LABORATORY INVESTIGATION INTO WHEEL/RAIL ADHESION

by

T.M. BEAGLEY

Thesis submitted to the University of Leicester for the degree of Doctor of Philosophy

June, 1975

UMI Number: U421311

All rights reserved

INFORMATION TO ALL USERS The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript

and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



UMI U421311 Published by ProQuest LLC 2015. Copyright in the Dissertation held by the Author. Microform Edition © ProQuest LLC. All rights reserved. This work is protected against unauthorized copying under Title 17, United States Code.



ProQuest LLC 789 East Eisenhower Parkway P.O. Box 1346 Ann Arbor, MI 48106-1346



THESIS -+88154 6.10.75

PREFACE

The work reported in this thesis formed part of an overall investigation into Wheel/Rail Adhesion by the Tribology Section of the Railway Technical Centre, Derby. My own laboratory experiments would not have been possible without the help of the other members of the Research Team, to whom I am indebted. The author also wishes to thank the British Railways Board for their permission to publish this thesis.

My thanks are due to Dr. Beazley (English Clay Lovering Pochin & Co Ltd.), Mr. Pinfold (Bostik Ltd.) and Dr. Cheng (Warren Spring Laboratories) who kindly discussed the implications involved in the rheological measurements, and to Mrs. Baglin for her help in considering the hydrodynamic equations.

The author is also extremely grateful to his two supervisors Dr. C. Pritchard (Head of Tribology Section, B.R.) and Dr. J.F. Archard (Leicester University) for their help, encouragement and inspiration.

Thanks are finally due to my wife, Mary, for her patience and understanding.

CONTENTS

.

Page

Preface			rugo	ii
CHAPTER	1	INTRODUCTION Introduction	1 1	
	1.2	Adhesion, a Railway Problem	1	
	1.3	Experimental Approach	3	
			_	
CHAPTER	2	LABORATORY SIMULATION	5	
	2.1	Introduction	. 5	
	2.2	Rolling Disc Tribometer	0	
	2.3	Correspondence with Track Measurements	Ö	
	2.4	The Amster Wear Machine	0	
, ,	2.5	The Greep Curve	10	•
CHAPTER	3	LABORATORY STUDIES OF THE EFFECTS OF OILY FLUIDS ON FRICTION	12	
	3.1	Introduction	12	• '
	3.2	Boundary Lubrication	12	•
	3.3	Characterisation of Oils by Chromatographic	14	
•	2 /	Separation Friction Measurements	16	· •
	$3 \cdot 4$	Friction of Oils	16	
	3.4.2	Friction of Separated "Oil Fractions"	17	
·.	3.4.3	Friction of Mixtures of Materials	18	
	3.5	Oxidation and Shear of Track Oils	. 22	. •
	3.6	Conclusions	24	
		LADOL TODY COUNTED OF THE DEPENDENCE OF COLT	0 5	
CHAPTER	4	LABORATORY STUDIES OF THE EFFECTS OF SOLID DEBRIS ON FRICTION	25	
•	4.1	Introduction	25	
	4.2	Laboratory Experiments on the Rolling	25	
•••	4	Disc Tribometer	-5	
	4.2.1	Experimental Method	25	. •
	4.2.2	Experimental Results	26	
	4.2.3	Discussion	27	
	4.3	Laboratory Experiments on the Amsler Wear Machine	29	
	4.3.1	Experimental Method	29	
•	4.3.2	Experimental Results	30	
	4.3.3	Discussion	30	
	4.3.4	Relevance of Dynamic Results	31	•
	4•4	Conclusions	<u>्</u> 31	
CHAPTER	5	LABORATORY STUDIES ON THE EFFECTS OF WATER ON FRICTION	32	, , .
	5.1	Introduction	32	
	5.2	Results on the Rolling Disc Tribometer	32	
	5.3	Discussion of Results obtained using Rolling	34	
		Disc Iribometer	<u>a</u> (/ .
	5•4	in Water	30	/ ,
	5.5	Washing Experiments	37	1
	5.6	Friction Results using the Amsler Wear Machine	38	
	5.6.1	The Effect of Humidity under Dynamic Conditions	38	
· ·	5.6.1.1	1 Experimental Method	38	
	5.6.1.2	2 Experimental Results	40	
	5.6.2	The Effect of Water under Dynamic Conditions	41	
	5.6.2.1	1 Experimental Results	41	
	5.6.2.2	2 Experimental Results on the Effects of Oil	43	
		and Water		

iv

	•		
	5.6.2.	3 Experimental Results on the Disc-Cylinder	43
· · ·		Rig	
	5.6.2.4	1 Discussion of the Effect of Water under Dynamic Conditions	44
	57	Discussion	45
	J•/	The Influence of Humidity	45
	5.7.1	The Influence of Natau	40
	5.7.2	Ine inituence of water	47
	5.7.3	The Friction of Slightly Wet Surfaces	4/
	5.8	Conclusions	48
CHAPTER	6	THE RHEOLOGY OF RATE CONTAMINANTS	50
	6 1	Introduction	50
·	6.0		- <u>r</u> o
	0.2	IFACK RESULTS	50
	0.3	Laboratory Experiments	52
	6.4	Basic Friction Equations	53
	-6.5	Yield Shear Stress	55
	6.6	Yield Shear Stress of Common Track Contaminants	56
	6.7	Discussion of Solid Track Contamination	58
	6.8	Flow Properties of Oxide/Water Mixtures	59
	6.0	Discussion of the Rheological Properties of	61
	~• /	Oxide /Water Mixtures	•1
•	6.10	Theoretical Analysis of Hydrodynamic Lubrication	63
· .		between Wheel and Rail	Ū
	6.11	Discussion of Hydrodynamic Lubrication	67
	6.11.1	The Amsler Machine	67
	6.11.2	Hydrodynamic Lubrication on the Track	68
	6 11 2	Hollow Wheel Profiles	60
	6 12	Conenal Discussion	70
	6 12	Demodies	70
	6 14		72
	0.14	Conclusions	13
CHAPTER	7	GENERAL DISCUSSION AND CONCLUSIONS	74
	7.1	Introduction	74
	7.2	Laboratory Experiments	74
	7.2.1	Oil	74
	7 2 2	Dehris	76
	7 2 2	Waten	78
	7.2.5	Matci An Aggaggment of the Johansterry Simulation	70 .
	7.3	An Assessment of the Laboratory Simulation	/9
-	7.3.1	Laboratory Test Rigs	80
	7.3.2	Comparison of Track and Laboratory Results	81
	7.4	Wheel/Rail Adhesion	83
·	7.4.1	Track Contamination	-84
	7.4.2	Loss of Adhesion and its Prevention	85
	7.5	Conclusions	87
APPENDIX	1 – REI	TERENCES	89

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Friction between railway wheels and rails ("adhesion") is fundamental to railway operation; without it locomotives could not pull trains nor be able to stop. Engineers have investigated adhesion since the conception of the railways and, although empirical methods of improving adhesion (such as the use of sand) have been tried, a more basic understanding of the phenomenon has proved elusive. In 1968 British Railways instigated a comprehensive investigation into the basic parameters affecting wheel/rail adhesion. The coefficient of friction found between clean dry steel surfaces (0.6 to 0.7) was known to be much higher than that usually found between wheels and rails (0.2 to 0.4). It was therefore decided to study the track contamination in detail and to survey adhesion using track tribometers. This information could then be used in a laboratory simulation, where the various parameters and conditions affecting wheel/rail adhesion could be carefully controlled. My own laboratory experiments, which form the basis of this thesis, were part of this overall investigation and would not have been possible without the help of the other members of the Research Team.

1.2 ADHESION, A RAILWAY PROBLEM

The 'coefficient of adhesion' is a railway term for the effective coefficient of friction between a wheel and the track; i.e. the maximum tangential force that can be exerted at the rail contact before gross sliding occurs, divided by the normal static load on the wheel. The coefficient of adhesion is found to decrease with speed but this does not imply that the coefficient of friction between the wheel and rail has decreased. The variation found between jointed track and continuous welded rail (Marta and Mels 1969) and between different locomotives (Kraft 1968) when examining the adhesion/speed relationship suggests that the decrease may be due to the vertical dynamic response of the wheels. It can be anticipated however that a decrease in the static coefficient of friction will also cause a fall in the adhesion of a locomotive travelling at speed. This thesis is basically concerned with variations in the fundamental coefficient of friction rather than dynamic effects. However in the later chapters the velocity of the train is shown to be important under some circumstances which are not associated with dynamic variation in load between wheel and rail.

The predictability and magnitude of the coefficient of adhesion is important in many aspects of railway operation. The available adhesion will determine the load a train can pull up a gradient as well as its stopping distance. Trains are generally loaded assuming a minimum coefficient of adhesion of 0.2. As a safety measure, however, stopping distances are calculated assuming a conservative coefficient of adhesion of 0.07 - 0.09. These design parameters are the optimum values adopted by railway engineers after years of operational experience. However, problems do occur. Over heavily utilised routes punctuality can be affected by slipping locomotives. Occasionally adhesion is so low that trains slip past signals. The major cost to BR due to the loss of adhesion is the provision of banking engines on some inclines and the damage that occurs to traction motors and to wheels and rails. A wheel that develops a flat from skidding along the track must be returned, and rails that develop "burns" due to wheels skidding and spinning must be replaced to improve the ride and prevent incipient cracks developing into rail fracture. The cost of the latter has recently increased dramatically due to the adoption of continuous welded rails.

The modern generation of train design imposes further demands on adhesion, faster trains requiring higher adhesion to stop within present signalling distances. Furthermore, recent developments in train suspension utilise lateral adhesion, at right-angles to the track, on curves (Wickens 1973). The Advanced Passenger Train is designed for high speed travel on present

- 2 -

track, unlike the Japansese trains that require their own straight track. The flange contact that usually occurs during curving is prevented on the APT by forces, generated by a new wheel profile combined with those due to lateral adhesion, that help steer the relatively soft suspension around the curve.

It is hoped that the study of adhesion in this thesis will not only help improve the efficiency of present railway operation but will also lead to methods of increasing adhesion. Fluids designed to improve adhesion may either be squirted onto the rail by lineside applicators situated where high adhesion is demanded e.g. steep inclines, or be applied from train mounted devices during acceleration or braking. Devices have been experimented with for many years but no fluid has yet proved successful. The results described in this thesis provide a new basis for choosing such a fluid. Any method guaranteeing adhesion above 0.2 will have a tremendous impact on ER. Even improvements of the order of 0.02 would result in large financial savings from the increased train loads and the reduction in wheel and rail damage that would be achieved.

1.3 EXPERIMENTAL APPROACH

Fig. 1.1 shows a replica of the debris coverage of a typical main line track, obtained by applying a piece of foam backed adhesive tape to the rail. The central portion along which most train wheels run is termed the wear band and has a bright metallic shine. There is very little solid debris on the wear band compared with the more heavily corroded areas at the side. This type of track is also typically covered with the equivalent of a few monolayers $(2 \times 10^{-7} \text{ gm/cm}^2)$ of oily contamination (Broster et al 1974). Oil contamination can occasionally be several / orders of magnitude more substantial when lubricants drip from trains or where flange lubricators apply grease to the side of the track to prevent flange wear. The solid contamination on the wear band is basically rust (Beagley et al 1975,2) and its coverage is dependent on track utilisation. A typical analysis shows a large proportion of iron oxide (Fe₂0₃), some hydroxides and small quantities of metallic iron. Occasionally rails can also be contaminated with other extraneous matter such as leaves or cement. Naturally the wear band is also wet when it rains or when dew forms on the rails. Adhesion may also be influenced by the relative humidity of the surrounding air.

Track contamination can therefore be broadly divided into three categories, oil, water and solid debris. The frictional phenomena associated with each one of these groups were examined in the laboratory. The interactions were then explored so that a comprehensive description of wheel/rail adhesion could be established. Concepts of boundary lubrication are applicable to a wide range of conditions when surfaces are contaminated with oil and/or water. However these concepts are shown to have their limitations when solid debris is trapped in the contact area. Serious losses of adhesion can occur under these conditions when small quantities of water mix with the solid debris. These effects have been reproduced in the laboratory and a new theoretical explanation for them has been developed.

- 4 -



FIG. I. I. TAPE REPLICA OF RAIL SURFACE.

CHAPTER TWO

LABORATORY SIMULATION

2.1 INTRODUCTION

In Chapter 1, the physical quantities of track contamination were found to be small (monolayers of oil and $\approx 1 \times 10^{-4}$ g/cm² of solid debris). This contamination together with the surrounding atmosphere controls the track adhesion. Clearly, controlled experiments could not be carried out in situ, so laboratory rigs were used to simulate track conditions. The conditions to be simulated are those encountered by a locomotive wheel, which typically supports a load of 100 kN (10 tons) and has a diameter of about 1 m (40 in.). The rail head is curved in crosssection with a radius of 0.3 m. The rail surface contacts the wheel over an elliptical area about 150 mm² in size, and with an average pressure of 650 MN/m^2 (40 tons/in²). The roughness of the wear band on main line track is usually between five and ten micro-in C.L.A; that of wheels sometimes exceeds 200 micro-in C.L.A. with the high asperities being worn flat (Broster et al 1974).

The majority of the experimental work was performed on the two rigs described in this chapter. The rolling disc tribometer was especially designed by the author as a machine, of simple design, on which it was possible to explore the influence of a large number of factors upon adhesion. The other rig was a standard Amsler wear testing machine. Further rigs used in the investigation are described at the relevant points in the text.

Both machines measure the friction between steel specimens, which represent the wheel and rail, and can be readily conditioned to simulate the presence of rail head contamination. Although relatively light loads are employed, contact pressures, close to those of the practical situation, are reproduced by virtue of the small contact areas. The contact size was considered to be the least important of the parameters to be reproduced, full scale simulation being impracticable. Although both machines use rolling components, the rolling disc tribometer essentially measures static friction whereas the Amsler machine provides continuously rolling surfaces.

2.2 ROLLING DISC TRIBOMETER

The specimens used in this rig (Fig. 2.1, 2.2) are a 152 mm (6 in.) diameter disc and a flat plate over which the disc rolls. The disc is weighted so that there is a normal load N between the specimens of 11.3 kg wt (25 lb). The edge of the disc is crowned with a radius of 76 mm (3 in.) and this results in the average Hertzian contact pressure between disc and plate being about 240 MN/m^2 (16 tons/in²) about one third of that between a locomotive wheel and the rail. However, the contact area is only 0.46 mm² (7 x 10⁻⁴ in²), about three hundred times smaller than that of a locomotive.

Friction measurements are made by pulling by hand at point 0 on the lever' attached to the disc. The disc rolls forward and extends the spring balance which exerts an increasing retarding force. Finally the disc slips rather than rolls against the plate and the reading, \mathbf{x} , of the spring balance is noted. By trial, the initial position of the disc can be adjusted so that the operating lever is vertical when gross slip occurs. Then, taking moments about 0 (Fig. 2.1)

$\mathbf{x} \mathbf{x} \mathbf{s} = \mathbf{F} \mathbf{x} \mathbf{t}$		Fxt	where $F = friction$ for		
Now, µ	=	<u>F</u> N_		N = normal loa	d
μ	-=	xs Nt			•

The disc rolls 25 to 50 mm before gross sliding occurs. To achieve similar rolling distance when the friction varies widely, spring balances of different strengths are used. Different specimen materials can be used. The flat plate specimen is easily replaced, the rolling disc less easily. Tests have been made with discs of tyre steel (BR Spec. No. 100) and of En.58 stainless steel. Plates have been used manufactured from rail steel (BS.11) and stainless steel.

To clean the specimens, the procedure finally adopted is to abrade the surface to a surface finish of about 25 micro-in. C.L.A. $(0.6 \times 10^{-0} \text{ m})$ with No. 2 grade (60 grit) emery paper and then to clean with solvent. Several times during the abrasion the specimens are wiped clean using paper tissues soaked in Analar grade acetone. The plates are then placed in a vapour degreasing apparatus in which pure iso-propyl alcohol vapour is condensed and allowed to drip over the specimen surface. The friction coefficient between surfaces prepared in this way is about 0.70 in dry air. Use of radioactive tracer compounds has shown that all but a fraction of a monomolecular layer of oil is removed by this cleaning technique. The plate is then treated with a known quantity of contaminant, such as oil or track debris, and is placed under the clean disc. Several measurements are made, each time the plate being moved laterally so that the disc rolls over a fresh track. In this way the disc becomes "equilibrated" and the contamination is shared between the disc and the plate. The later friction measurements, which achieve a constant value, are noted. The friction coefficient is determined in this way to an accuracy of about + 0.01. It is assumed that the contamination is evenly applied. The major source of error probably lies in achieving an even coating of the small quantities of contaminant involved. Oils are usually made up in a chloroform solution and sprayed from an aerosol bottle.

To study the effect of increasing ambient humidity, the apparatus is enclosed in a perspex box. The operating lever protrudes through a slot which is sealed by two rubber strips. Air is pumped into the perspex box after being bubbled through water, or through a drying agent, and the change in humidity is measured by a paper dial-hygrometer. Enough water vapour can be introduced to form dew, with water condensing over the apparatus. Alternatively, the air can be dried to below 1% relative humidity. 2.3 CORRESPONDENCE WITH TRACK MEASUREMENTS

The action of the rig is designed to simulate a locomotive starting a To determine how representative are its measurements, a temporary train. frame was built so that the apparatus could be taken out to measure friction on running rails. Several sites were chosen and the adhesion was determined using the laboratory rig alternatively with a portable track tribometer (Beagley et al 1971). Oils and other contaminants were sprayed on the rail surfaces to give a range of adhesion values. Figure 2.3a shows the correlation obtained between the two types of apparatus. On one site the measurements were compared with those of a locomotive which is instrumented to measure static friction by applying power to its leading axle until the wheels slip. Figure 2.3b shows the correlation between the measurements. They were obtained on a little used, worn The portable track tribometer had previously been compared with the track. locomotive in a similar way. The results of Figure 2.3a are included in Figure 2.3b by making use of this previous correlation to determine, from the track tribometer measurements, the adhesion that would be measured by the locomotive. The results obtained seemed to indicate that the action of the rolling disc tribometer simulated quite well the starting action of a locomotive.

2.4 THE AMSLER WEAR MACHINE

The Amsler machine (Fig. 2.4.) is a standard rig that can be used for a number of friction and wear experiments. Two discs (approximately 40 mm diameter and 10 mm wide) are mounted axially on two counter rotating geared axles and are loaded edge to edge so that they roll against each other. Greep (slide/roll ratio) in the contact area is governed by machining the rollers to predetermined diameters. The lower shaft rotates at 200 r/min, a factor of 1.104 1 times faster than the top shaft. A torque dynamometer on the input shaft enables the friction generated because of the creep between the rollers to be recorded.

- 8 -

Thus if rotational speed of top roller = ω

diam. of top roller = A

-- 9 --

diam of bottom roller = B

surface velocity of top roller = $\omega \times \pi \times A$ surface velocity of bottom roller = $\omega \times \pi \times B \times 1.104$ 1 and creep, in relation to bottom roller

 $= \frac{(\omega \times \pi \times B \times 1.104 \ 1) - (\omega \times \pi \times A)}{(\omega \times \pi \times B \times 1.104 \ 1)}$

. creep = $\frac{(B \times 1.104 \ 1) - A}{(B \times 1.104 \ 1)} \times 100\%$

Assuming perfectly smooth and aligned discs, the pressures produced by a given load can be calculated using Hertz's equations. e.g. for 50 kgm load, Po (maximum pressure) = 433 MN/m^2 (30 tons/in²) 100 kgm load, Po = 866 MN/m^2 (40 tons/in²)

The following procedure was adopted :-

The specimens, suitably machined to produce the desired creep, were mounted on the shafts. The rollers were then loaded together and run under dry conditions until the torque (friction) stabilised and the surfaces developed a characteristic, run in, appearance (Fig. 2.5). Fig. 2.4 also shows the variation in the coefficient of friction normally observed as the rollers were run in. Earlier exploratory measurements of friction showed a great deal of scatter until this running in procedure was adopted, which markedly improved the repeatability.

