between the results from the modern rheometer and the rheometer used in the previous study is that the rheometer used in this work cannot recreate the pressure of the real wheel–rail contact. However, the yield shear stress results produced are all higher than those obtained previously [6] and would likely become even higher still if the pressure could be increased to representative values, as there would be preferential squeezing out of the water component in the paste (de-watering) and a higher chance of particles locking together.

A schematic of the de-watering process, where the applied load exceeds the network strength between oxide particles [23], is shown in Fig. 20. The solid phase is loaded and differential compression occurs, which causes liquid to escape and densification of the remaining iron oxide.

As in the previous tests, there is still a rapid increase in yield shear stress as the solid oxide fraction increases.

The viscosity of oxide suspensions tested decreased throughout the tests. This decrease in viscosity could be due to time dependent shear thinning behaviour, where movement between particles becomes easier over the test duration due to the breakdown of the electrostatic network between particles as shear occurs. This may also explain the hysteresis behaviour seen, where the viscosity is lower on the decreasing rate than the increasing rate due to the particles already having been in motion during the increasing shear rate. Alternatively, shear heating may play a role with the temperature of the fluid increasing throughout the test due to the high shear rate, which would also explain the hysteresis effects. Further experiments would be required to better understand this and determine whether these effects would occur in the real wheel/rail contact.

All the oxide pastes used in this work show shear thinning to some extent, with the higher percentages exhibiting Bingham pseudoplastic behaviour, with a high yield shear stress. The plots of shear stress and shear rate can be split into three categories. In the mildest cases, such as the 50 nm oxide powder at 50 and 60 wt%, typical shear thinning is represented by a gentle curvature of the shear stress against shear rate plot in Fig. 13.

Departures from this typical behaviour occur with oxide powders such as the 2 µm at 50 and 60 wt%. The decrease and then subsequent recovery of shear stress with increasing rate suggest that a time-based change such as de-watering occurs, similar to that seen in the 50 and 60 wt% hematite in Fig. 10.

Different behaviour is seen in the 100 mesh samples at 40 and 50% in Fig. 12, where a very high yield shear stress is observed before a rapid decrease. This is likely an example of the pastes developing a network structure under quiescent conditions and producing an increase resistance to shear. This could be due to the electrostatic interactions between these particles, or increased interactions due to the more angular shape of the 100 mesh particles.

During these tests, the oxide–hydroxides, goethite and lepidocrocite produce higher yield shear stresses than the hydroxides magnetite and hematite. This is likely due to stronger interactions between water and the oxide–hydroxides, which would play a role in oxide behaviour on the railhead and therefore affect the wheel–rail contact.

The different types and particle sizes of iron oxides have produced very different paste properties. The more angular particles, as well as the oxide–hydroxides with stronger interactions with water, produce the pastes with the highest yield stress for their respective solid oxide fractions. A further study to collect and analyse railhead oxides and other debris from the field would be useful as a comparison, especially if taken from sites of prevalent low adhesion.

The results show that at least in the case of hematite, only the pastes with a high yield shear stress cause very low adhesion and the variation in rheometry results with different types of iron oxides helps explain why the wet-rail phenomenon remains so difficult to predict.

4.2 Modelling

As a result of the twin disc work, the roughness, layer thickness and baseline wet traction coefficient could be updated in the model. The rheometry work produced new results for shear yield stresses of different oxide types which were also added. Changes to the model affect the initial "wet" traction coefficient and shift the adhesion minimum but the trend in adhesion coefficient remains the same. There is a very sudden reduction in traction coefficient at a certain weight percentage of paste, followed by a steep rise back up to dry values. This reduction, which on the railway would resemble the transient adhesion minimum before the wheel/rail contact dries, is observed in Beagley's initial work [6], as well as a more recent twin disc study using wear particles [24]. The model using the updated input variables predicts a low adhesion zone at a 2 µm hematite solid weight fraction of approximately 0.8, whereas low adhesion occurs at lower solid fractions for the experimental results.

The effect on the model of different shear yield stress curves, extrapolated from rheometry results using other types of iron oxides has predicted changes in the adhesion minimum. The oxide–hydroxides produce an extended adhesion minimum compared to hematite and magnetite. In the case of the wet-rail phenomenon (occurring under transient conditions as the rail moves from a wet to a dry state) the oxide–hydroxides would cause low adhesion for a longer period of time than the oxides. This supports a previous study where a high proportion of oxide–hydroxides were found in a mountain tunnel suffering from regular low adhesion problems [10]. The modelled friction coefficient minimum for all oxide types was below the value of 0.09, which is required for sufficient deceleration on the UK network [25].

The dynamic effects of the twin disc rig, in comparison to quasi-static HPT testing, will likely change the layer thickness of oxide paste in the contact and move the adhesion minimum, but it is unclear by how much. However, qualitatively the model is in agreement with the adhesion results from the SUROS test rig. Thus, it seems to consider the most important physical phenomena even if refinements are needed.

The second dynamic effect, separation of oxide paste into water and hematite, is one that has been seen using the rheometer and during SUROS tests. Water has been seen during testing to be squeezed out preferentially to the hematite and therefore increasing the concentration of hematite in the contact. This is visible in the experimental results, where lower hematite weight percentages still reduce the traction coefficient, possibly due to water being squeezed out preferentially which increases the hematite weight percentage in the contact. A compressed layer of hematite is formed on the SUROS discs during testing, which supports this hypothesis.