The reason why the friction varies during running in is not clearly understood, although various tentative mechanisms have been proposed (Krause 1971). The initial wear conceivably cleans the surfaces, allows the rollers to achieve greater conformity, and so causes the friction to rise. Subsequently the friction decreases as the slower roller is seen to develop a shiny metallic surface while wear debris adheres to the lower, faster roller. The lowering of friction is possibly because the accumulated wear debris has a low shear strength, in comparison to the thin oxide films initially formed by oxygen/iron diffusion. The accumulation of debris on the faster of the two rollers in this configuration has been observed by many workers. Dawson & Coyle (1969) described some simple simulation experiments using "Plasticine" as artificial wear debris. Small bits of "Plasticine" fed into the contact area always emerged adhering to the surface with the faster relative velocity. No mechanism for this accumulation of debris has been proven, although Heath (1972) suggests that nascent cracks in the debris, close to the surface of the slower disc, tend to open and grow, thus allowing the material to leave the contact area adhering to the faster surface. This mechanism has not been directly observed on the track, although it has been noted that the ascending rail on inclines tends to be cleaner than the descending line. This agrees with the laboratory observation, the rail being the "slower" of the two surfaces when the locomotive is exerting traction.

2.5 THE CREEP CURVE

At the rolling/sliding interface between a tyre and the rail, there are two important "friction" parameters; firstly the maximum friction that can be transmitted, which governs the maximum load a locomotive can haul and the maximum braking force that can be exerted; secondly the degree of slip associated with the transmission of a particular friction force, which is important when considering traction motor characteristics, vehicle guidance and rail/tyre surface damage (Wickens 1973). Both parameters are shown in the fundamental "creep curve" where the ratio (T/N) of the frictional force to the normal load is plotted against the rate of slip between the surfaces, expressed as a percentage of the rolling speed (known as "creep" or "slip").

Fig. 2.6 shows a typical creep curve obtained on the Amsler machine. At 3% creep the ratio T/N approaches the limiting coefficient of friction of the surface. Theoretical analysis by both Vermeulen and Johnson (1964) and Kalker (1966), predicts a steeper creep curve which reaches the limiting value at approximately 1% creep. In these theoretical models

- 10 -

slip is envisaged as occurring in only part of the contact area formed by two smooth surfaces. Nayak (1972) considered the contact formed by rough surfaces. Using this, more accurate model, he predicted shallower creep curves, similar to Fig. 2.6 and to measurements made on the track (Yokose 1973, Hobbs 1967).

In this thesis emphasis is placed on the limiting coefficient of friction. This is shown to be justified in Chapter 5 where the shape of the creep curve remains essentially unaltered as the limiting coefficient of friction between two surfaces is changed.



4/ 17644



FIG.2.2. ROLLING-DISC BENCH TRIBOMETER.



4/17645

•



RAIL STEEL 50K LOAD 3-2% CREEP

μ



FRICTION TRACE DURING RUNNING IN

FIG. 2 . 4 AMSLER FICTION AND WEAR MACHINE





FIG. 2.6. CREEP CURVE OBTAINED ON AMSLER.

P4/17646

FIG. 2.6.

CHAPTER THREE

LABORATORY STUDIES OF THE EFFECTS OF OILY FLUIDS ON FRICTION

3.1 INTRODUCTION

This chapter describes work carried out on oils. Friction measurements were made using the specifically designed rolling disc tribometer. 0n this, carefully controlled measurements could be made taking special precautions against unwanted surface contamination. Further tests on the chemical degradation of oils were made on the Amsler wear machine. Friction is found to depend sensitively on the amount of oil on the surfaces and, to a lesser extent, on chemical changes. Substantial chemical changes are detected in oils sampled from running rails. The adsorption characteristics of these oils are described, and analyses have been carried out which have enabled suitable chemicals to be chosen to simulate track contaminants in the laboratory experiments. The way in which mixtures of these chemicals govern friction has been studied in some detail. Results on the effects of water and debris on oily surfaces are described, in the following chapters.

3.2 BOUNDARY LUBRICATION

It has been calculated (Broster et al, 1974) that if the amount of oil found on running rails is assumed to be spread evenly over the surface then its thickness is of the order of the length of five oil molecules, $1 \times 10^{-6} \text{ gm/cm}^2$. Because this is such a thin layer the chemical nature of these molecules is assumed to be of greater importance than are the bulk physical properties of the oil, and lubrication is then of the type which is termed "boundary lubrication". *Equily* investigations (Bowden and Tabor, 1950) into boundary lubrication indicated that the coefficient of friction on a metal surface was reduced to about 0.1 by the application of as little as one monolayer of lubricant. Our surveys show there is enough to form more than one molecular layer on running rails and yet the average adhesion is as high as 0.30. Clearly it is desirable to investigate why this should be so. If it is accepted that the oils on rails act as

- 12 -

boundary lubricants, several theories can be invoked to describe how such lubrication takes place. A simplified summary of the generally accepted features is as follows :-

Metal surfaces clean of oil and with no oxide present weld when sliding against each other and the friction coefficient is greater than 1.0. Normal surfaces are covered with oxide which acts as a barrier so that, although some metallic welds are formed, most friction is due to oxideoxide interaction and, in the absence of oil, the friction is about 0.7. The strength of the oxide interactions is possibly weakened by increased humidity or by becoming wet with water and this may explain, at least in part, why adhesion on rails is reduced in wet conditions. Oils on the surface will also affect the strength of the oxides although boundary lubrication has usually been explained on the basis of the oil forming strongly bonded surface layers. The "strength" of these layers, a measure of how effective they are in preventing contact between surfaces, is greater when the oils are surface-active. Surface-active oils may therefore be expected to cause the lowest friction. However, friction may also be governed by the closeness of the packing of the oil molecules. This can depend on the shape and length of the molecules involved, which are sometimes envisaged as standing away from the surface rather as bristles on a brush (Fig. 31 gives a pictorial representation). The longer straight chain molecules are usually thought to provide lower friction coefficients. From a simple mixture of two oils, the most surface-active will theoretically adsorb in preference on a metal surface. It may then be expected that the lubricating properties of the mixture will be governed by the properties of the most surface-active constituent. With more complex mixtures, all types of molecule will compete for the available surface sites and the friction properties of the resulting adsorbed layers may then be intermediate between those of the best and the worst lubricants.

3.3 *CHARACTERISATION OF OILS BY CHROMATOGRAPHIC SEPARATION Rails are contaminated with fuel oil and various lubricants that drip from passing trains, as well as greases that are applied directly to the track from flange lubricators. However, compared with a fresh mineral oil, the fluids sampled from running rails are generally darker in colour, more viscous, and the proportion of surface-active compounds is much greater (Beagley et al 1975,1). The oily contamination undergoes accelerated oxidation while spread thinly on the rail surface, and because the fluid is a very complex mixture full analysis is impracticable. The oils have consequently been characterised largely by their adsorption behaviour. The oils are separated into three or four "fractions" according to the strength with which they adsorb on silica gel (Jenkins and Humphreys 1955). Table

3.1 shows the proportions separated from an unused lubricating oil (Talona 945), the same oil oxidised by being held at 180°C for 12 hours while having air bubbled through it in the presence of iron filings (which possibly simulates the effects of a rail surface), and typical oils sampled from the track. It is evident that the proportion of surface-active matter in the oily contamination sampled from the track is even greater than in the oxidised oil.

TABLE 3.1

	Proportion of Oil in :-				
011	Wt of Sample (grams)	Least - Active Fraction (%)	2nd Fraction (%)	Most Active Fraction (%)	Total Recovered (%)
Unused lubricating oil	0.497	67.5	25.9	2.0	95.4
Oxidised lubricating oil	0.483	60.7	23.6	12.6	96.9
Oils sampled from track	0.1	30–60	5–20	2050	80

SEPARATION OF OILS INTO THREE FRACTIONS

* I am indebted to Dr. I.J. McEwen for examining the chemical nature of the oils which supplements my own measurements of their frictional properties.

- 14 -

The first, least active, fraction is eluted by heptane and is almost always a colourless or light, straw-coloured, clear liquid of relatively low viscosity. Analysis has shown that it is usually made up of an almost pure mixture of aliphatic branched chain hydrocarbons of carbon number C_{18} and above. Squalane, a readily available pure compound, is typical of this type of hydrocarbon and has been used in laboratory simulation experiments as being representative of the non-surface-active fraction of

- 15 -

track contamination.

The second fraction, eluted by toluene, is darker and more viscous than the first fraction; it has been found to contain aromatic as well as aliphatic matter and in several cases the ester grouping has been found to be present. Most of the molecules are large, in the $C_{20} - C_{36}$ carbon number range.

The third, most active fraction, eluted by methanol, is always very dark in colour. Analysis reveals molecules of the same carbon number range as in the second fraction, but the C = 0 grouping is almost always present, probably as acid, ester or ketone. Amines are also found. This fraction forms 20 to 50% of the oily contamination and because of its ability to form strongly bound surface lubricating films is probably the most important in terms of lubrication. Because it is difficult to choose any one material as being representative three alternatives have been used to simulate this fraction :

- a) the third fraction separated from a large quantity of oil
 oxidised in the laboratory;
- b) oleic acid, a simple pure organic acid which has a carbon number C_{18} , just within the correct carbon number range;
- c) naphthenic acid, the general name for a number of compounds containing an acid group attached to one or two naphthenerings by a straight carbon chain. A representative formula is :

 $(CH_3)_3(C_8H_{10})$ $(CH_2)_nCOOH,$ where n 🛩 8

A fourth, even more active, fraction has sometimes been obtained by using acetic acid to displace any remaining oil sample from the silica gel column. However, this forms a very small proportion, 1 or 2% only, of oil sampled from the track.

3.4 FRICTION MEASUREMENTS

The lubricants to be tested were dissolved in chloroform and sprayed on the test surface using an aerosol spray. The oils were "labelled" with a radio-active tracer so that the amount applied to the surface could be calculated by monitoring with a Geiger-Muller tube. The accuracy of these measurements is determined by the activity of the labelled oil and the background count from a non-radioactive surface (generally 50 counts/100 sec). For the most accurate determinations enough tracer was added so that one monolayer of the labelled oil would give a count of about 100 counts/ Care was taken to ensure that the oil spray was applied evenly. 100 sec. The quantity of oil on the surface was then calculated in terms of weight per unit area. To provide a rough guide this can be converted into the number of molecular layers present using two assumptions. The true surface area is assumed to be equal to the apparent area, whereas measurements indicate that the true area of an abraded surface can be as much as 3.4 times the apparent area (O'Connor and Uhlig, 1957). The second assumption (which is suggested by boundary lubrication theory) is that the oil molecules are arrayed with their lengths, about 25 x 10^{-10} m, perpendicular to the surface, each molecule occupying 25 x 10^{-20} m² of the surface area.

3.4.1 Friction of Oils

The friction obtained using an oil extracted by hot solvents from rust scraped from the head of a running rail is shown in Fig. 3.2 The shape of the curves is characteristic of all oils; the friction falls until the amount of oil is greater than 5-10 x 10^{-6} g/cm² (\approx 5-10 x 10^{-8} m thick) when the friction approaches a constant value which is characteristic of the particular oil being tested. The results shown in Fig. 3.2 were

- 16 -

obtained on two days, one humid, one dry. When little oil was present, friction was lower at high humidity. The same effects were observed using another sample of oil extracted from rail rust and also using naphthenic acid as the test lubricant. A few tests were also made on clean main line track using a temporary rig to accommodate the disc of the rolling disc tribometer (Broster et al 1974). A similar relationship was again found between friction and the amount of oil applied. Gross scuffing or adhesive wear takes place when the friction is high; as more lubricant is applied there is a transition stage until, when the friction is less than about 0.3, wear becomes wholly of a mild nature. The arrows in Fig 3.2 indicate how the friction increased when the humid air surrounding the apparatus was dried. These results are discussed in more detail later (in Chapter 5) together with the effects of adding bulk water to oil contaminated surfaces.

For reasons described earlier (Section 3.3) squalane was chosen as a typical non-surface-active material and naphthenic acid as a typical surface-active material found in an oil. Fig. 3.3 shows the friction measured as a function of the amounts of these materials applied to the test surface. Curves of similar shape to that shown in Fig. 3.2 were obtained, the friction due to an excess of lubricant being slightly higher for the squalane ($\mu \approx 0.19$) than it is for the surface-active naphthenic acid ($\mu \approx 0.15$).

3.4.2 Friction of Separated "OilFractions"

Fig. 3.4 shows the friction obtained with the four fractions separated from an oil sampled from the track. All measurements were made using an excess of fluid. As might be expected, the least surface-active fraction resulted in the highest friction. The separation procedure did not yield enough material to perform many experiments and, to overcome this difficulty, separations were subsequently made using a much larger column of silica gel (Beagley et al 1972). Two oils representative of those spilled on the track were examined in detail : rape oil which is

- 17 -

naturally surface-active, and a mineral oil which is relatively inert and which contained no surface-active additives. The fractions obtained from these oils were measured several times both on rail steel and on stainless steel plates. The lubricant was left on the place for varying lengths of time, during which the friction was usually found to decrease. This is possibly due to the molecules becoming better orientated on the surface or, alternatively, to some chemical reaction slowly taking place.

Fig. 3.5 shows the results obtained with the mineral oil. As with the track oil, the friction of the complete oil is higher than the friction of its surface-active constituents. It appears that a "weighted average" friction is obtained, in which each fraction contributes to the friction in proportion to the relative amount present. This weighted average is obtained by adding together the products of the friction of the individual fractions and the proportion in which they occur. The agreement between the measured coefficient of friction of the complete oil and the weighted average was surprisingly good using both rail steel and stainless steel plates.

The results obtained with rape oil are shown in Fig. 3.6. It is more difficult to obtain a good separation from rape oil because of its surface-active nature. A regular flow through the large column was difficult to obtain because of the limited solubility of rape oil in heptane. (Solubility is related to the activity of the molecules). Further, rape oil is so surface-active that acetic acid eluted a large proportion and this is the least dependable part of the fractionating process. The results show the same effects as with the mineral oil, but the friction caused by the complete oil is much closer to that of the fourth fraction because of the large proportion of fourth fraction present.

3.4.3 Friction of Mixtures of Materials

The above experiments suggest that the effect on friction of the surface-active components in oils is roughly in proportion to their

- 18 -

concentrations. In contrast, the friction of non-surface-active aliphatic hydrocarbons was found to be highly susceptible to the slightest amount of impurity. The friction caused by nominally pure fluids (> 99%) was increased by as much as 0.10 when they were further purified by being passed through a silica gel column (Beagley et al 1972). Other workers (Bowden and Tabor 1950) have found that the friction of a mixture is reduced to that of its most surface-active constituent provided that enough is present to form one molecular layer on the surface. If this were true on running rails adhesion would be very low. To study these effects more directly, mixtures were specially made up and their friction measured. Fig. 3.7 shows the effect of adding naphthenic acid to hexadecane. In each test the same weight of the mixture was applied to a known area of the plate before the coefficient of friction was measured. It can be seen that the naphthenic acid had a dominant effect. The lowest friction was reached when the concentration was only 0.4%, which was enough to form several monolayers on the plate if all the naphthenic acid was associated with the surface. However, to determine the amount attached to the surface, adsorption measurements * were made in which the amount of naphthenic acid adsorbed on to iron oxide power was measured. The iron oxide simulates the oxide covering the steel surfaces. The amount adsorbed is shown in Fig. 3.7 where it can be seen that adsorption increases until the concentration is 0.6%, after which a plateau is reached. Adsorption theory indicates that this plateau marks the formation of one molecular layer adsorbed on the surface. Taken together, these results suggest that the one molecular layer of naphthenic acid from hexadecane solution is sufficient to cause the lowest friction.

Experiments were then made on mixtures of "naturally occurring" fractions to compare with the idealized materials used in Fig. 3.7. Figs. 3.8 and 3.9 show the results of mixing the components of oils separated by the silica gel columns. In the first experiment (Fig. 3.8) the fourth fraction

* these measurements were made by Dr. I.J. McEwen

obtained from rape oil was added to the first fraction from a mineral oil and, in the second, (Fig. 3.9) the third and first fractions of a partially oxidised lubricating oil (Talona 945) were mixed. In both cases, although small concentrations of the surface-active component had a greater than proportional effect on friction, neither was as dominant as naphthenic acid. For example, it was necessary to add 55% of the fourth fraction (Fig. 3.8) before the friction was at its lowest. When the third and first fraction from the same oil were mixed, 100% of the third fraction was necessary before the lowest friction was attained (Fig. 3.9). (In this last experiment, only small quantities were available, so that about 1/12th of the volume, compared with the earlier test, was applied to the test plate. Even so, 100% of the surface-active fraction provided enough to form 165 molecular layers).

Fig. 3.10 shows the results of a decisive set of experiments. Squalane was mixed with two surface-active components and, unlike the previous experiments, the amount of the active component was held constant, so that the number of surface-active molecules present in each application was the same (except obviously for 100% squalane). A mixture of third fraction and squalane behaved in the same way as the mixture of third and first fractions, while the result of mixing naphthenic acid and squalane was similar to that of mixing naphthenic acid and hexadecane.

It is thus evident that naphthenic acid in solution affects friction far more readily than do the naturally occurring third and fourth fractions although the surface-activities of these fractions (as ranked by silica gel chromatography) are similar to that of naphthenic acid and when measured on their own reduce friction to a similar level. However, the natural fractions are complex mixtures of compounds each of which competes to be adsorbed on the surface. Individually, some of the compounds probably give friction coefficients greater than that of naphthenic acid (e.g. such as surface-active aliphatic acids) and some less. The low friction of the third fraction, used alone, may be due to one constituent present in

- 20 -

such a small proportion that it is adsorbed in sufficiently large quantity only when the fraction is not diluted.

A precisely "weighted average" friction is not obtained from any of these two-component mixtures; if it were so, there would be a straight line relationship between the friction and the concentration of the mixture. A complete oil is made up of a mixture of three or four fractions each of which is itself a mixture and, although three-component mixtures have not been investigated, their action would probably be to smooth out the friction curves (of, for example, Fig. 3.9) so that the influence of each fraction was more closely in proportion to its concentration.

Surface-active material on running rails has a considerable time available during which it can become strongly adsorbed on the surface. To study whether such adsorbed materials were affected by subsequent application of non-surface-active fluids, experiments were done in which pure surface-active compounds were left on the surface of a test plate for a considerable time. The friction was measured and then a non-surfaceactive fluid was added and the friction measured again. Fuel oil, which is often spilled on track, and squalane were chosen as the non-active fluids. Table 3.2 shows that, except when naphthenic acid was the initial lubricant, the friction was always increased on addition of the fuel oil or squalane. This indicates that, even though the molecules had time to form adsorbed layers, they were taken into solution by the newly applied hydrocarbon molecules which, presumably, then competed in theadsorption process as before.

TABLE 3.2

Surface-Active Lubricant	Initial Friction	After Subsequent Fuel Oil	Application of Squalane
Rape Oil	0.13	0.19	0.19
Oxidised Lubricating Oil	0.15	0.20	0.22
Mineral Oil	0.15	0.19	0.19
Naphthenic Acid	0.15	0.15	0.15

FRICTION OF SURFACE LUBRICATED FIRST WITH A SURFACE-ACTIVE COMPOUND TO WHICH A NON-SURFACE-ACTIVE FLUID IS ADDED

3.5 OXIDATION AND SHEAR OF TRACK OILS

It has been shown in Table 3.1 that the oils sampled from the track are composed of a much greater proportion of the surface-active third fraction than are the materials from which they originate. Contamination on the track is not only exposed in a thin layer to the atmosphere and the sun but is also subjected to shear during the passage of trains. This shearing action, together with the high local temperatures it could produce, may play an important part in the modification of track contaminants (Fein and Kreuz 1964). Several attempts were made to simulate the oxidation that occurs on the track by heating oils and bubbling air through them. The viscosity and surface-activity were found to increase and Fig. 3.11 records how the friction decreased as these oils were oxidised, but it was not possible to produce a typical track sample in this manner (see Table 3.1).

To study how a shearing action affects oils, a few tests were performed using an Amsler wear testing machine. Two 40 mm diameter rail steel rollers were rolled together under a load of 100 kg, at a speed of / 200 r/min, and were geared so that, instead of undergoing pure rolling, they slipped against each other with a slide/roll ratio of 0.10. The tests were run for about forty hours with the bottom roller dipping into about 1 cm³ of the fluid contained in a glass dish. Fresh rollers were used for each test, the coefficients of friction were noted, the surfaces of the rollers were examined and the chemical changes in the lubricating fluids were examined using I.R.S. and G.L.C. techniques.

Hexadecane, paraffin oil and squalane were used to simulate the nonsurface-active fractions. Mineral oil, Talona 945 and rape oil were used because they are typical of oils used in trains. The friction to begin with was approximately the same as that found using the rolling disc tribometer, but after a few minutes it usually fell substantially, typically from about 0.1 to 0.07 in fifteen minutes. Most of the fluids underwent only small chemical changes. Analyses revealed increased carboxylate, carboxylic acid, and oxidised aliphatic hydrocarbon concentrations.

Hexadecane, however, started with a friction of 0.32 which, after fifteen minutes, fell to 0.13. After twenty-eight hours, analysis of the hexadecane revealed there was about 5% of a strong acid present. This shows how easily the activity and thus the lubricating properties of a non-surface-active material can be changed.

In thirty minutes the friction of rape oil fell from 0.09 to 0.03. Interesting chemical changes were observed. More carboxyl and acid substances were found but some acids used in identifying rape oil erucic, oleic, linoleic and linolenic acid - were greatly reduced in volume. It thus appears that the absence of these identifying acids in track samples cannot be taken as evidence that rape oil was not deposited on the rail in the first instance.

With each oil, a lacquer appeared to build up on the rolling surfaces after forty hours. This lacquer varied in thickness and, because it was insoluble in solvents, had to be removed for examination by scraping.¹ Analysis of these lacquers by I.R.S. always showed a higher percentage of chemical change than in the surrounding oil in the dish, indicating that the changes were caused by tribological action at the surface. There was too little fluid to do extensive tests but, when measured on the rolling disc tribometer, the friction of the residual oil was found to be
substantially lower than that of the non-sheared oil. It was not established how much of the reduced friction measured on the Amsler was due solely to the changes in the lubricating properties of the fluids and how much was due to the building up of the surface lacquer.

3.6 CONCLUSIONS

Friction has been shown to depend both on the nature of the oil under test and on the quantity applied to the surface.

When varied in quantity, all fluids produce a similar curve in which friction falls as more fluid is applied, until a constant low value, characteristic of the particular fluid, is reached. This variation in friction could account for much of the variations in adhesion observed on running rails on dry days.

The characteristic friction coefficient is dependent on the nature of the particular fluid. For most lubricants it is about 0.13. However, the nature of the oil can be substantially changed by oxidation or shear such that, in the laboratory, friction coefficients as low as 0.03 to 0.08 have been measured.

In agreement with classical boundary lubrication theory, the most active fractions, separated from oils, have lower coefficients of friction. However, the friction of an oil is <u>not</u> that of its most active constituent. Experiments with oils have shown that their complex mix results in a "weighted average" friction, apparently caused by competitive adsorptio".

MODEL OF TWO IDEALIZED METAL SURFACES WITH MATERIAL THE HIGH SURFACE ACTIVITY AND PACKING STRENGTH OF HIGH SURFACE ACTIVITY BETWEEN' THEM. RESULTS IN SMALLER AREAS OF CONTACT. MODEL OF TWO IDEALIZED METAL SURFACES WITH MATERIAL 6 OF LOW SURFACE ACTIVITY BETWEEN THEM.

4/17647

BOUNDARY LUBRICATION. ЦO REPRESENTATION FIG.3.1. PICTORIAL

FIG, 3.1.



94/17648

٩



FIG. 3.3,



17650



94/17651



RS/A4/17652



4/17653



FIG 3.8.

17654



FIG. 3.9.

¢

194/17655



FIG. 3.10.



FIG. 3.11.

'A4/17657

CHAPTER FOUR

LABORATORY STUDIES ON THE EFFECTS OF SOLID DEBRIS ON FRICTION

4.1 INTRODUCTION

Particles of solid debris are present on even the cleanest looking rail (Broster et al 1974). The solid contamination is usually in the form of small compacts made up of very fine particles. Chemical analysis shows that track debris is largely a mixture of varying proportions of iron oxide and hydroxides.

In this chapter the effects of solid debris on friction are examined. As many oxides/hydroxides as were commercially available in pure form were tested to see if any single component of track debris could cause low friction. Experiments on mixtures of solid debris and oil established the relative importance of abrasive and adsorptive mechanisms.

4.2 LABORATORY EXPERIMENTS ON THE ROLLING DISC TRIBOMETER

In Chapter 3 clean, uncontaminated, steel specimens were found to give a coefficient of friction of about 0.65 on the rolling disc tribometer. However, when samples of track debris were sprinkled onto the plate the friction fell to approximately that measured on the track from which they were scraped. On subsequently soxhleting the debris samples to remove any oil, a friction of 0.65 was once more attained. The following series of tests were conducted in order to examine the effect of adsorbed oils.

4.2.1 Experimental Method

Known weights of oxide and naphthenic acid were mixed in chloroform. The chloroform was then carefully evaporated to leave a homogeneous mixture that could then be applied to the rail steel plate using either a sieve or a spatula, according to the consistency. Conveniently the friction was found to be independent of the quantity of mixture applied. The relative movement between the disc and plate appeared to push aside all but a small quantity of mixture from the contact. Metallic contact still occurred between the plate and disc; severe metallic wear accompanying high friction

- 25 -

with clean or slightly oily powder, mild wear accompanying the low friction produced by oily mixtures.

The "adsorbency" of the powders was measured using solutions of naphthenic acid. The proportion, by weight, of naphthenic acid needed to form one monolayer was found by adsorption from a heptane solution using a microcalorimeter to measure the Langmuir isotherm plateau * (Beagley et al 1975,2).

4.2.2 Experimental Results

The results are shown in Figs. 4.1 and 4.2. In Fig. 4.1 the experimental points are shown both for the mixtures when dry and when subsequently sprayed with water (this is discussed in the following chapter). In Fig. 4.2 the forms of the results for all the various powders used are In both figures the adsorptive quality of the powders is compared. denoted by the weight of naphthenic acid required to form one monolayer per gram of powder (in mg/g). However, it must be carefully noted that in Fig. 4.1 the mixture of oil to lubricant is expressed in mg/g, but in Fig. 4.2 this ratio has been converted into the number of equivalent monolayers (using the ratio of weights needed to form the first monolayer). The above results were obtained by mixing a powder with an oil and then applying the mixture to the specimen plates. In practice, oil will drip from trains onto a debris covered rail. As a rough simulation of this, further experiments were carried out in which a thin covering of Fe₂O₂ powder was dispersed over one of two clean steel plates. An oil solution was then evenly sprayed over both the plates using an aerosol device, taking care that the debris particles were not blown away. The amount of debris and oil falling on the plates was measured by weighing and the resulting friction coefficients are shown in Table 4.1. It was also possible, knowing the oil/powder ratio and referring to Fig. 4.2, to estimate what the friction would be if all the oil and powder was thoroughly mixed. These figures are also shown in Table 4.1

* Measurements made by Dr. I.J. McEwen

TART	A	1
TADLE	4.	T

	FRICTION	0F	0IL	SPRAYED	ON	DEBRIS	COVERED	SURFAC
--	----------	----	-----	---------	----	--------	---------	--------

Wt of Debris (g/cm ²)	Wt of Oil (g/cm ²)	Measured Friction		Calculated Friction
		Oil only	Oil & Debris	Oil & Debris
2.7×10^{-3}	8.0×10^{-5}	0.17	0.57	0.66
0.6×10^{-3}	3.2×10^{-5}	0.20	0.36	0.64
0.4×10^{-3}	2.7×10^{-5}	0.19	0.30	0.61

The calculated coefficients of friction are higher than those measured in the test. This suggests, not surprisingly, that the oil sprayed on the debris covered plates did not mix completely. However in each case the presence of debris maintained a higher friction than was obtained on the debris free plate, and the greater the debris/oil ratio the greater was the friction.

4.2.3 Discussion

In Section 4.2.1 it was noted that metal-to-metal contact still occurred even when the plate was initially covered with a thick layer of debris. A "boundary lubrication" model can still be considered as being appropriate. However, in Fig. 4.2 the minima in the curves obtained with the powders with high surface areas (precipitated rust and alumina) occurred when the mixtures appeared to be viscous enough to completely support the disc and prevent metal-to-metal contact. Obviously under these conditions a boundary lubrication model is no longer appropriate. The rheological equations involved under these circumstances, and those where a moving locomotive wheel and rail does not make metal-to-metal contact, are examined in Chapter 6.

In Fig. 4.2 it can be seen that in the absence of oil none of the powders except $\text{Fe}_{3}^{0}{}_{4}$ and alumina had any effect on the friction of a clean plate. Fe₃ ${}_{0}{}_{4}$ has previously been associated with low friction under dynamic

conditions (Bisson et al 1957), and so to has FeO. FeO is found in small quantities on the track but was found to be unstable in its pure form in the laboratory. However mixtures of oxides that contained 30% FeO still gave high friction when applied to a clean plate.

Alumina, unlike the other samples is not a constituent of rail debris, but was used in order to observe the effects of its hardness (2 100 kg/mm² in contrast to the hardness of iron and its oxides of approximately 250 kg/mm² (Tabor 1951)). The alumina caused more surface damage, raised the friction of clean steel to 0.8, and even when mixed with excess oil maintained a friction of 0.24. The other oxides, whose hardness is similar to that of steel, only cause small changes in the friction when clean (0.7) and when mixed with excess oil (0.13).

As more oil was added to the powders, the friction of the mixtures fell and the consistency changed from that of a loose powder, to that of a thick paste and finally to an oily slurry. From Fig. 4.2 it can be seen that the number of equivalent monolayers necessary to reach the low friction state is dependent on the surface area of the powders (proportional to the number of mg/g of naphthenic acid needed to form 1 monolayer). In Fig. 4.3 the surface areas of the powders is plotted against the amount of oil needed to cause low friction. The amount of oil is plotted both in terms of the percentage oil content and the number of equivalent monolayers. Similar curves can be plotted using intermediate frictional values. The remarkably smooth curves in Fig. 4.3 show the importance of the adsorption properties of the powders. The frictional behaviour of all the powders and oil mixtures are governed by their adsorption properties (even if, like alumina, they are significantly harder than steel). It should be noted that this well defined behaviour was not apparent until the adsorption qualities of the powders were measured in a manner similar to that used during the preparation of the mixtures (i.e. adsorption from solution). These results, together with the fact that only the hard alumina raises the friction of an oily slurry, indicates that natural

debris adds little or no abrasive component to the frictional mechanisms. The reason why powders of high surface area need fewer equivalent molecular layers of oil to form a low friction oily paste is probably because of the geometry and adsorption qualities of the particles. The surface area of the powders is initially important in adsorbing the first molecular layers, in all the pores and fissures of the particles. Subsequent layers are less strongly bound until the particles have effectively soaked up all the oil possible. Further oil eventually joins so that the mixture coalesces into an oily paste. One "equivalent molecular layer" naturally contains more oil when the surface area of the powder is high, each layer representing a larger volume of oil. It can be considered that the surplus oil, which is not tightly bound to the particles, is free to adsorb on the surfaces of the steel specimens and thus control adhesion.

4.3 LABORATORY EXPERIMENTS ON THE AMSLER WEAR MACHINE Unlike the rolling disc tribometer, friction measuring machines in which the test surfaces are continuously rolling together generate their own wear debris. This debris is found to adhere to the specimens and its effect on the friction measurements can be profound. In order to understand these effects, measurements were carried out on the Amsler wear machine.

4.3.1 Experimental Method

Two rail steel rollers were loaded together and run with a creep ratio of 3.1%. Preliminary experiments showed that this "creep ratio" is enough to ensure that the friction force exerted between the discs is the limiting friction, i.e. is the highest attainable. Wear debris invariably builds up disproportionately on the two surfaces, the greater volume visibly adhering to the lower faster moving disc. Small amounts of oil were sprayed on the specimens in a solvent and the resultant friction was noted as the test continued. As in the experiments in Chapter 3 the amount of oil on the specimens was monitored by using radioactive tracers added to the oil.

- 29 -

4.3.2 Experimental Results

Fig. 4.4 shows what happened to the friction and to the amount of oil on both the top and bottom roller (expressed as if there were no debris present). The stops necessary to measure the quantities of oil present are shown by breaks in the friction trace. Radioactive measurements were also made immediately after each application of oil. (Subsidiary tests showed that the debris was not thick enough to mask the counts from the underlying oil).

4.3.3 Discussion

It can be seen that the friction falls immediately oil is applied and then recovers to a high value as the coverage of oil decreases due to wear. Note however that the amount of oil remaining on the surfaces, even when the friction coefficient is as high as 0.55, was usually enough to provide as many as 100 molecular layers. In the experiments using clean plates on the rolling disc tribometer this amount of oil invariably caused the friction to fall to its lowest value. However, these steel plate specimens were free of debris particles whereas the oil in the Amsler tests is adsorbed onto the wear debris. As fresh debris is formed during rolling, the oil/debris ratio becomes progressively less and, in accord with the results shown in Fig. 4.2, the friction rises. More oil is always detected on the faster specimen surface which is visibly coated with the greater amount of debris. At the beginning of the experiment, when the debris is initially oil free, the friction increases quickly as the oil is rapidl, mixed and adsorbed by the particles. After many cycles the debris is initially coated with oil and more time is needed to generate fresh debris before the friction recovers to its high value.

The wear debris was found, not surprisingly, to be radioactive when brushed from the surfaces. A rough calculation of the quantity of oil and debris present on the rollers, coupled with a measurement of the surface area of the wear particles, showed that the friction coefficients were close to those predicted by Fig. 4.1 and 4.2.

- 30 -

4.3.4 Relevance of Dynamic Results

These results are important since they indicate a mechanism whereby oil is removed from the track. The oil is adsorbed on to the debris which is eventually thrown clear of the wear band. However the exact correlation between the friction results on the Amsler and the track is difficult. Because true metal-to-metal contact does not occur between the rollers the boundary lubrication model is no longer applicable. The shear strength of the debris mixtures separating the surfaces becomes important, and although this will decrease with increasing oil content, coefficients of friction are no longer universally applicable for the same surface condition. This will be discussed further in Chapter 6.

4.4 CONCLUSIONS

The constituents of rail debris, apart from $\operatorname{Fe}_{3}^{0}{}_{4}^{0}$, behave in a similar manner. $\operatorname{Fe}_{3}^{0}{}_{4}^{0}$ lowers the coefficient of friction of clean steel to 0.48. Debris raises the friction of an oily surface depending on how much oil it adsorbs.

The friction caused by a mixture of oil and debris of known surface area can be predicted.

Iron oxide and hydroxide do not appear to raise friction due to a "keying in" or "abrasive" mechanism.

Oil is worn from surfaces in rolling contact by being adsorbed on naturally occuring wear debris.



ERS/A4/17658



FIG. 4.2.

ERS LAY /17







CHAPTER FIVE

LABORATORY STUDIES ON THE EFFECTS OF WATER ON FRICTION

32 -

5.1 INTRODUCTION

This chapter deals with the frictional effects associated with rainfall and changes in relative humidity. The track is not only wetted by rain, but also by condensation (dew) which forms when the surface temperature of the rail falls below the dew point of the surrounding air. Railwaymen have always associated wet rails with low adhesion and, when examining track conditions, measurements with a portable tribometer have confirmed that low adhesion is often associated with the track being wet (Broster et al 1973).

5.2 RESULTS ON THE ROLLING DISC TRIBOMETER

Fig. 5.1 (and Fig. 3.2) shows how the coefficient of friction depends on the amount of oil applied to a rail steel plate. On a humid day lower friction coefficients were obtained compared with those measured on a dry day. Arrows show the increase in friction observed when, on a humid day, the atmosphere surrounding the experimental rig was dried and held at a humidity less than 1% R.H. for a period of thirty minutes. The friction did not reach as high a value as was found on a naturally dry day even when the drying period was extended to several hours. Possibly the properties of the oxide film formed during the cleaning operation, which includes abrasion, is dependent on the humidity during the abrasion process in such a way as to influence all subsequent friction measurements. Fig. 5.1 also shows how adhesion was lowered when water was sprayed on the oily test surface. The same results were obtained both on humid and dry days. With little lubricant present the friction falls and, provided there is enough lubricant to prevent rusting, friction rises to its original value as the water dries. When there is so much lubricant that the initial friction is at its lowest value, then neither water nor high humidity has any effect.

Fig. 5.2 shows how the coefficient of friction of a plate, on which a few equivalent monolayers of track oil had been sprayed, changed when the humidity of the surrounding atmosphere was increased. The relative humidity was changed from 50 to 100% in 30 minutes, and the friction was reduced only when 100% R.H. was achieved and condensation formed on the rubbing surfaces. When the enclosure around the apparatus was opened to the laboratory, the air rapidly dried (to approx 50% R.H.) and the friction immediately increased, to 0.25, again.

It was observed that the change in friction depends on the surface-activity of the lubricant on to which the water is sprayed. Surfaces lubricated by surface-active compounds such as lubricating oil, rape oil, naphthenic acid, oleic acid and stearic acid behave in a similar way to that shown in Fig. 5.1; the friction is lowered by the addition of water. Friction measured when water is sprayed on surfaces lubricated by non-surface-active compounds such as squalane, hexadecane, and fuel oil approaches that measured on a clean wet surface. Consequently, when excess of a nonsurface-active lubricant is present, the friction usually increases on the application of water (Fig. 5.5). It was observed that these materials floated on the water and rust spots could be seen to form on the metal surface. In contrast, water sprayed on surface-active material formed characteristic beads on the oily surface and produced no rust. To eliminate the frictional changes due to rust formation, tests were conducted using discs and plates of stainless steel. Figs. 5.3, 5.4, 5.5 and 5.6 show the results obtained when using naphthenic acid and squalane on both the rail/tyre steel and stainless/stainless steel systems. As previously mentioned, naphthenic acid is representative of the surfaceactive components of an oily lubricant, squalane of the non-surface-active components.

Fig. 4.1 showed how similar reductions in friction occurred when water was sprayed on to a plate covered by mixtures of iron oxide and naphthenic acid. This shows two interesting points: firstly the reduction in friction appears to be dependant on the ratio of oil to solid, secondly the friction caused by clean wet debris is higher ($\mu = 0.4$) than that of a clean wet plate alone ($\mu = 0.3$). Possibly the wet oxides help remove the last vestiges of oil.