The adhesion model can be used in future to qualitatively assess the role that different oxide characteristics play in reducing adhesion. In particular, it is able to show the range of conditions that may present an adhesion minimum under different oxide types, which could be used in further work alongside railhead oxide measurements (using railhead swabs or in situ spectroscopy) to assess the likelihood of the wet-rail phenomenon occurring at different times and locations on a railway.

4.3 Experimental Validation

The experimental results showed that hematite and water, when mixed into a paste, are able to produce very low traction conditions that simulate the wet-rail phenomenon. A decrease in traction coefficient with increasing wt% between 0 and 70 is observed, with a very low traction coefficient minimum of 0.02 being achieved when the 70 wt% paste entered the contact. In comparison, the modelled traction coefficient remains as a wet value until a rapid decrease at a solid oxide fraction of approximately 75 wt% hematite, where the traction falls to the very low minimum of 0.01 before rapidly rising up to very high traction coefficient at approximately 85 wt%.

The surface of the twin discs will increase in temperature throughout the tests [26]. However, the short test duration, addition of additional paste throughout the test and relatively stable traction coefficients observed show that thermal effects are unlikely to play a significant role on the resulting traction coefficient.

The experimental results show a more gradual decrease in traction coefficient than the model, even 30 wt% hematite shows a slightly lower traction coefficient than water alone. It is important to note that the solid oxide fraction of hematite paste added to the SUROS contact is not necessarily the fraction that will be present in the contact. A compacted layer of hematite was present on the discs after testing so the suspension had separated to some extent in the contact and water was pushed out of the contact preferentially to the hematite particles. This concentrated layer of hematite particles may explain why even 30 wt% hematite suspension was able to lower the traction coefficient compared to water alone, even if the model predicts otherwise.

This preferential squeezing out of water (de-watering) that is observed in both the rheometry and the twin disc testing is important when looking at these results in the context of the wheel/rail interface. Under wet conditions the iron oxide and other wear debris is either washed off the railhead or pushed aside by the passage of the wheel. Solid material, or that with a water content that is too low is also pushed aside by the wheel passage which is why under most operating conditions a clean and shiny wear band is observed. This was also observed in the twin disc testing, where a solid oxide fraction of 0.7 "bounced" off the twin discs rather than sticking to them and being pulled into the contact. It is at a critical point, where the iron oxide has a sufficient yield strength to form a layer and is also pliable enough to sustain the deformations caused by the wheel passage where the wet-rail phenomenon will occur [6].

It was difficult for the solid oxide (hematite) fraction of 0.7 to enter the contact as it was not sufficiently pliable and was simple pushed aside by the twin discs. Because of this, no higher oxide fractions were tested. However, when a small amount of it did enter the contact, the lowest traction coefficients observed in this testing were recorded as seen in Fig. 18.

This may mean that the preferential squeezing out of water is necessary for the wet-rail phenomenon to occur. A higher water content may be required for the paste to stick to the running band and not be pushed aside by the passage of the wheel, but the yield strength of this may not be high enough to cause separation of the wheel and rail without further water removal (which is achieved through compression and shear of the paste during wheel passage).

The model predicts that the traction coefficient will only drop to very low values when the combined roughness of the wheel and rail is low. Mild wear occurs and the twin disc specimens naturally become smoother when paste is added during the test. The low roughness values seen during the tests are similar to those collected during a previous railway study, which found that the roughness of wheel and rail was high after grinding, but decreased rapidly [18].

The measurements of oxide layer thickness allow the generation of approximate values that can be fed into the model but need to be treated carefully, as the thickness of oxide layer after disc contact may be different from that in the contact itself due to evaporation of water or damage during transportation.

5 Conclusions

Using a combination of rheological measurements, adhesion modelling and twin disc traction testing this work provides novel information of the role that different types, particle sizes and moisture content of iron oxides play in affecting the friction coefficient when present as a paste in the wheel/rail interface. It helps explain the transient and unpredictable nature of the wet-rail phenomenon and could provide a step towards predicting when, where and whether the wet-rail phenomenon may cause low adhesion problems.

This work has extended the adhesion model to cover a range of iron oxides, as well as providing new experimental inputs and assessed the validity of the model alongside experimental results. The updated adhesion model followed a similar pattern to the previous version, but showed a reduction in traction at lower weight percentages of hematite paste than previously predicted. The model could not be entirely modified to suit the dynamic SUROS contact but predictions were made to how these would affect the output. The model was expanded to include a range of iron oxides and oxide–hydroxides, which expands its usability for future applications and provides a novel study on how the wet-rail phenomenon may vary due to oxide type. Based on the rheology data collected in this work, the model predicts that the low adhesion minimum for the oxide–hydroxides will occur for a wider range of solid oxide fractions than for the oxides.

In a real railway situation, on a railhead that is transitioning through the critical point between wet and dry, the presence of these oxide–hydroxides could result in the wet-rail phenomenon occur more regularly, over a longer time period and over a wider window of conditions. Further twin disc testing, comparing the oxides to the oxide–hydroxides, would be useful to support this hypothesis.

Both the experimental and modelling work in this paper explain why the wet-rail phenomenon will occur in a narrow band of conditions and show that water content of the third body layer on the rail surface will play a large role in dictating adhesion conditions. De-watering of the oxide paste is observed in both the rheometry and the twin disc testing, which has led to a new hypothesis of the railhead conditions needed for the wet-rail phenomenon to occur. On a drying railhead, or if the rail is dried due to the passage of wheels, the point at which low adhesion will occur would be difficult to predict. The traction coefficients seen in both the model and experimental results are low enough to cause significantly low traction issues on a railway and this is supported by field observations, where the wet-rail phenomenon occurs irregularly and unexpectedly, but can have severe consequences.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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