5.3 DISCUSSION OF RESULTS OBTAINED USING ROLLING DISC TRIBOMETER It can be seen from Figs. 5.1 and 5.3 that the presence of water reduces the friction coefficient between clean rail steel surfaces from 0.7 to about 0.3, and Fig. 5.1 further shows that friction can be reduced, to about 0.6, when no liquid water is present but simply when the relative humidity is high. On a surface lightly contaminated with a surface-active compound water reduces the lowered friction still further. It appears there are two frictional mechanisms to be explained: firstly, what is the mechanism that causes the friction of a wet oil-free surface to be reduced and, secondly, why is the friction of a slightly oily (surfaceactive) surface further reduced by the action of water?

Any fluid present on a surface reduces the coefficient of friction between two bodies by becoming either physically or chemically adsorbed and thus reducing the extent of true surface to surface contact at the sliding interface. Friction between wet rail steel and tyre steel is 0.31, and the wear is of a mild nature, appearing to be confined within the oxide The coefficient of friction between wet stainless steel specimens layers. is 0.57 and the surfaces still suffer damage due to severe, scuffing type It seems likely that it is the strength of the wet oxide which wear. governs the friction under these conditions. It is known that, in general, the oxide on rail steel is thicker, less cohesive and less adherent than that on stainless steel. The different behaviour of the two types of steel can thus be accounted for by the lower shear strength of the wet oxide layer on rail steel and the further factor that, whenever a fresh steel surface is bared by oxide being worn away, the presence of water generates more oxide more rapidly on rail steel than it does on stainless Thus, in the wet, metal to metal bonding takes place with less steel.

interference from oxide formation on stainless steel surfaces and consequently adhesive type wear more readily occurs and friction remains high.

The reason why water further reduces the friction of surfaces lightly contaminated with surface-active oils can be explained by assuming that water adds its lubricating effect to that of the oil already present. Less than excess oil is postulated to lubricate only a proportion of the true contact surface while the remaining area experiences either the dry friction coefficient of about 0.65 or, when wet, a coefficient of 0.31. Although this gives a good qualitative picture, it is rather unsatisfactory since frequently there can be enough oil present to completely cover the surfaces with several monolayers.

A rival theory suggests that the lubricating action of surface-active cil is enhanced because the water increases the mobility of the lubricant molecules within the contact region, so that freshly worn surfaces are more rapidly protected by a lubricant film. Surface-active compounds are not readily soluble in water but, for example, stearic acid is soluble enough at 20°C to provide 15 molecular layers on 1 cm² of surface from 1 cm³ of water solution (Markley 1960). Any lubricant molecule not strongly bonded to the metal surface, or any molecule which becomes temporarily desorbed, may thus enter into water in solution from where it is readily available and mobile enough to adsorb on any fresh surface exposed by wear.

It is difficult to conceive of a test to tell which of these theories is closest to the truth, but a number of experiments have been conducted which show that surface-active molecules can be transported in water. These are described next. In all of them, lubricant molecules are found to be mobile over relatively long distances. It is probable that the smaller distances and high pressures and shear forces that exist in the contact area of a friction experiment are even more conducive to the movement of oil molecules.

35 -

5.4 EXAMINATION OF THE MOBILITY OF OIL MOLECULES IN WATER

In the first study of oil mobility a flat steel plate was lightly contaminated with oleic or naphthenic acid and then wetted with water. A second, clean plate was then brought into contact, and subsequent friction measurements showed that the second plate had become contaminated with the lubricant ($\mu = 0.17-0.20$).

Similar results were obtained when the second plate was not brought into contact, but was held close enough to allow the water layer to bridge the gap. Several experiments were conducted to show that the oil did not float on the surface of the water, but was in fact transferred in solution (or as an emulsion). For example, a plate was sprayed with a few monolayers of radioactive oil, and subsequently with 100 cm³ of water. The water was then collected and placed in a measuring cylinder so that any surface film would be compressed into a small area. There was no activity associated with the surface, but when the water was evaporated to dryness very high activity was recorded.

In another series of tests the physical mixing of oils and water was examined. Both surface-active materials (Talona 945 oil, oleic acid, naphthenic acid) and non-surface-active materials (squalane, hexadecane, fuel oil, mineral oil) were agitated with water (in a ratio of 1:10) in a separating funnel and then allowed to settle for one hour. An aliquot from the water fraction, which appeared to be completely clear, was then sprayed on a clean rail steel plate. When surface-active materials were used this water fraction reduced the friction of the clean steel plate typically to 0.18 (low compared with the friction of clean water, 0.3), the plates had a greasy appearance, and blotchy rust marks formed as the water evaporated. When non-surface-active materials were used, the water fraction behaved simply as pure water, resulting in a friction of 0.3 and the formation of an even rust layer.

It is not clear whether the above results are because the oils are really soluble in the water or because they form a fine, invisible emulsion. A

few tests were performed leaving the water/oil mixtures to stand for different lengths of time, but the results were inconclusive. With oleic acid the lubricating properties of the water fraction did appear to worsen with time, whereas lubrication by water shaken with naphthenic acid still resulted in a fraction of 0.18 after having been left standing for two weeks.

5.5 WASHING EXPERIMENTS

The importance of the solubility of oils in water is connected not only with these friction mechanisms but also with the possible removal of oil from the track by rain. Several experiments were performed to examine this aspect.

First, a steel plate contaminated with a small quantity of a surfaceactive oil, enough to reduce the friction coefficient to 0.40, was placed under a shower of water, representing heavy rainfall. Initially the coefficient of friction fell but then steadily increased as the test proceeded (Fig. 5.7). Visible rust formed on the plate, which made it difficult to distinguish whether the oil was being washed off or being adsorbed on the rust. Some such dual mechanism is probably representative of the action of rain on the track. The final dry friction was as high as 0.68 but, because of the presence of the rust, it was not possible to say whether this corresponded to the surface being thoroughly cleaned of oil. It is of interest to note that, under these conditions, the friction on a wet rusty plate ($\mu = 0.45$) can be higher than that on a wet clean non-rusty plate ($\mu = 0.30$). This result is related to that observed earlier (Fig. 4.1) where the friction of a wet clean plate is raised by the application of an iron oxide powder. In this case, however, the real area of contact is increased by the thick tenacious rust layer, which is not penetrated by the rolling disc.

Experiments were also performed in which the amount of oil on the steel surface was monitored by adding a small quantity of a radioactive compound to the oil. The results showed that oils were washed from the steel surface by water, although the final layers were more tenacious.

5.6 FRICTION RESULTS USING THE AMSLER WEAR MACHINE The relevance of the creep curve has already been discussed in Chapter 2. This curve expresses the relationship between the ratio of the normal to tangential force at the contact and the relative movement between the surfaces, expressed as a percentage of the distance rolled. Experiments were performed on the Amsler machine in order to examine the effects of both water and changes in humidity under dynamic conditions.

5.6.1 The Effect of Humidity under Dynamic Conditions

5.6.1.1 Experimental Method

In order to examine the effect of relative humidity on the creep curve, apparatus was constructed that could supply a constant flow of air, of variable moisture content, to the specimens while being rolled against each other (Fig. 5.8). The two discs were enclosed in a polythene bag which was sealed against the faceplates from which the stub shafts that carry the specimens emerge. The bag was not completely air-tight but positive pressure from the air supply ensured a controllable atmosphere. The moisture content was monitored using a dew point hygrometer in the air supply line.

When specimens were run in an atmosphere of constant moisture content the relative humidity experienced by the running <u>surfaces</u> slowly decreased because frictional heating warmed the rollers. Consequently, to calculate the relative humidity at the <u>specimen surface</u> its temperature had to be known. In these tests it was measured with a temperature sensing thermistor probe, which just touched the surface. The relative humidity was then calculated as the water vapour pressure in the atmosphere expressed as a percentage of the saturated water vapour pressure at the temperature of the surface.

- 38 -

Tests were conducted to check whether frictional heating due to the contact pressure of the probe itself increased the recorded temperature. Fig. 5.9 shows the temperature changes recorded on two probes, one secured against the surface as described and one held in close proximity to, but never touching, the specimen. In one experiment the temperatures were measured as the discs rolled in contact at 3.33% creep under 50 kg load. In a second experiment the discs were held apart so that any heat generated could only have been conducted along the stub shaft from the motor and bearings. As can be seen, the contact probe recorded temperatures less than 1°C greater than that recorded by the probe held close, and almost the same as the temperature recorded using a third, static contact probe immediately rolling stopped. Thus, within the accuracy of the measurements, the frictional heating due to the pressure of the contact probe had no significant influence upon the measured temperature.

Using clean, oil free rollers running at various percentage creep rates, the coefficient of friction was determined at many different relative humidities. The slowly increasing surface temperature of the specimens provided a range of relative humidities without the moisture content of the air flow having to be changed. The specimens were also heated a further 10° C by an infra-red lamp (used in Fig. 5.10). Thus, the same surface relative humidity was achieved by various combinations of surface temperature and air moisture content. However, high surface humidity levels could not be reached at all temperatures because it was only possible to supply saturated air at room temperature. In later tests this problem was partially solved by pre-cooling the specimens.

Most results were recorded as the running surfaces heated up. Obviously this is valid only if the coefficient of friction responds quickly enough to changes in surface relative humidity. Tests were therefore made to find out how quickly the friction changed. Fig. 5.8 shows a torque record traced out as the air supply was switched from laboratory air to a high humidity supply and then back to dry air. It demonstrates quite clearly that the coefficient of friction changes rapidly and reversibly. A simple calculation, based on the rate of air supply, showed that the time taken corresponded to the time for the atmosphere in the polythene bag to change to the new level of humidity. This rapid change of friction confirms that valid results could be obtained as the rollers heated up relatively slowly due to frictional heating. Furthermore it shows that the mechanisms involved in changes in the friction must be both rapid and reversible. Clearly this conclusion eliminates any theories connected with long term oxide growth.

5.6.1.2 Experimental Results

Figs. 5.10 and 5.11 show results obtained at creep rates of 3.4% and 2.4% respectively. It is evident from both sets of data that the friction is defined by the relative humidity calculated as described above, relative to the saturated water vapour pressure at the temperature of the rolling surfaces. At 2.4\% creep the scatter of friction results at any given humidity is within ± 0.02 (at 3.4% corrugations that occasionally formed on the rollers resulted in increased scatter).

In Fig. 5.12 the results of Fig. 5.11 are shown with the friction replotted against the relative humidity of the surrounding air. It is immediately evident that there is an unacceptable scatter and that consequently there is no obvious relationship to be derived between friction and ambient humidity. This explains why many workers in the past have reported no connection between friction and humidity. For example, Barwell (1963) found quite high friction coefficients under conditions of high humidity. It seems clear, however, from the size of the machine used that the rolling/sliding surfaces must have become hot and therefore the relative humidity at the specimen surface must have remained relatively low.

Fig. 5.13 shows less extensive results obtained at other creep rates, and all these results are presented in Fig. 5.14 in the form of creep curves at five different levels of surface relative humidity. The limiting Figures 5.10 - 5.14 show that the coefficient of friction decreases rapidly as the surface relative humidity approaches 100%. However, experiments were difficult to carry out at high relative humidities since non-reproducible results were obtained if water was allowed to condense on the rollers or the polythene bag. Fig. 5.15 shows the results of four tests in which the rollers were first cooled by packing the machine with ice while dry air was passed over the rollers. The machine was then started and, simultaneously, saturated air at room temperature was admitted into the polythene bag. Although there was some spread of results it can be seen that the friction fell below 0.2 when the temperature of the rollers was below the dew point of the surrounding air. Under these conditions water must condense onto the specimen surfaces. Surprisingly, however, these coefficients of friction were lower than those produced when the rollers were sprayed with water:

5.6.2 The Effect of Water under Dynamic Conditions

5.6.2.1 Experimental Results

Since experiments at high relative humidities proved difficult and unreliable, experiments were made in which the degree of wetness of the roller surfaces was visually noted.

Fig. 5.16 shows the variation of friction with temperature when the rollers were purposely run wet, and were pre-cooled using dry ice. The friction was low at temperatures below 0° C, when ice formed on the rubbing surfaces, but it increased when the ice melted. The debris formed was continually washed away and the coefficient of friction was 0.3 - 0.35. However if the water was allowed to dry out, the slightly wet debris adhered to the faster running roller as a surface film and the friction fell to approximately 0.2. As the debris further dried, some flaked off, leaving a stable wear condition. The friction increased and the rollers

regained their characteristic dry-worn appearance.

Fig. 5.17 illustrates the three running conditions, specified A, B and C, diagramatically. It was found that the slightly wet condition (B) could be maintained by carefully allowing a very slow, steady stream of water to wet the roller surfaces via a wick. This water replaced that lost due to evaporation from the warm rollers, (at double the load exactly double the rate of flow of water was required).

A test was devised to examine how one condition lead to another :-First, the dry specimens were allowed to run-in (Condition A). Second the slow wetting apparatus was used to achieve the low friction of Condition B.

Third, bulk water was applied (Condition C).

Fourth the water was allowed to dry, going through Condition B in returning to the original state, Condition A.

Fig. 5.17 is a stylised diagram of the results obtained. Fig. 5.18 shows actual results of several experiments aligned in terms of the various stages. A spread of friction measurements is especially marked in Condition B which was found to be extremely sensitive to the amount of water present. Fig. 5.19 shows results obtained when run-in specimens were sprayed with different quantities of water and allowed to run until dry, proceeding through Condition B as they dried out. Naturally, the more water is applied the longer the rollers take to dry out. These tests were carried out using creep rates of 0.36% and 3.06%. Fig. 5.20 shows the form of the results, for a "four minute drying time" at 0.36%, 0.86%, 1.5% and 3% creep. Under dry conditions rollers running at higher percentage creep appeared to carry larger quantities of loose wear debris. The differences in Fig. 5.19 suggested that the rollers running at 0.36% creep were forming debris while running wet. Alternatively, it could be that both sets of rollers needed to experience a certain amount of slip in order to loosen the debris that had been compacted on the surfaces while running dry. (Naturally, ten times more slip occurs during a specific

time for rollers running at 3% creep than for rollers at 0.3% creep).

43

5.6.2.2 Experimental Results on the Effects of Oil and Water Experiments were also performed on rollers lubricated by an oil, to which a radioactive tracer compound had been added, in a similar manner to the test carried out in Section 4.3 of the last chapter. Fig. 5.21 shows the coefficient of friction as a function of running time, together with the amount of oil present on each roller. More oil was found on the bottom roller because of the build up of wear debris already described. It can be seen that water reduces the friction without having any appreciable affect on the amount of oil present. Fig. 5.22 shows two examples of the results compared with the typical curve obtained when water was sprayed onto clean rollers. The same drying out conditions were observed together with an initially greater decrease in friction, possibly because the oil and debris did not immediately mix with the applied water.

When water was sprayed on rollers contaminated with non-surface-active materials the friction was found to increase. Upon drying out, the friction followed a similar pattern to that obtained on clean wet surfaces.

5.6.2.3 Experimental Results on the Disc-Cylinder Rig The disc-cylinder rig (Fig. 5.23) can measure dynamic friction under various conditions of load and speed. A crowned 150 mm diameter disc is loaded against a rotating parallel cylinder that is traversed axially so that lateral and rotational motions are superimposed. The disc is effectively dragged sideways while rolling so that the contact area describes a helical path over the cylinder, the lateral creep forces being obtained via a load cell measuring the axial forces on the cylinder. Friction was measured when traversing the cylinder at a slip/rolling ratio greater than 0.015 (i.e. when the creep is above the "Knee" of the creep curve and therefore the measured value is of the limiting friction coefficient). The coefficient of friction was measured by traversing the cylinder every 20 seconds; friction cannot be measured continuously, so only an indication of the changes associated with drying could be obtained. Conditions are further complicated by the disc having a higher running temperature than the cylinder. By applying an iron oxide/water paste to the surface of the cylinder the drying rates were slowed down and the frictional processes more readily observed. Fig. 5.24 shows friction traces measured during successive traverses of the disc across the cylinder as the water/ oxide mixture dried. Each trace shows the friction measured from the left hand end of the cylinder to the right hand end; the cylinder was traversed in the opposite direction between each measurement. The low friction stage, Condition B, is once again observed as drying occurs. It was noticed that the metallic wear band of the disc was obscured by an oxide layer as drying occurred, the disc and cylinder being physically separated by the drying oxide film.

5.6.2.4 Discussion of the Effect of Water under Dynamic Conditions It appears from these results that low friction can occur due to the rheological properties of the drying debris. Further evidence for this was gained from experiments using stainless steel rollers on the Amsler Their behaviour when wetted was different from that observed machine. using rail steel. Fig. 5.25 shows how the coefficient of friction decreases to only 0.4 and remains almost constant before rising rapidly as the water dries out, without passing through the low friction stage of Condition B. Far less wear debris was observed to build up on the rollers; this frictional behaviour was therefore ascribed to the protective oxide film being relatively thin and more rapidly worn away as the water dried. However, when a paste of iron oxide (Fe_20_3) and water was applied to the stainless steel rollers, the frictional behaviour was found to become almost identical to that of rail steel! The added debris collected on the faster running roller, and a pronounced low friction stage ($\mu = 0.2$) due to the drying paste gave a clear

- 44 -
illustration of the occurrence of Condition B.

Further experiments were conducted to assess whether friction was dependent on the amount of slightly wet debris on the rollers. In one extreme, a wire brush was allowed to rub on the faster of the two rail steel rollers; the build up of debris was impeded and no reduction in friction was observed as the surfaces dried. However, when two heavily rusted, slightly wet, rollers were loaded together, friction lower than 0.05 was initially recorded. All these results support the view that it is the rheological properties of the wet debris that cause the changes in friction and that the lowest friction is found when the debris, that has either built up or been painted on the rollers, passes through a slightly wet state while drying out.

5.7 DISCUSSION

The agreement between measurements made on the static and dynamic rigs is close when the surfaces are clean and dry ($\mu = 0.6$) and when the surfaces are clean and visibly wet ($\mu = 0.3$). The changes in friction observed when the surfaces are lubricated by both surface-active and non-surfaceactive materials and then subsequently wetted are also similar. However, the surfaces used in the static tests are more severely worn during the friction measurement than those used in the dynamic tests. The construction of the static rig is such that the surfaces move relative to one another until there is 100% slip, when the disc slides approximately 3 cm against the plate. Relative movement also occurs with the dynamic rigs but the slip distance experienced by a point on one of these surfaces passing through the contact region is minute (slide/roll ratio x Length of contact \approx 10⁻³ mm). It can be postulated that the contrast in wear behaviour is due to the difference between the effective slip distances. Archard (1958) showed that relative movement has to occur between surfaces before the surface oxide layer shears to expose the metallic "substrate".

When considering how these tribometers simulate true conditions it may be considered crudely that the static rig simulates the slipping wheel of a static locomotive whereas the dynamic rigs more closely simulate the wheels of a locomotive at speed exerting traction or braking forces.

5.7.1 The Influence of Humidity

Changes in humidity were found to have a substantial effect on the friction between the rolling discs of the Amsler and of the disc-cylinder machines (Beagley and Pritchard, 1973), but to have little effect on the static rig. Friction on the Amsler changed immediately there was an adjustment of the relative humidity. On the static rig, it was only when humid conditions were experienced over an extended period that lower friction coefficients were obtained. This is probably because the two rigs are measuring friction under the two different wear conditions described above. It is to be expected that the friction in the mild wear regime is more susceptible to changes in humidity, since the friction forces are at all times transmitted by the surface oxide layers. On the static rolling disc apparatus little debris is formed until the moment friction is measured. Surface-to-surface contact then occurs unimpeded by loose particles and, in the absence of a lubricant, severe metallic wear takes place and the friction remains high. During severe wear, water adsorbed from a humid atmosphere has a comparatively small effect on the forces involved.

A layer of oxide wear debris forms on the surface of the continuously rolling Amsler specimens. The wear particles which adhere quite strongly to the rolling surfaces obviously modify the nature of the contact. The layer prevents contact between the true surfaces of the steel specimens and the effect of humidity then seems to be one of controlling its shear strength. Presumably the layer is weakened as water is adsorbed from the surrounding air; it is thus more readily sheared and the friction falls. Adsorption theory (Beagley et al 1975, 2) tells us that the quantity

- 46 -

of water adsorbed on a surface is dependent on the humidity relative to the temperature of the surface. The experiments on the Amsler show convincingly that the friction is directly governed by this parameter. It follows that friction under dynamic conditions must be a simple function of the quantity of water (per unit weight of debris) adsorbed on the thin compacted surface layer of debris.

5.7.2 The Influence of Water

When examining phenomena associated with water three factors have to be considered. Firstly it must be remembered that all liquids, including water, act as "lubricants" whose effectiveness is governed by the degree with which the adsorption of the molecules hinders surface-to-surface contact. Secondly, water lowers the shear strength of iron oxides and thus alters the friction between two surfaces according to the degree of oxide contamination present. Thirdly, water reacts with exposed iron surfaces and the reaction products further complicate the friction mechanisms. The coefficient of friction of wet stainless steel, when the first factor predominates, is 0.57. On wet rail steel, all three factors are involved and the friction is 0.31.

The results discussed above apply to clean steel surfaces. On the static rolling disc rig it has been shown that water further reduces the friction of surfaces contaminated by small amounts of oil. Experiments with oily surfaces are difficult to perform on dynamic rigs since the continuous rolling and sliding causes the formation of wear debris that adsorbs the oil. A discussion has already been given in sections 5.3 and 5.4 which suggested that water either adds its lubricating effect to that of the small amounts of oil, or that the water promotes extra mobility and thus extra lubricating efficiency to the small amounts of oil already present on the surfaces.

5.7.3 The Friction of Slightly Wet Surfaces

Using dynamic rigs a minimum value of friction was observed as wet rubbing surfaces dried. The phenomenon was most marked on the Amsler

- 47 -

The experiment using stainless steel specimens on the Amsler machine demonstrate most clearly that the properties of the surface layer govern the friction behaviour. When coated with a slurry of iron oxide powder the frictional behaviour becomes similar to that of rail steel rollers; as the material dries, a typical minimum friction coefficient of about 0.2 is obtained. These results suggest that the rheology of the slightly wet oxide is important. With excess water, the debris forms a thin slurry and the coefficient of friction is similar to that found on the static rig. However, on the dynamic rigs the debris/water mixture forms a thick paste as it dries, the surfaces are forced apart and the friction falls. The low friction observed under slightly wet conditions is important because of the frequency with which such conditions could arise on the track. However since the phenomenon is only observed on certain rigs the assumption that similar coefficients of friction will be observed on the track and the Amsler machine under similar surface conditions is

of oxide/water mixtures are examined in the next chapter.

5.8 CONCLUSIONS

The friction between clean steel surfaces, free from oil, has been found to be substantially decreased by the action of water, both visible and when adsorbed from the atmosphere.

not necessarily valid. The full rheological equations and the properties

The humidity of the surrounding air affects the friction between continuously rubbing surfaces. It is important to express this humidity relative to the temperature of the steel surface, which may be considerably different from the temperature of the air. When expressed relative to the surface temperature a direct relationship is observed between humidity and friction. Visible water films decrease the friction of clean steel surfaces to a value of about $\mu = 0.3$. If oil contamination is present on the steel, water reduces the friction still further, the lower limit being the coefficient of friction of the oil. However if the contaminant is non-surface-active (i.e. fuel oil) the friction due to the oil can be raised on the application of water.

Sufficient water, from heavy rain, results in adequate adhesion. Water has been shown to wash most oil from the surface, although some remains firmly adsorbed.

Under dynamic conditions the coefficient of friction between two slightly wet rusty specimens can be 0.05. Furthermore the friction can fall to 0.15 as/wet surfaces dry. The wide variation in friction due to debris and water is examined both theoretically and experimentally in the next chapter.



Ĭ,

1A4/17662







èri.

FIG.5.2. FRICTION VS HUMIDITY ON OIL CONTAMINATED PLATE. ON ROLLING DISC TRIBOMETER.







4

FIG. 5.6.





FIG. 5.7



4

FIG. 5 · 8



5/A4/17397

э, **ЗЯUТАЯЗ**ЯМЭТ



s[A4/17



€.,

00

000

80

2

õ

50Kgm. LOAD,

RELATIVE HUMIDITY ON AMSLER. 2.4% CREEP, RAIL STEEL.

% AMBIENT RELATIVE HUMIDITY

FIG. 5.12. FRICTION VS AMBIENT

XX XXX XXX XX XX XX X X X X

XXXXXXXX XXXXXX X X X X

XXX X XXXXX XXXX X X XXX

XXXXXXX X X X

XXXXXXXXX X X X X



XXX X XX



es / #4 / 17671

0.6



14/17672



FRICTION COEFFICIENT

·

س، براند کر بر

FIG, 5.14.



FIG. 5.15.





A4/17676











PS/A4 17678







CHAPTER SIX

THE RHEOLOGY OF RAIL CONTAMINANTS

6.1 INTRODUCTION

In the previous chapters a boundary lubrication model has been used to explain the changes in adhesion. In this model the friction coefficient $(\mu = F/N)$ between two surfaces is considered to be constant regardless of the normal load applied. Track tribometers and laboratory experiments can then investigate changes in the coefficient of friction using light loads. This approach is applicable to main line track where small changes in oil contamination substantially change the friction of the debris free wear band.

However, when solid contamination is trapped between the wheel and rail the boundary lubrication model no longer holds. The load, velocities of the surfaces, real area of contact and the rheology of the trapped material become important. The coefficient of friction between lightly loaded surfaces is no longer that experienced by a locomotive wheel under similar conditions. Equations that are applicable to a rheological model of wheel/rail adhesion are developed in this chapter. The rheological properties of common track contaminants are examined and conditions that can lead to loss of adhesion on the track are explored.

6.2 TRACK RESULTS

This section outlines the various conditions during which solid track contamination has been found to cause loss of adhesion.

A common but localised source of thick film track contamination is leaves (Broster et al 1970), which have a bad reputation for causing wheel slip (Awdry 1953) and subsequent delays (Guardian 1973). The tenacious films that form on main line track also lead to the production of wheel flats and rail burns (Pritchard and Tanvir 1973). Similar layers build up due to sawdust from saw mills and coal from coal merry-go-round hoppers. Grease from flange lubricators, mixed with solid debris, also forms thick low friction layers (Broster et al 1973).

- 50 -

In contrast to the above <u>localised</u> problems, rust can contaminate any rail. The first trains on Monday mornings have a reputation for slipping (Greaves 1972). This is possibly due to rust layers built up during the week-end being dampened by the early morning dew. A recent specific case of wheel slip underlines this condition. On 9 Jan 1973 an experimental train overran its prescribed stopping point at 45 mile/h, even though it had had over a mile to stop from its original speed of 60 mile/h. The test track had not been used during the previous winter and was covered with a thick layer of rust. The conditions were misty with occasional rain and presumably produced a "slightly wet" rail condition.

Although loss of adhesion has been connected with slightly wet conditions in the past (Greaves 1972, Allen 1954, Marta and Mels 1969) not much experimental work has been pursued where all the relevant factors have been considered under operational conditions. However, a thorough investigation was conducted by Barwell and Woolacott (1956 and 1963) who recorded incidents of slipping by detecting the sudden change in frequency of exhaust beats of steam locomotives operating on a 1 in 60 gradient. Some 4 000 measurements were made, the weather conditions and the wetness of the track being noted. It was found that only 8% of all locomotives suffered slip but that 21% slipped if there had been slight (0.05" to 0.005") rainfall in the preceding hour and that 69% slipped if there had only been a trace of rain (<0.005"). It was also noted that "dirty rails" were conducive to wheel slip. This was confirmed in a subsidiary set of experiments (Grunberg and Campbell 1956) where a correlation was obtained between the quantity of debris on the track and a high incidence of slip. Frequently used main line track is generally free from debris. When dry, the debris is continually compressed into small flakes which are thrown clear of the wear band on the passage of a train (Beagley et al 1973). When the track is thoroughly wet any debris or rust easily mixes with the water and is pushed to the side of the wear band. However, track tests using a sampling device (Beagley 1974, 1) have shown that debris coverage

on main line track (Derby/Birmingham) can be substantial. The quantity of debris on the wear band was determined by sealing off an oblong area and brushing up as much debris as possible into a suspension with water which was then removed using a syringe. Coverage varied rapidly and was a complex function of both traffic density and weather conditions. Dirty track, although rare, was more prevalent in the morning and during slightly wet conditions, and took the form of either a "slick" of oxide and water or of a compressed layer of oxide that was not easily removed using the sampling device. Under both these conditions the debris coverage $(1 - 4 \times 10^{-4} \text{ g/cm}^2)$ on main line track was equivalent to that found on little used track. Fig. 6.1 shows the difference between normally clean track and these two conditions. These results suggest that wheel slip due to rusty rail is not a problem uniquely connected with little used branch lines.

6.3 LABORATORY EXPERIMENTS

In the previous chapter low friction was observed when surfaces were contaminated with slightly wet oxide. Fig. 6.2 shows a typical result using the Amsler wear machine. Two rail steel rollers are rolled together with a relative slip of 3%, forming oxidised wear products on the surfaces. When the rollers are sprayed with water the friction coefficient falls Then, as the water dries (due to frictional heating) the oxide to 0.3. forms a tenacious paste on the surfaces and the friction falls to 0.17. Stainless steel rollers behave very differently when sprayed with water (Fig. 6.3) because of their resistance to corrosion. However, when an iron oxide slurry is applied to the rollers their behaviour is similar to those made of rail steel. Further experiments with the rail steel rollers (Fig. 6.2) showed that the low friction of 0.17 did not occur if brushes rubbing the surfaces prevented the build-up of the slightly wet oxide layer. In the other extreme two rollers on which a thick rust layer had been allowed to form gave a friction of 0.05 when subsequently loaded together under slightly wet conditions. This coefficient of friction

is significantly lower than that caused by most oily contaminants! Similar behaviour was observed when coal dust or leaf debris was applied to the Amsler rollers, Fig. 6.4 In this case, however, the solid contaminant lowered the friction even when dry and in contrast to the dry oxide formed relatively thick stable films.

An air gauge was attached to the Amsler machine in order to try to measure the physical separation between the rollers as wet debris dried. The instrument was accurate to 2.54×10^{-3} mm (1/10 000") but no separation could be detected as the iron oxide paste dried, showing how little debris is needed to cause low friction. Small separations were observed when other materials such as coal slurry dried on the rollers.

These experiments on the Amsler machine show qualitatively how a mixture of iron oxide and water can cause a substantial lowering of adhesion. The results also seem to indicate that the slightly wet oxide is behaving as a viscous lubricant, where the force transmitted by a viscous film is inversely proportional to its thickness (the quantity of debris trapped).

6.4 BASIC FRICTION EQUATIONS

In this section we consider how much tangential force can be sustained by surface films of materials with various idealised properties. No interfacial slip is assumed, the forces calculated being those at which the material itself will yield. Under any given condition this force can be divided by the sustained load to give the coefficient of friction.

The tangential force transmitted across a film of any material can be expressed in a general form, as the area (A) transmitting the force multiplied by a function of the rate of shear.

Equat 6.1 $F = A \times f_1$ (rate of shear) Equat 6.2 or $F = A \times f_1 (\frac{U_1 - U_2}{h})$

where $(U_1 - U_2)/h$ is the rate of shear, $U_1 - U_2$ being the velocity difference between the surfaces and h their separation. The rate of shear is usually expressed in sec⁻¹. Alternatively, σ y, the yield shear stress of the material can be introduced into the equations.

Equat 6.3
$$\mathbf{F} = \begin{bmatrix} \mathbf{A} & \mathbf{x} & \mathbf{\sigma}_{\mathbf{y}} \end{bmatrix} + \begin{bmatrix} \mathbf{A} & \mathbf{x} & \mathbf{f}_{2} & (\frac{\mathbf{U}_{1} - \mathbf{U}_{2}}{\mathbf{h}}) \end{bmatrix}$$

Now if this equation is divided through by the area, A, the force, F, becomes the shear stress (σ) sustained at the surface of the material. Equat 6.4 $\sigma = \sigma_y + f_2 \left(\frac{U_1 - U_2}{h}\right)$

Fig. 6.5 shows the various forms of equation 6.4. For a Newtonian fluid (Fig. 6.5a) equation 6.4 becomes: Equat 6.5 $\sigma = \eta \left(\frac{U_1 - U_2}{h} \right)$

The relationship is linear,
$$\eta$$
, (tan θ in Fig. 6.5a), being the viscosity
of the liquid. A Newtonian fluid has no yield stress and only transmits
a force due to the relative motion of the surfaces. However, for a simple
plastic solid (Fig. 6.5b) equation 6.4 becomes;

Equat 6.6 $\sigma = \sigma_y$

There is no "viscous" term, the transmitted stress being σ y regardless of the rate of flow.

In between these two extremes are three groups of behaviour. Fig. 6.5c represents a shear-thinning (pseudoplastic) material where the effective viscosity falls as the rate of shear increases. Fig. 6.5d represents a Bingham solid. These materials (e.g. clays) have a yield shear stress, but after this is exceeded the relationship of stress with shear rate is linear :

Fig. 6.5e, represents a shear-thickening (dilatant) material. These materials can again have a yield stress but the effective viscosity increases with shear rate. It should be noted however that, unlike the other modes of behaviour, dilatant behaviour cannot continue indefinitely with increasing shear rate. The material must eventually start shearthinning (or merely shearing).

Dry rust can easily be compressed into a solid pellet. However as the water concentration of a rust/water mixture is increased, it first resembles a moist clay (at approx. 30% by weight of water) and then a viscous slurry. A complete physical description of a varying rust/water mixture must embody many of the equations discussed in this section. There are then two coincident explanations for the low adhesion caused by slightly wet rust. The friction caused by a solid film will decrease as the water content is increased (i.e. σ_y is decreased) until such a time that the film is not strong enough to prevent the surfaces touching and equation 6.6 is no longer applicable. Alternatively, water alone cannot hydrodynamically lubricate either the Amsler specimens or a railway wheel until enough solid is added to increase its viscosity and cause friction to fall as the surfaces separate. In practice both points of view are relevant, low adhesion coinciding with the transition from solid to liquid behaviour of the rust/water mixture. In the following, the tribological consequences of these considerations will be examined both theoretically and practically with the support of simple experiments.

6.5 YIELD SHEAR STRESS

For a solid the maximum sustainable force equals its yield shear stress (shear strength) multiplied by the area sustaining the force: Equat 6.8 $F = \sigma_y \propto A$ or expressed as a coefficient of friction ($\mu = F/N$) where the solid is in the form of a surface film and N is the normal load.

Equat 6.9
$$\mu = \frac{\sigma_y \times \mu}{N}$$

Furthermore the shear strength of <u>any</u> material (not merely a solid) determines the resultant film thickness formed when it is plastically compressed between two flat surfaces. The following equation has been found to hold (Dukes 1970); Equat 6.10 $Y = \frac{1}{2} \frac{Nh^{\frac{5}{2}}}{2}$

- 55 -
Where Y is the yield stress (not yield shear stress), V the volume of material and h the separation of the surfaces.

Now, according to Tresca's criterion, Y, the yield stress (in compression) is double σ y, the yield stress in shear (Cottrell 1964). So equation 6.10 can be re-arranged.

Equat 6.11

$$\sigma_{y} = \frac{N}{4\pi^{2}r^{5}}$$

where r is the radius of a deformed disc of material $(V = \pi r^2 h)$ or

Equat 6.12
$$h = \frac{Oy}{N} \frac{4\pi r^3}{N}$$

where h is the separation of the platens.

6.6 YIELD SHEAR STRESS OF COMMON TRACK CONTAMINANTS Solid contaminant films scraped from the track can be reconstituted as pellets under the appropriate wheel/rail pressures (283 MN/m²) in a laboratory press. Hardness measurements can then be made using a pyramid diamond indentation test. If repeatable, well defined, indentations can be made, the material is homogeneous and can be ascribed a specific shear strength, calculated from the Vickers pyramid number:

Equat 6.13
$$Oy \approx \frac{V.P.N.}{6}$$
 Kg/mm² (Cottrell 1964, Tabor 1951)

For softer materials (e.g. debris plus water) it is easier to make use of equation 6.11. Mixtures of iron oxide and water were made up by hand, (precipitated $\operatorname{Fe}_{2}O_3$ was used because of its similarity to rail debris (Beagley et al 1973)). Samples of the mixtures were placed between glass plates and were carefully compressed by various loads. The resultant radius of the compressed sample and the separation of the plates were noted. A further sample from each mixture was dried and weighed in order to determine the percentage solid. By plotting the results on log/log paper, as NV versus r^5 , equation 6.11 is shown to be of the correct form, Fig. 6.6. It is possible to calculate σ y for each mixture, Fig. 6.7, from the regression lines fitted to the experimental points in Fig. 6.6. Table 6.1 shows the shear strength of the oxide/water mixtures, a mixture of oxide and oil and two leaf debris samples scraped from the track, compressed as pellets under 283 MN/m². From these values, theoretical stable film thicknesses can be calculated from equation 6.12 and coefficients of friction from equation 9, assuming railway loads of 5×10^4 N and 10^5 N. Typical wheel/rail contact areas are assumed to be 1.5×10^{-4} m² for a 5×10^4 N load and 2×10^{-4} m² for a 10^5 N wheel load. In Fig. 6.7 the yield shear stress for the oxide/water mixtures is extrapolated to the value for the dry oxide. This extrapolation has to be considered cautiously since only the dry oxide was subjected to compression before measurement of its properties. However, the trend probably does represent the change in physical properties of debris as it dries on the track. The theoretical yield shear stress for a 90% solid mixture included in Table 6.1 is obtained by using the extrapolation of Fig. 6.7.

Since iron oxide pastes are not true solids (the force transmitted being dependent on the shear rate, equation 6.4) theoretical coefficients of friction cannot be calculated. The viscous nature of the pastes must be taken into account and is considered in Section 6.8. However, both the predicted coefficients of friction and theoretical film thicknesses of solid track contamination are reasonable in comparison to those values found in practice. The film thicknesses represent the thickest stable layer given sufficient debris; any layer thinner than this value would also be stable.

- 58 -

TABLE 6.1

THE	SHEAR	STRENGTH	OF	IRON	OXIDE	MIXTURES,	THE	RESULTING	MAXIMUM	FILM
		THTC	KNES	SS AN	D FRIC	TTON COEFF	TCTE	νT		

	-					
Material	V.P.N.	Shear Strength	Resultant T mm	hickness	Coefficient of Friction μ	
		N/m бу	Load 5×10^4 N	Load 10 ⁵ N	Load 5×10^4 N	Load 10 ⁵ N
Precipitated Fe ₂ 0 ₃	60	10 ⁸	8.3	6.4	0.3	0.2
Fe ₂ 03 + 7.5% oil	25	4.2×10^7	3•5	2.7	0.13	0.03
Leaf Debris Sample 1	15	2.5×10^7	2.1	1.6	0.08	0.05
Leaf Debris Sample 2	7	1.2×10^7	1.0	0.8	0.04	0.02
Fe ₂ 0 ₃ /H ₂ 0 mix 90% solid		2.2×10^5	1.8×10^{-2}	1.4_{10}^{1}	(6.6×10^{-4})	$(4.4_{10} \times 10^{-4})$
Fe ₂ 0 ₃ /H ₂ 0 mix 80% solid		1.4×10^3	1.2×10^{-4}	9.0 ₅ x 10 ⁻⁵		
Fe ₂ 0 ₃ /H ₂ 0 mix 70% solid		38	3.2 x 10 ⁻⁶	$\frac{2.4}{10}$ x	Frict	tion
Fe ₂ 0 ₃ /H ₂ 0 mix 60% solid	2 ⁰ 3 ^{/H} 2 ⁰ mix % solid		3.2×10^{-7}	$\frac{2.4}{10}$ $\frac{4}{7}$ x	on flow	
Fe ₂ 0 ₃ /H ₂ 0 mix 50% solid		0.85	7.1×10^{-8}	5. <u>4</u> 8x 10		

6.7 DISCUSSION OF SOLID TRACK CONTAMINANTS

Film thicknesses tabulated in Table 6.1 represent the maximum possible under the stated conditions of load and area. A paste of iron oxide and water can only form a film thicker than $1 \ge 10^{-4}$ mm when it contains more than 80% solid. However the yield strength of a solid does not completely describe its behaviour as a film. On the passage of a wheel the elastic deformation of the wheel and rail causes the film to be strained. If the material is not pliable it retains the imposed deformation, detaches itself from the rail and is subsequently thrown clear of the wear band as a flake (Graver and Kendall 1971). Thus, in spite of the high yield stress of compressed iron oxide (enough to give good friction), its nonpliability results in a clean wear band being formed on well used track. This is a physical explanation for the capricious nature of natural rail contamination, which can only be trapped on the wear band under certain well defined conditions.

Grease by itself does not have a sufficiently high yield stress (\Im y approx. 500 N/m²) to maintain a film between wheel and rail. However, when grease, or oil, is mixed with rail debris, the debris effectively supplies the "yield strength", the oil the "pliability" and a stable film of low shear strength can be formed. Films formed on the railhead near flange lubricators are found to contain a high percentage of iron oxide mixed with grease (Broster et al 1973).

During an investigation into the removal of leafy contamination (McEwen 1974) attempts were made to simulate this type of film on the track. It proved remarkably difficult; either the material was pushed aside or it flaked off on the passage of a train! Finally a satisfactory simulant was concocted using a mixture of filter paper pulp and iron oxide. This confirms the particular nature of leafy track contamination. The fibrous nature of the leaves, combined with the track debris (found by analysis), forms films that are both strong enough and pliable enough to remain on the track. The low friction, calculated from the shear strength of the leafy contamination in Table 6.1, agrees well with values observed using an experimental train (McEwen 1974).

6.8 FLOW PROPERTIES OF OXIDE/WATER MIXTURES

The torsional friction rig (Beagley et al 1971) reproduces the conditions of load and contact area found between wheel and rail by compressing a central platen between two plain ended cylindrical plungers (15 mm diam.). Various mixtures of iron oxide and water were loaded between the test surfaces. Torque was then slowly applied to twist the platen against the plungers. Small movements occurred at even the lowest torques. The coefficients of friction shown in Table 6.2 were calculated from the torque finally required to produce a full 15⁰ twist.

- 59 -

TABLE 6.2

FRICTION OF OXIDE/WATER MIXTURES ON THE TORSIONAL FRICTION RIG.

% <u>debris</u> debris + water	58.8%	61.7%	63.8%
μ under 2 tonnes load	0,10	0.03	0.01
μ under 4 tonnes load	0.24	0.14	0.05

The stable films formed by the mixtures were thicker than the equilibrium thickness predicted in Table 6.1 because the mixtures "de-watered" forming small islands of water and solid mixture within the contact area. This important phenomenon will be considered later. However, the small movement experienced at low torques confirmed the low order of magnitude of the shear strength. Furthermore the friction <u>decreased</u> as the shear strength <u>went up</u> (increased percentage solid). The higher shear strength caused a thicker stable film to be supported by the solid "islands", resulting in lower shear rates at any given slip speed. The viscous component then apparently dominates slip in this complicated situation; the lower shear rate results in lower friction. Although these figures give a useful qualitative result, the physical conditions, with material being squeezed out as twist occurs in a jerky manner, are too complex for the physical properties of the mixtures to be calculated.

In order to measure directly the shear properties of iron oxide/water mixtures a simple disc viscometer was constructed. In this the material to be examined was placed between a disc and a ring of perspex held a fixed distance (h) apart. The ring was driven at a constant speed and the torque transmitted by the ring of trapped material was measured by restraining the perspex disc with a spring balance. The separation of the surfaces was changed to produce measurable torques transmitted by mixtures with a wide range of viscosities. Over a limited viscosity range, obtained with fairly liquid mixes, comparable results were obtained using a Ferranti-Shirley viscometer. The viscometer measured the force, F, in equation 6.3. The apparent viscosity, η' , of each mixture measured was calculated using :-Equat 6.14 $\eta' = \frac{F \times h}{A \times v}$

where v is the effective surface speed and A is the area being sheared. The apparent viscosity ignores the yield stress (shown later to be small) and is plotted in Fig. 6.9 versus percentage solid. In order to obtain measurable transmitted torques the shear rate had to be increased (from 10 to 88 secs^{-1}) as the viscosity of the mixtures decreased. The effect of shear rate on viscosity was determined using a Brookfield Viscometer. This is a more sensitive instrument than the specially designed viscometer but because of its geometry, a disc rotated at constant speed in the material, only approximate shear rates can be ascribed to each situation (Wichterle and Ulbrecht 1967, Beazley 1972). Initial readings at low shear rates sometimes increased with time. Final readings were taken by increasing and decreasing the spindle speed several times over the whole range until stable values were obtained at all four shear rates. These results are shown in Fig. 6.9 along with a curve translated from Fig. 6.8. The trend of the constant shear rate curves was inferred from the maximum torque being registered on the instrument as the solid content was increased.

6.9 DISCUSSION OF THE RHEOLOGICAL PROPERTIES OF OXIDE/WATER MIXTURES Fig. 6.9 shows two interesting features. Firstly, the viscosity of the mixtures varies rapidly with percentage solid (approximately logarithmically, see Fig. 6.8). Secondly, below approximately 60% solid the viscosity tends to fall as the shear rate increases (the material is shear-thinning, pseudoplastic), but above this value the viscosity increases with increasing shear rate (the material is shear-thickening, dilatant). The comparison in Fig. 6.9 of the disc viscometer results (with its shear rate decreasing from 88 to 10 secs⁻¹ as solid concentration increases) with those of the Brookfield show a coherent trend of pseudoplastic behaviour turning to dilatant behaviour as solid concentration increases. This is to be expected (Fischer 1950, Roberts 1962) especially with the plate-like oxide particles, which become enmeshed as the shear rate increases.

Table 6.3 presents the Brookfield results in another form. The measured stresses at different shear rates are shown together with the corresponding yield shear stresses for various percentage solids. These are the values σ and σ y from equation 6.4;

-U₂)

Equat 6.15
$$\mathcal{O} = \mathcal{O}y + f\left(\frac{U_1}{U_1}\right)$$

TABLE 6.3

STRESSES (σ) OBSERVED AT DIFFERENT SHEAR RATES COMPARED WITH DEDUCED YIELD

	Yield Shear	Stress	N/m ²	σ	
%Solid	Stress ØyN/m ²	$0.75 \mathrm{sec}^{-1}$	$1.5 {\rm sec}^{-1}$	$3.0 \ {\rm sec}^{-1}$	$6.0 \mathrm{sec}^{-1}$
55%	1.6	6.5	18.0	27.0	27.6
60%	3.8	7.5	19.8	48.0	120
65%	12	12.3	27.9	_	······································
70%	38	21.15	39.0		

STRESS (σ_y) .

By comparing the two sets of values it can be seen that the "viscous" force predominates over the yield stress at all but the lowest shear rates i.e. the apparent viscosity is numerically equivalent to the real viscosity.

With a high percentage solid content the yield shear stress is greater than the force sustained at low shear rate. This is not as incongruous as it appears. Even during the yield stress tests the material is sheared as it is compressed between the glass plates and therefore dilates (i.e. becomes more viscous) if there is more than 60% solid present. This effect is also seen in Fig. 6.6 where at high values of r^5 values (which can be equated to high shear rates) several points fall well outside the natural scatter. Shear rates on the track will be several orders of magnitude (up to 10^6 sec^{-1}) larger than those used in these experiments. However, practical problems mitigate against reproducing these higher shear rates in test instruments. Interfacial slip between sample and measuring face is a great problem at high solid concentration (Cheng 1974). Furthermore dilatant materials are notoriously difficult to deal with. By their very nature they tend to form solid areas in the bulk of the material which expand as the shear rate around them increases. This process rapidly spreads until the instrument is jammed solid! Generally, however, water/solid mixtures show consistent behaviour (Beazley 1972, Roberts 1962) over a wide range of shear rates. A few tests, kindly conducted by Dr. Beazley, (English Clay Lovering Pochin & Co. Ltd.) show this is also true for our iron oxide/

water mixtures in the pseudoplastic regime (50% solid) over a wide range of shear rates $(10^{-1} \text{ to } 10^4 \text{ sec}^{-1})$.

6.10 THEORETICAL ANALYSIS OF HYDRODYNAMIC LUBRICATION BETWEEN WHEEL AND RAIL

In Section 6.7 it was shown how the yield stress of a material will control its film thickness on the track. For a solid it also limits the force that can be exerted across it, and thus the coefficient of friction. However, in Section 6.8 three important rheological properties of oxide/ water mixtures have been established. Firstly, the viscous nature of the material predominates over its solid nature (especially at the high shear rates seen on the track). Secondly, its viscosity can reach very high values. Thirdly, large changes in viscosity occur with only small changes in the amount of water present. Hydrostatic pressure within a contaminant mixture trapped between wheel and rail will be several orders of magnitude larger than that produced by the laboratory rigs used to measure the physical parameters. However since the viscosity of water exhibits very little pressure dependance it can be assumed that the aqueous mixtures are also iso-viscous.

- 63 -

In this section a simplified model for the hydrodynamic lubrication of a train wheel is developed. The oxide/water mix is assumed to be fundamentally viscous. The low friction, "slightly wet", condition is shown to be caused by hydrodynamic lubrication, where the wheel and rail are separated (at least partially) by the contaminant on the track.

Martin (1916) formulated rheological equations, describing two <u>infinitely</u> <u>long undeformed</u> cylinders submerged in a lubricant. The resulting pressure distribution and uniform flow pattern are shown in Fig. 6.10A, while the minimum separation, h_{o} , between the cylinders is given by :

Equat 6.16 $h_{o} = 2.445 \frac{(\eta \, \overline{u})R}{W}$

Where W is the load per unit width of cylinder, supported by a lubricant of viscosity η . R is the effective radius of the cylinders $(1/R = 1/R_1 + 1/R_2)$ and \overline{u} is the vector sum of the surface velocities $(U_1 + U_2)$. Real separation occurs (i.e. hydrodynamic lubrication) if the generated thickness, h_0 , calculated from equation 6.16 is greater than the combined roughness of the surfaces in terms of asperity heights.

Now, a railway wheel will normally be deformed by the load to form a flat contact area with the rail. Only if there is very thick and viscous contaminant on the track will the wheel remain cylindrical. Equation 6.16 does not take account of the finite shape of the contact or of the fact that there is only a limited supply of "lubricant". Fortunately the effects of these factors on the basic equation 6.16 have been analysed.

For an undeformed contact :-

and for a deformed contact :-

Equat 6.17 $h_0 = 2.445 \eta \,\overline{u} \, R \, W^{-1} \, x \, I.F. \, x \, S.L.F.$ (Wolveridge, Baglin and Archard 1971).

Equat 6.18 $h_o = 2.04 (\eta \ \bar{u} \ R)^{3/5} E'^{-2/5} W^{-1/5} x I.F. x S.L.F. (Baglin and Archard 1972).$

Where $E' = \frac{E}{1-P}^2$ where E = Young's Modulus and P = Poisson's Ratio (0.3 for Steel) S.L.F. is the side leakage factor and represents the effect of pressure loss from the side of the contact, as shown in Fig. 6.10B (i.e. material being pushed aside). S.L.F. is a number that approaches unity as the geometry approaches that of two aligned cylinders.

Equat 6.19 S.L.F. = $\left[1 + \frac{2}{3} \frac{Rx}{Ry}\right]^{-1}$ (Archard and Cowking 1965) Where R_x is the effective radius in the direction of motion and R_y the lateral radius. For the same surface geometry S.L.F. appears to have the same value for both equation 6.17 and 6.18 (Wolveridge, Baglin and Archard, 1971, discussion).

I.F. is the inlet factor and is a complex function of the quantity of lubricant present, represented by the length (x), approaching unity as the contacts become fully submerged. Obviously no hydrodynamic lubrication can take place if there is no lubricant present!

The geometry of the contacts is shown in Fig. 6.11. The contact deformation is assumed to be that found if no lubricant were present (Grubin and Vinogradova 1949) i.e. Hertzian.

h_o was calculated from equation 6.17 and 6.18 for the following conditions:-A. Wheel load (N) of 5 x 10^4 N (5 tons) and 10^5 N (10 tons). B. Two conditions of wheel/rail conformity.

- A partially worn wheel (417 mm (16.4") lateral radius) on a worn rail (229 mm (9") radius) giving an equivalent lateral radius of 508 mm (20") and thus forming a circular contact.
- 2. A hollow tread (351 mm (13.8") lateral radius) on a new rail (305 mm (12") radius) giving an equivalent lateral radius of
 2 388 mm (94") and thus forming a contact in the form of a wide ellipse across the railhead.

C. Five levels of rail contamination shown in Fig. 6.12

Fig. 6.12 shows the solutions for a circular contact supporting a 10^{5} N load. h_{o} is plotted versus $\eta \bar{u}$ for both the undeformed (equation 6.17)

and deformed contacts (equation 6.18). The deformed solution is relevant when the calculated magnitude of the separation is greater than that predicted by the undeformed solution. In fully flooded conditions the surfaces could conceivably become sufficiently separated at high values of viscosity and speed. However as conditions become progressively more starved the surfaces approach one another, deform and are separated by the value calculated using the deformed solution (equation 6.18). Curves are given for six conditions of 'starvation' or initial material thickness as measured by the parameter x mm.

Using the deformed solution Figs. 6.13 and 6.14 again show the separation, h_o , as a function of η \bar{u} , but instead of using the inlet factor **x**, curves are presented for four starvation conditions in terms of a more practical parameter, the thickness of material, H, on the track in front of the wheel. Naturally h_o tends to H as the viscosity and speed increase. Fig. 6.13 shows the solution for a $10^{5}N$ load on a circular contact and, in contrast, Fig. 6.14 shows the solution for a $10^{5}N$ load and an elliptical contact. The wider contact of the latter leads to the development of thicker films. For a given side leakage factor (i.e. wheel/rail contact geometry) results using the load of 5 x $10^{4}N$ are similar to those for the $10^{5}N$ load (the smaller deformed contact area caused by the lighter load develops similar films).

Now the hydrodynamic lubrication of wheel and rail (h_o greater than the roughness of the surfaces) is of little consequence until torque is exerted on the wheel, either to accelerate or decelerate the train. To determine the frictional forces some relative slip has to be assumed. Consider braking, when maximum force will theoretically be exerted when the wheel is locked (U_2-U_1 is at a maximum). Then :-Equat 6.20 $\mu = \frac{1}{N} x$ (contact area $x \eta \propto \frac{U_2}{h}$) (See Equat 6.5)

Using equation 6.20 isofriction lines are drawn on Fig. 6.13 and 6.14. This assumes that all the material being sheared is in the contact area and that \overline{u} has not changed. The latter is not strictly true. The isofriction lines represent the maximum force that can be exerted before the development of wheel flats (shown later to be more prone to hydrodynamic lubrication than the above theory suggests).

Fig. 6.13 and 6.14 can be used in the following way : Take, for example, the experimental train discussed in Section 6.2 travelling at 60 mile/h on slightly wet rusty track. Assume the contamination was 2.54×10^{-2} mm thick with viscosity of 10 poise and the wheels had a hollow wheel profile. From Fig. 6.14 the wheels and rail would have been separated by a film thickness, h_0 , of 1.05×10^{-2} mm. The combined roughness of a wheel and the track would have been less than this value, complete hydrodynamic lubrication taking place with adhesion dependent on the material properties of the film. From the graph it is predicted that the maximum coefficient of friction obtainable by any wheel is less than 0.01. Coefficients of friction of this order must have occurred in practice, giving rise to the exceptionally long stopping distance.

6.11 DISCUSSION OF HYDRODYNAMIC LUBRICATION

6.11.1 The Amsler Machine

The Amsler rig (Section 6.3) provides the closest laboratory simulation of hydrodynamic track conditions. Although the velocities (0.4 m/sec) are low, the contact width is of the same order as that on the track. It can be assumed that the surfaces experience the same mechanism as occurs on the track, underestimating the range of conditions in which low friction may occur in practice at higher surface velocities. Theoretical analyses similar to that in Section 6.10 predict very low coefficients of friction $(\approx 10^{-3})$ and show that viscosities of 10^2 to 10^3 poise are necessary before hydrodynamic lubrication can occur. Calculations involving inlet factors and coefficients of friction are difficult because of the relatively small size of the deformed area. However the friction of 0.05 obtained with slightly wet rust and 0.02 with slightly wet leaf debris can be accounted for by the rolling resistance (Dowson and Whomes 1967), indicating that complete hydrodynamic lubrication was taking place.

The minimum coefficient of friction of 0.17 that occurs as the wet oxide on the rollers is drying is a result of the restricted quantity of "lubricant" being unable to provide the increased film thickness that would be commensurate with the increased viscosity of the slightly wet mixture. When self-generated wear debris is initially wetted it forms a thin slurry which, because of its low viscosity (0.01 poise), causes no surface separation and the resultant friction ($\mu = 0.3$) is that of clean wet rollers in contact. As the surfaces dry, most of the debris mixture is pushed to the side of the roller where it no longer has any effect on friction. The fact that the small remaining quantities of paste still cause a loss of friction indicates that, at higher velocities, locomotives will see a drop in available adhesion under slightly wet conditions, even on nominally "clean" main line track.

6.11.2 Hydrodynamic Lubrication on the Track

Hydrodynamic lubrication is not possible on the track with a film thickness less than approximately 10^{-3} mm, dependent on the roughness of wheel and The surfaces begin to touch if the conditions specified in Figs. rail. 6.13 and 6.14 result in a film thickness h_0 less than this. It follows that water, with a viscosity of 0.01 poise, could never produce separation even for flooded conditions (large H and \mathbf{x}) and high train speeds. The theory, however, shows that a paste of high viscosity can cause separation together with low coefficients of friction. Iron oxide/water pastes can provide this viscosity. Fig. 6.8 shows how the viscosity changes from 5 to 1 000 poise as the percentage solid varies from 50% to 65%. For a given inlet condition the minimum friction occurs just as the surfaces come into contact (minimum h_0). However, if the resultant film thickness, h, is much smaller than H (Fig. 6.13 and 6.14) each wheel is effectively pushing some of the material aside, thus presenting a lower H to the subsequent wheel. Thus, although individual axles may spin or skid the behaviour of most of the wheels of a train is described by the "plateau"

of the appropriate curve, where $h \simeq H$. It can be seen that hydrodynamic lubrication is more likely to occur at high speeds, with heavy contamination of high viscosity. Smoother surfaces also allow smaller values of h_0 to sustain hydrodynamic conditions.

The results have been presented as if material is not carried around on the circumference of the tyre. However, when locomotive wheels spin on wet, rusty track the debris is carried round and a situation similar to a journal bearing is established.

Consideration of the inlet conditions also explains why locked wheels are reputed to have poor braking efficiency. Two factors are important. Firstly, the debris begins to pile up in front of the wheel, altering the initial film thickness H. Secondly, as the wheel skids along the rail, the development of a worn flat enlarges the area of contact which can more easily sustain hydrodynamic lubrication, thus increasing the probability of low friction. It was because of locked brakes that the train, referred to in Section 6.2, skidded for over a mile.

In Section 6.8 (Fig. 6.9) the viscosity of an iron oxide paste was shown to vary rapidly with percentage solid content. Furthermore below 60% solid the material is pseudoplastic (shear-thinning). Hydrodynamic lubrication is unlikely under these conditions since the effective viscosity of the paste will rapidly drop as it is sheared, finally resulting in surface contact. However above 60% solid the dilatant behaviour of the material will be conducive to hydrodynamic lubrication. As the paste is either pushed aside or sheared by the wheel it will thicken and resist further deformation. On rails this condition is obtained in slightly wet or misty conditions where the supply of moisture is limited and the debris mixture naturally contains more than 60% solid.

6.11.3 Hollow Wheel Profiles

Hollow tread profiles have often been associated with a loss of adhesion (Greaves 1972). This report suggests there are two reasons for this.

described in Section 6.2 (Fig. 6.1), was due to wheels that pumped the wet rust onto the wear band.

Secondly the width of the contact has a significant effect on side leakage (the proportion of material pushed to the side of the contact under slightly wet conditions). The result of increasing profile hollowness, can be seen by comparing Figs. 6.13 and 6.14. At low η \bar{u} the increased width of the contact increases the resultant film thickness, h_0 , thus increasing the <u>probability</u> of hydrodynamic lubrication on lightly contaminated rails. It is interesting to note that Greaves (1972) specifically associates the loss of adhesion caused by hollow wheels with slightly wet conditions.

6.12 GENERAL DISCUSSION

Three theoretical models can be used in describing wheel/rail adhesion. The boundary lubrication model is valid when the rail is free from oxide and debris; the adhesion then being controlled by the degree of fluid contamination. However when surface interactions are significantly hindered by the presence of trapped debris other theoretical models must be invoked. These have been shown to take two forms. One rheological model is applicable to debris when it is "solid", the other when it is "viscous". Naturally, the transition conditions between the three models are important in understanding wheel/rail adhesion.

Transition between the rheological models occurs as debris contamination dries and "viscous" behaviour is replaced by "solid" behaviour. This transition will also be encouraged by the dilatant nature of the iron oxide paste. Tests using a press showed that de-watering of the debris/ water mixtures could be brought about under high pressure gradients. This time dependent effect has been observed elsewhere (Cheng 1974) and is a result of the water being squeezed out of the mixture leaving areas of higher solid concentration to support the load. For slower trains this must again result in a viscous/solid transition.

Although the viscous/solid transition is analytically interesting, it is of little practical importance since low friction occurs on either side; with a highly viscous material because of hydrodynamic lubrication or a weak solid due to its low shear strength. However it should not be forgotten that even during viscous behaviour the yield stress of the material is still important in determining the film thickness that can be left on the track.

The transition that occurs between the boundary lubrication and rheological models is very important. In the former, small quantities of debris improve adhesion by adsorbing oil (Chapter 4 (Beagley et al 1973)). In the latter, debris can cause low adhesion. The problem is to decide the debris coverage necessary to give rise to the low friction conditions predicted by the rheological equations. Simplistically, the debris coverage shown in Fig. 6.1B obviously separated wheel and rail since the metallic wear band is obscured! The debris coverage on main line track was found to rise to 2×10^{-4} g/cm² under certain conditions. (This was the quantity removed from the track using the sampling device (6.2), and, as such, is probably a conservative estimate). In a low friction, rheological, situation this debris would be in the form of a paste containing approximately 35% by weight of water, making 3.0 x 10^{-4} g/cm² or a layof approximately 2 x 10^{-3} mm thick. Clearly if a similar amount were also present on the wheel the hydrodynamic lubrication predicted by Figs. 6.13 and 6.14 could occur. This calculation shows, reassuringly, how practical experimental evidence agrees with the broad theoretical model adopted here; the quantity of debris on main line track only occasionally being sufficient to cause wheel slip. However, even relatively light debris coverage, when slightly wet, will cause a drop in available adhesion by producing partial hydrodynamic lubrication as seen on the Amsler machine.

Significantly, both rheological models predict that the lowest coefficient of friction occurs as the surfaces are just separated (Table 6.1, Figs. 6.13 and 6.14).

6.13 REMEDIES

This chapter has clearly shown why trains are liable to slip on debris covered track, especially under slightly wet conditions. An examination of track contamination, along with Barwell's results, suggests that even on main line track most adhesion problems could be caused by debris. Further verification of the theories and proposed remedies should only be pursued using an instrumented train. Track tribometers are generally unsuitable because on thick debris the contact area is badly defined and because conditions differ vastly from those seen by a locomotive.

On inclines etc. where good adhesion is regularly required, an obvious solution to the above problems is to prevent corrosion using a lineside applicator. However, this technique is unlikely to be successful on little used track. Another approach is to "upset" the slightly wet conditions when it occurs. Sand probably achieves this by absorbing the water as it is crushed, although it adds to the bulk of the debris encountered by subsequent axles. An application of water should also be beneficial, causing the paste to revert to a slurry and so be pushed aside by subsequent wheels.

Alternatively, chemicals may be added which change the physical nature of the debris/water mixture. In water, iron oxide takes the form of flocculated solid. It should be possible to deflocculate such a mixture by small additions of an appropriate surfactant. Deflocculation is accompanied by vast changes in physical properties (e.g. Van Wazer et at 1963). The viscosity changes are large, but more significantly the yield stress drops, sometimes disappearing altogether (Beazley 1972). In Section 6.6, the yield stress of a material was shown to control its film thickness when compressed between wheel and rail. Thus by applying the correct surfactant significant debris coverage on main line track

- 72 -

might be eliminated. A few tests using parallel plate plastometry showed that a 4% solution of sodium metasilicate (a promising remedy (S.N.C.F. 1971)) reduced the yield stress of the iron oxide mixtures. Tertiary butylamine (Fig. 6.15) was even more effective, reducing the yield stress of an 80% solid/water mixture by a factor of 10. Furthermore the trend of the points in Fig. 6.15 suggests that mixtures including butylamine are pseudoplastic (shear-thinning) rather than dilatant (when no surfactant is added). This would significantly help the wheel to squeeze the material away from the wear band. Indeed, a material that caused shear-thinning at high shear rates would make a suitable train mounted remedy.

6.14 CONCLUSIONS

The causes of low adhesion on the track due to solid contamination have been analysed. Under these conditions the classical boundary lubrication equation ($\mu = F/N$) no longer holds. Coefficients of friction measured with lightly loaded tribometers under debris contaminated conditions cannot be transposed to describe wheel/rail adhesion.

A permanent build-up of track debris is only possible when the contaminating material has specified properties combining both yield strength and pliability.

Solid contaminant films reduce adhesion if their shear strength is low. Leaves, oil and coal contamination can form films of low shear strength. Very low adhesion can be caused by slightly wet track debris. This acts as a viscous lubricant fully or partially unloading the wheel from the rail according to the degree of contamination present.

Track observations have shown that significant debris coverage occurs on / main line track under certain conditions.

The rheological properties of wet rail debris changes rapidly with water concentration; misty conditions or light rain being necessary before severe loss of adhesion can occur.

The poor adhesion of hollow wheel profiles has been explained.



WEAR BAND

TYPICAL DEBRIS COVERAGE

Debris removed using sticky foambacked tape.



DEBRIS COVERAGE DURING SLIGHTLY WET CONDITIONS.

Debris removed using sticky foambacked tape.



DEBRIS COVERAGE DURING SLIGHTLY WET CONDITIONS.

Debris / water "slick" removed using filter paper.

FIG 6.1 DEBRIS COVERAGE OF MAIN LINE TRACK.



HG.62 FRICTION OF RAIL STEEL ROLLERS ON AMSLER AS A FUNCTION OF SURFACE CONDITION. <u>3%CREEP.</u> IOO kgm. LOAD.



FIG. 6.4.



FIG.6.4. FRICTION OF COAL DUST AND LEAF DEBRIS ON AMSLER. <u>3% CREEP.</u> IOO kgm, LOAD. RAIL STEEL ROLLERS.

ERS/A4/17683

4





FIG. 6.7

Ċ



FIG. 6.7 YIELD SHEAR STRESS OF Fe2031 WATER MIXTURES

RS/A4/17401



RS/R4/17685

.





A4/17686



CONDITIONS OF WHEEL / RAIL CONFORMITY

I. PARTIALLY WORN WHEEL	417 mm LATERAL RADIUS 229 mm. LATERAL RADIUS LON	IVALENT LATERAL RADIUS 508mm. IGITUDINAL RADIUS 508mm. (R)
FOR 5 x 10 ⁴ N LOAD	CIRCULAR CONTACT	IO 8mm. DIA.
FOR IO ⁵ N LOAD	CIRCULAR CONTACT	13 8mm. DIA.
2. HOLLOW WHEEL	351mm LATERAL RADIUS 305mm LATERAL RADIUS LONGI	LENT LATERAL RADIUS 2388mm. TUDINAL RADIUS 508mm.(R)
FOR 5 x 10 ⁴ N LOAD	ELLIPTICAL CONTACT	21- 4mm x 7 [.] 2mm
FOR 10 ⁵ N LOAD	ELLIPTICAL CONTACT	27mm x 9 Omm. /

FIG. 6. II IDEALISED GEOMETRY OF RAIL / WHEEL CONTACT









CHAPTER SEVEN

GENERAL DISCUSSION AND CONCLUSIONS

7.1 INTRODUCTION

In the previous chapters the frictional behaviour of each of the principal groups of track contaminant was examined individually. Although water and oil generally lowered adhesion, it was found that solid debris could either increase the coefficient of friction by adsorbing oil under dry conditions, or significantly lower adhesion when mixed with small quantities of water. In this chapter the experiments on the various laboratory rigs will be discussed with special reference to the interactions of water, oil and solid debris. The accuracy of the laboratory simulation will then be critically assessed. The thesis concludes with a description of how rail contamination controls wheel/rail adhesion.

7.2 LABORATORY EXPERIMENTS

7.2.1 Oil

Oil, not surprisingly, reduced friction when applied to laboratory specimens. The degree by which the coefficient of friction was lowered was found to depend on the quantity of oil present (3.4.1) and, to a lesser extent, on its surface-activity (3.4.2). When specimens were contaminated with surplus oil similar coefficients of friction, dependent on the fluids surface-activity, were observed on both the Amsler machine (3.5) and the rolling disc tribometer (3.4). It can be concluded that equivalent boundary lubrication mechanisms control the surface interactions on both rigs despite their different mode of operation. Prolonged testing on the Amsler machine showed, however, that friction fell as oils degraded and formed polymeric lacquers on the rollers (3.5). No such surface was formed on the plates of the rolling disc tribometer although the friction of non-surface-active oils did decrease with time (3.4.2). Undoubtedly oil oxidises on the track (3.3), probably reacting with the steel of the wear band to form a surface with characteristics between those of the Amsler rollers, run for several hours in oils, and those of a rail steel plate

on which oil has merely chemisorbed. On the machines involving continuous rolling contact, measurement of friction associated with lightly contaminated "run-in" surfaces is difficult since the debris continuously adsorbs the oil (4.3). For this reason friction on dynamic machines is generally much higher than that observed on the rolling disc tribometer, given the same degree of oily contamination.

Experiments on the rolling disc tribometer have shown how the relationship between oil coverage and friction is of fundamental importance to wheel/ rail adhesion. Small changes in the degree of contamination about the mean level found on main line track produces large changes in the coefficient of friction (3.4). However in our experiments several monolayers of oily contamination did not cause the low friction that might be expected from earlier experiments on boundary lubrication (Bowden and Tabor, 1950), in which just one monolayer was sufficient to lower friction to 0.1. This difference in behaviour presumably arises from the different apparatus used in the two experiments. On the rolling disc tribometer several measurements are initially made on fresh tracks on the contaminated plate in order that the contamination may become "equilibriated" between disc and plate (2.2). The disc slides on one area of the plate as a measurement is made, with any tendency to form wear debris causing friction to rise as boundary lubrication is further interrupted. When the disc is moved on to a new track friction is either progressively lowered, if the plate is more oily than the disc, or raised as the cil is transferred to the cleaner plate and subsequent metallic wear helps clean the disc. A wear transition occurs at a coefficient of friction of about 0.3, below which only mild wear was apparent. It is perhaps surprising that stable equilibrium coefficients of friction were found between the two extreme values associated with the clean and oily conditions respectively. The experimental rig used by Bowden and Tabor draws a ball across the contaminated plate. The ball, which tends to wear to a flat during the traverse, can collect surplus oil on the leading edge of the contact

area. Although one monolayer on such rigs is initially sufficient to cause low friction (Beagley et al 1971), friction increases rapidly with repeated traverses as the protective oxide and oil film are worn away. For a similar reason higher coefficients of friction are found on the rolling disc tribometer where friction is calculated from the force exerted by the worn disc as it slides on one small area of the plate. This is equivalent to an extended sliding distance (Archard 1958) where metallic welds can form which interrupt the boundary lubrication of the surfaces.

7.2.2 Debris

The oxides and hydroxides that contaminate every rail in varying degrees consist of fine particles which have high surface areas. Laboratory experiments clearly show how this surface area is important in controlling the resultant friction when debris contamination is mixed with oil (4,2). The results indicate that adsorption mechanisms predominate over abrasive mechanisms. This is hardly surprising when the fundamentals of boundary lubrication are considered. Degassed, oxide free, surfaces generate coefficients of friction of the order of ten (Bisson et al 1957). It is the oxides naturally formed on most surfaces that give rise to coefficients of friction less than unity. Consequently additional amounts of similar oxides introduced between specimens have little influence either in dry conditions or when surrounded by surplus oil or water. Debris only affects friction when it is able to adsorb the oil that would otherwise lubric te the specimen surfaces.

Boundary mechanisms cannot be used to describe the force transmitted due to creep between the rollers of the Amsler machine which are covered in wear debris. Shearing occurs in the oxide layers with no metal to metal interaction being apparent. When the rollers are run in a copious supply of fluid (water or oil) the debris is washed from the surfaces and it is not surprising that coefficients of friction similar to those on the rolling disc tribometer are observed (5.2, 5.6.2). However, it is
surprising that the friction between rollers of the Amsler machine contaminated with dry or slightly oily iron oxide is comparable to the friction caused by similar debris sprinkled on the plate of the rolling disc tribometer (4.3.3).

Under some circumstances very significant differences in the coefficient of friction can be observed on the various laboratory rigs. This usually occurs when the contaminant e.g. leaf debris or coal dust, causes low friction on the Amsler machine due to the formation of stable films adhering to the rollers (6.3). Higher friction is found when this kind of contaminant is spread on the plates of the rolling disc tribometer where the disc usually makes metallic contact with the underlying plate. This difference between the rigs is very important not only because of the low coefficients of friction that can arise but also because simple mixtures of water and iron oxide can behave in a similar manner. Boundary lubrication mechanisms with the coefficient of friction being largely independant of the loading and relative movement of the surfaces, are no longer applicable when solid contamination is interposed between specimen surfaces. Under these circumstances agreement between rigs must be regarded as being fortuitous rather than a fundamental measurement i.e. the coefficient of friction associated with a specific contaminant. In order to examine the effects of solid contamination on wheel/rail adhesion, theory was developed in Chapter 6 based on the contaminant's material properties. The rheological analysis examined various aspects that need consideration when two surfaces separated by trapped material are moved relative to one another. Due to the complexity of the equations several factors were not considered. Tangential forces were calculated from material properties assuming that the trapped contaminant was homogeneous and that it sheared rather than that slip occurred between it and one of the specimen surfaces. This, latter behaviour has been observed on the torsional friction rig when oil was squeezed from contaminated debris allowing slip to occur between the surface of the pellet and a plunger (Beagley et al 1973). When interfacial slip occurs the measured coefficient of friction will, of

course, be lower than the theoretical maximum calculated from the shear strength of the pellet. The shear strength is in turn calculated from diamond indentation tests made on the face of a pellet formed by compression under a given load. However, the assumption that a pellet has a uniform shear strength throughout its thickness can lead to further errors when considering thick contamination. The individual grains or particles of debris are compressed into a coherent mass by the hydrostatic pressure that exists between specimen surfaces. A thinner pellet will be more thoroughly compressed and can be expected to have a higher shear stress than a thicker pellet of the same material compressed by the same load (Cottrell 1964). Experiments on the torsional rig (Beagley et al 1973) indicated that this was indeed the case, with resultant coefficients of friction reducing as thicker films of dry compressed rust were sandwiched between the plungers and the central platen. A similar effect was observed on the Amsler machine (6.3), with freshly applied debris causing a temporary reduction in friction. As some of the debris was worn off and the rest compressed the adhesion increased to a stable value.

7.2.3 Water

Water is perhaps the single most important component of track contamination, not only because of the large changes in friction it can cause but also because of the rapid variation in the degree of wetness that can occur. A number of experiments (5.2) showed how water further lowered the friction of oily surfaces. Extensive tests (5.4) indicated that water promotes the mobility of surface-active oil molecules thus explaining the pronounced decrease in friction that occurs when water is applied to slightly oily surfaces. The only occasion that water is ever associated with an increase in friction is when it is applied to specimens contaminated with a nonsurface-active material (5.2). The contamination (e.g. fuel oil) is then displaced by water and the coefficient of friction increases.

Significantly a coefficient of friction as low as 0.05 was observed when only water and solid debris contaminated the rollers of the Amsler

- 78 -

machine (6.3). This again occurred in the rheological regime. Friction was much higher on the rolling disc tribometer under similar circumstances (5.5). The low friction on the Amsler machine was dependent on the formation of stable films which fully or partially separated the rollers and caused low adhesion due to their low shear strength (or high viscosity). When oil was added to the clean debris (checked by adsorption experiments) the stability of the films was enhanced (5.6.2.2). Although high humidity or a light water spray could cause the shear strength of such layers to fall, surplus water quickly destroyed the films, resulting in coefficients of friction similar to those observed on the rolling disc tribometer. The debris rapidly mixed with the water to form a thin slurry that was easily pushed to the side of the rollers. In this manner water plays a significant part in controlling contaminant films.

7.3 AN ASSESSMENT OF THE LABORATORY SIMULATION

The relevance of laboratory experiments can be examined by either \ considering the accuracy of the simulation or by comparing wheel/rail adhesion with the coefficient of friction observed in the laboratory under similar conditions. Both approaches have their limitations. The laboratory simulation must always be a compromise since nothing short of a full size railway can reproduce all the relevant factors. Even full size roller rigs are unsatisfactory due to the elevated surface temperatures caused by slip at high velocities. Further, when comparing adhesion values the accurate assessment and reproduction of track conditions is difficult, and the appropriate values of wheel/rail adhesion rarely available. Many of the wheel/rail adhesion measurements quoted in this chapter were made by a tribometer train (Watkins 1975), a newly developed research facility on which the author is currently working. It is planned to use this train to assess some of the theory presented in this thesis. The tribometer train takes measurements by alternately disc braking the axles of an air braked covered wagon (HSFV5) until wheelslip occurs. Coefficients of adhesion are then computed from the traction rod forces and logged on

to punch tape, which a computer subsequently uses for the statistical analysis.

7.3.1 Laboratory Test Rigs

The rolling disc tribometer has been a useful tool for examining in detail the more complex frictional effects associated with surface contamination. The torque exerted on the restrained disc until it slips against the plate resembles the slipping of a stationary locomotives wheels exerting traction. The initial repeated measurements ensures that, like the wheel and rail, contamination is present on both specimens. However, despite the fact that the rig is clearly better than a simple measurement of static friction, or of kinematic friction using a specimen slid across a plate, there are certain drawbacks. The mechanism cannot be equated with the wheelslip of a moving locomotive and there is a much smaller contact area between the specimens (required in order to reproduce contact stresses of the right magnitude). It is when examining solid contaminants that the rig is most suspect due to an increased tendency for the disc to penetrate the layers of debris applied to the plate. The importance of the real contact area when a thin layer is applied to a hard substrate is well known (Bisson et al 1957). The real area between the disc and plate will increase substantially as the profile sinks into a thin layer of debris contamination.

The Amsler Testing Machine complements the rolling disc tribometer. The force due to the relative movement (i.e. creep) of the specimen rollers can be continuously monitored. A locomotive generates a similar relative movement by exerting sufficient torque on its driving wheels to pull the train along at the desired speed. There is a small amount of creep (less than 1%) between the wheel and rail as long as the demanded adhesion (torque) does not exceed the available wheel/rail adhesion. The Amsler machine has been used to simulate this relative movement although the surface velocities are low and similar only to a train exerting traction at low speed. The area of contact is again smaller than that between wheel and rail although the contact width is similar. Thus, unlike the

- 80 -

rolling disc tribometer, debris films similar to those on the track can form on the Amsler rollers. The quasi hydrodynamic effects that are observed on the machine are more likely to occur between wheel and rail due to the higher surface velocities. On the other hand the steady slip rate and load between the rollers and the continual production of wear debris tends to increase the probability of debris layer formation on the laboratory machine.

7.3.2 Comparison of Track and Laboratory Results

The preliminary experiments described in Chapter 2 showed that the friction measured on rails by the disc of the rolling disc tribometer agreed well with that measured by a static locomotive slipping its leading axle. A few experiments were also made by the author on clean main line track (Broster et al 1974) which showed that the relationship between friction and the amount of oil applied to main line track was the same as that found in the laboratory when oil was applied to rail steel plates, Fig. 3.2 However, low coefficients of friction were only rarely observed (3.4.1).during the measurements on rails. This was also true for the more extensive results made with track tribometers which employed discs similar to that used on the rolling disc tribometer that were braked while being pushed along the wear band. The very low coefficients of friction that are known to cause wheels to spin on leafy or slightly wet rusty track were not observed at all. The discussion in both this chapter and Chapter 6 has shown that relevant values for the wheel/rail adhesion of debris contaminated rails cannot be reliably measured using a small sharply profiled disc at low velocities.

Fig. 7.1 shows the adhesion measurements made by the tribometer train over a hilly route in Scotland. It can be seen how the mean adhesion of each test section varied with the weather conditions with adhesion falling to 0.15 in light rain. The adhesion of wetter rails was found to vary from 0.3 to 0.2. This agrees well with the coefficients of friction of wet specimens measured by both the rolling disc tribometer and the Amsler machine. There is similar agreement on the coefficient of adhesion due to oily debris layers (0.1) measured by the tribometer train near flange lubricators.

Fig. 7.2 shows three successive adhesion profiles measured by the tribometer train on an infrequently used test track (Beagley 1974,2). The test section had been wire brushed on the previous day to remove the loose The track was initially wet with morning dew and both the test and rust. control sections exhibited mean adhesion levels of 0.18 (excluding the higher adhesion measurements that were found in the tunnels). As the track dried adhesion fell to a minimum on the control section and appeared to rise on the brushed section. These changes in adhesion are very similar to the effects produced by drying specimens on the Amsler machine, and further substantiate the effect of light rainfall observed by Barwell (1963). Apart from the skidding of the experimental train on rusty slightly wet track mentioned in Chapter 6, coefficients of adhesion of the order of 0.01 and as low as 0.005 have been observed under similar conditions during braking tests on individual wheelsets (Murray 1973). These low values were predicted by the rheological analysis of Chapter 6 and indicated by the coefficient of friction of 0.05 observed on the Amsler machine using slightly wet heavily rusted rollers. These effects have not yet been observed on the tribometer train. This may be because of the unrealistic continual braking of the wheelsets causing tyre temperatures to rise.

Fig. 6.4 showed how friction fell to 0.1 as leaf debris was applied to the rollers of the Amsler machine. This agrees well with the adhesion seen during tests in the Autumn using the tribometer train, Fig. 7.3. Water applied to the track during these tests further lowered adhesion to 0.05, the same order of magnitude as was observed when water was sprayed onto the leaf covered rollers.

Sand has long been used to prevent wheelslip and a sand paste using a cellulose thickener was developed in order to ease its application. This

paste was applied to the Amsler rollers and unexpectedly the friction gradually fell until a coefficient of 0.05 was obtained (Beagley and Pritchard 1973)! Moreover, in subsequent track tests not only was very low adhesion observed using this material but a diesel multiple unit was unable to stop on the tenacious layer that had been left on the track. This underlines good simulation of wheel/rail conditions found on the Amsler machine. In spite of the theoretical reasons for <u>not</u> equating the coefficients of friction determined on laboratory machines with those experienced on the track, the Amsler machine appears to correlate remarkably well.

7.4 WHEEL/RAIL ADHESION

This thesis has examined how the maximum transmittable force between two surfaces is changed by surface contamination. There are other facets to wheel/rail adhesion which can be broadly divided into problems associated with locomotive design and those associated with wheel/rail dynamics. In the former, power to weight ratios, motor torque and control characteristics and weight transfer are the most important parameters to be considered. In the latter, longitudinal and lateral creep, and the reduction of effective adhesion with speed are the major factors that remain to be examined. The experiments on the Amsler machine using various longitudinal creep ratios showed that the shape of the creep curve did not change as the limiting coefficient of friction was varied (5.6.1.2). However, all the above problems are subservient to the limiting transmittable force, the coefficient of adhesion determined by the state of the interacting surfaces.

Standard wheel/rail coefficients of adhesion are used as design parameters for both track and rolling stock. Brakes and braking distances are designed assuming wheel/rail adhesion of 0.07 to 0.09. This low figure is used to ensure a safety margin since adhesion as low as this rarely occurs. Locomotives are designed to develop tractive effort equivalent to a coefficient of adhesion between 0.18 and 0.24. An adhesion of about 0.2 is also used in conjunction with the track gradient in determining permissible train loadings along specific routes. It can be seen that only adhesion below approximately 0.2 is of interest to Railway Engineers although, of course, great benefits would accrue if values higher than this could be guaranteed. Adhesion measurements made by the tribometer train are now being used to compile precise statistical information in the form of probabilities of slip occurring at specific demand adhesion levels over specific routes. This will enable Railway Engineers to assess whether the optimum design adhesion coefficients have been chosen with regard to both safety and economy.

7.4.1 Track Contamination

Adhesion on B.R. track is usually more than adequate. However certain forms of track contamination often give rise to wheel spin or skidding. Knowing the process of track contamination is at least as important as understanding the resulting friction mechanism in a complete understanding of wheel/rail adhesion. Only by understanding the build up of track contamination can improvements in wheel/rail adhesion be achieved. The laboratory experiments have elucidated some of the mechanisms involved and these are used in the following description.

Dry main line track generally has a shiny clean metallic wear band; the debris coverage is low since the oxides, brakeblock dust etc. are rapidly compressed into small flakes that are then thrown clear of the wear band by passing wheels. The small quantity of oil that occasionally drops from passing traffic is rapidly spread along the line and mixes with the debris. Even a large blob of oil applied to the track only causes low friction along a few yards of the line for the duration of a couple of train passages (Broster et al 1974). Most of the oil is squeezed to the side of the wear band leaving only a small quantity to be spread along the track and be rapidly removed with the debris. This squeezing action is very significant. Oily fluids will only cause a persistent adhesion problem when they are continually applied to the track e.g. where locomotives

- 84 -

stand and drip oil or near flange lubricators. Under these circumstances a tenacious mixture of solid debris and oil can form over the wear band. These films are very stable since the high solid content ensures that they cannot be pushed aside and the oil content helps resist the washing affects of rain. Similar layers can also be formed from other solid debris provided that the film of compressed material is sufficiently pliable not to flake from the surface like the dry clean rust on main line track mentioned above. A wide range of materials, coal, sawdust, leaves etc. fall into this category although the most troublesome is leaves. Although these films are softened by heavy rain then pushed aside by train wheels, leaves are continually trapped between wheel and rail in cuttings during Autumn and rapidly re-form the troublesome film as soon as the rain stops. The heavy rain discussed above helps clean solid debris from the track. However light rain or high humidity can increase the degree of track contamination by imparting sufficient pliability to the solid debris that would otherwise be thrown clear of the wear band. This phenomenon is particularly important with regard to rust. On main line track the quantity of debris on the wear band rapidly increases under slightly wet conditions as rust is squeezed in a slurry from the sides by the lateral oscillation (hunting) of passing wheels. Naturally the lower the track utilisation the more corroded its wear band will be, although even the wear band of main line track can form significant layers of rust when early morning dew helps corrode the track.

7.4.2 Loss of Adhesion and its Prevention

Track conditions can be divided into three broad categories according to their influence on adhesion. The first, which includes clean main line and dry corroded track, have adequate adhesion for all present traction demands (μ > 0.25). The second category includes slightly wet track contaminated by leaves or heavy corrosion. These films can cause such low adhesion (0.05) that high speed wheel spin can occur on level track at steady train velocities causing rail burns. Very severe operating

- 85 -

difficulties occur if these conditions exist when higher adhesion is demanded during starting or braking.

The third category of rail condition only presents a problem when higher traction is demanded e.g. during starting, acceleration, on inclines etc., equivalent to a coefficient of adhesion above 0.15. In this case wheel/ rail slip only appears as a problem on certain sections of track e.g. near signals, stations, on inclines etc., even though similar variations in available adhesion occur on all track. Flange lubricators can often cause adhesion of 0.1 (Broster 1975). They are installed on curves to reduce not only rail wear but also curving resistance. Although the liberal quantities of grease applied to the track achieve the latter, the lubricators often defeat their own purpose by causing locomotives to slip. Flange lubrication, point lubrication, fishplate grease and the oils and greases that drip from trains are detrimental to adhesion expecially when it rains. However preliminary results from the tribometer train show that low adhesion due to this oily contamination is rare compared with that caused by solid debris and slightly wet track. Although Barwell concluded that slightly wet track could cause low adhesion, there was no physical explanation of the mechanisms involved. This thesis has provided this physical explanation and has shown that the presence of debris on the wear band enhances the probability of wheel slip. Trains readily slip in this manner on corroded track in the early morning when it is wet with morning dew. Adhesion can also be lowered on wet main line track during the day, when sufficient debris is moved onto the wear band from the adjacent corroded areas.

Remedies for low adhesion must be carefully considered since all the major types of track contamination i.e. oil, water and debris play some part in keeping adhesion within tolerable limits. Although large quantities of oil are detrimental to adhesion, a few monolayers can reduce the corrosion rate of the wear band. Debris helps continually remove oil while water softens the thick layers of debris that can build up on the wear band.

- 86 -

Adhesion problems must be tackled by identifying the cause of a wheel slip before a specific remedy can be used. A sand/water jet is presently being developed to clean leafy contamination from the rails during Autumn. However such a remedy will not be effective where wheelslip is caused by slightly wet corroded track. It is planned to test two sand based, train mounted, remedies under these conditions. One is a suspension of sand in a shear thinning medium, the other consists of small quantities of sand that are blown into the wheel/rail nip using compressed air. Lineside applicators, however, would be more convenient than train mounted devices, although an effective fluid remains to be found. Furthermore, many applicators are already installed along track where adhesion problems occur. A new criterion for choosing fluid remedies has been proposed in this thesis. A range of deflocculating agents is now being screened in order to select the one that will most efficiently reduce the strength of iron oxide pastes. Using the appropriate chemical it may be possible to significantly reduce the quantity of debris on the track and thus eliminate the most insidious cause of low adhesion, slightly wet rail contamination.

7.5 CONCLUSIONS

Wheel/rail adhesion is an extremely complex phenomenon controlled by the interaction of water with oil and solid contamination. There is insufficient oil on most track to cause low adhesion when dry. Water further lowers the adhesion of slightly oily rails whereas dry iron oxides increase adhesion by adsorbing the oil. Under some specific circumstances debris helps form thin layers that cover the wear band. These are strong enough to support heavy loads but can be weak enough in shear to reduce adhesion and cause wheel slip. Leaves readily form such films although the most common constituents are rust and water. Laboratory experiments have

- 87 -

shown that low adhesion can be caused by mixtures of iron oxide and water, and a theoretical explanation for this has been developed based on their rheological properties. It is concluded that low wheel/rail adhesion is usually caused by a combination of solid debris and small quantities of water. It is because Britain has such a cold, damp climate that wheel/ rail adhesion on B.R. is such a problem.



FIG. 7.1 ADHESION OVER SHAP SUMMIT TRIBOMETER TRAIN FEB. 1974



LEADING AXLE ONLY

FIG. 7-2 TRIBOMETER TRAIN ADHESION PROFILES OF DRYING TRACK.



ć



FIG. 7-3 ADHESION IN KEGWORTH CUTTING. TRIBOMETER TRAIN AUTUMN 1973.

/A4/17409

APPENDIX 1

REFERENCES

Note: Some internal B.R. reports are included as references so that the thesis may be placed within the context of the research at the Technical Centre.

Allen R.K. (1954) "Wheelslip, Science Tells Why", Railway Locomotives and Cars, October 1954.

Archard J.F. (1958) "A Crossed-Cylinders Friction Machine", Wear 2.21

Archard J.F. and Cowking E.W. (1965-66) "Elastohydrodynamic Lubrication at Point Contacts", Proc. Instn. Mech. Engrs. <u>180</u> (Pt 3B) 47.

Awdry W. (1966) "Gordon the Big Engine", Railway Series No. 8 Pub. Kaye and Ward.

Baglin K.P. and Archard J.F. (1972) "An Analytic Solution of the Elástohydrodynamic Lubrication of Materials of Low Elastic Modulus", Instn. Mech. Engrs. Elastohydrodynamic Lubrication Symposium, 1972.

Barwell F.T. and Woolacott R.G. (1956) "Further Studies of Adhesion", D.S.I.R. Mechanical Engineering Research Laboratory, Report L.D.R. 1/56.

Barwell F.T. and Woolacott R.G. (1963) "The N.E.L. Contribution to Adhesion Studies", Proc. I. Mech. Engrs. 178, Paper 9 of a Convention on Adhesion.

Beagley T.M., Jackson R., Pritchard C. and Sewell J.D.W. (1971) "A Basic Study of Wheel/Rail Adhesion, 4 - Laboratory Simulation Rigs", B.R. R & D Div. Technical Note TRIB.1.

Beagley T.M., McEwen I.J. and Pritchard C. (1972) "A basic Study of Wheel/ Rail Adhesion, 5 - Laboratory Studies of the Effects of Oily Fluids on Friction", B.R. R & D Div. Technical Note TRIB.2.

Beagley T.M., Broster M. and McEwen I.J. and Pritchard C. (1973) "A Basic Study of Wheel/Rail Adhesion, 8 - Laboratory Studies of the Effects of Solid Debris", B.R. R & D Div. Technical Note TRIB.5.

Beagley T.M. and Pritchard C. (1973) "A basic Study of Wheel/Rail Adhesion, 7 - Laboratory Studies of the Effects of Water", B.R. R & D Div. Technical Note TRIB.4.

Beagley T.M. (1974,1) "A basic Study of Wheel/Rail Adhesion, 10 - The Rheology of Rail Contaminants Causes Low Friction", B.R. R & D Div. Technical Note TRIB.8.

Beagley T.M. (1974,2) "Tribometer Train Tests on APT Test Line", B.R. R & D Div. Internal Memo. ADH18.

Beagley T.M., McEwen I.J. and Pritchard C. (1975,1) "Wheel/Rail Adhesion -Boundary Lubrication by Oily Fluids", Wear, 31, 77-88.

Beagley T.M., McEwen I.J. and Pritchard C. (1975,2) "Wheel/Rail Adhesion - The Influence of Railhead Debris", Wear, 33, 141-152.

Beazley K.M. (1972) "Viscosity - Concentration Relations in Deflocculated Kaolin Suspensions", Journal of Colloid and Interface Science, Vol. 41, No. 1.

Bisson E.E., Johnson R.L. and Swikert M.R. (1957) "Friction, Wear and Surface Damage of Metals as Affected by Solid Surface Films : A Review of N.A.S.A. Research", Proc. Conf. on Lubrication and Wear, I. Mech. E. Paper 31.

Bowden F.P. and Tabor D. (1950, 1964) "The Friction and Lubrication of Solids", Oxford University Press, Part I, 1950, Part II, 1964.

Broster M., Pritchard C. and Smith D.A. (1970) "A Basic Study of Wheel/ Rail Adhesion, 3 - Observations on the Effect of Fallen Leaves" B.R. Research Report CR.47.

Broster M., Pritchard C. and Smith D.A. (1973) "A Basic Study of Wheel/ Rail Adhesion, 6 - Adhesion and Contamination on B.R. Track", B.R. R & D Div. Technical Note TRIB.3.

Broster M., Pritchard C. and Smith D.A. (1974) "Wheel/Rail Adhesion : its Relation to Rail Contamination on British Railways", Wear, <u>29</u>,309.

Cheng C.H. (1974) (Warren Spring Laboratory), private communication.

Cottrell A.H. (1964) "The Mechanical Properties of Matter", Pub. J. Wiley.

Dawson P.H. and Coyle M.B. (1969) "Metal Transfer During Rolling and Sliding - A Challenge" Wear, <u>14</u>, 385.

Dowson D. and Whomes T.L. (1967) "Side - Leakage factors for a Rigid Cylinder Lubricated by an Isoviscous Fluid", Proc. Instn. Mech. Engrs. <u>181</u> (Pt 3B), 165.

Dukes W.A. (1970) "Determination of the Yield Stress of Stiff Pastes by Parallel Plate Plastometry", Proc. of Fifth International Congress on Rheology, Vol. 2. University of Tokyo Press & University Park Press.

Fein R.S. and Kreuz K.L. (1964) "Chemistry of Boundary Lubrication of Steel by Hydrocarbons", A.S.L.E./A.S.M.E. Lubrication Conference, Washington.

Fischer E.K. (1950) "Colloidal Dispersions", Pub. J. Wiley.

Graver G.G. and Kendall K. (1971) "Failure of Track Circuits due to Rail Contamination" B.R. Research Dept. Report No. CR.53.

Greaves T.A. (1972) "Traction Adhesion Problems", Railway Engineering Journal, May 1972.

Grubin A.N. and Vinogradova I.E. (1949) Central Scientific Research Institute for Technology and Mechanical Engineering Book 30 (Moscow) D.S.I.R. Trans. No.337.

Grunberg L. and Campbell R.B. (1956) "Investigation of the Nature of Debris found on Rails", D.S.I.R. Mechanical Engineering Research laboratory, Report L.D.R. 14/56.

Guardian Editorial, 27 November 1973.

Heath H.H. (1972) "Discussion on Metal Transfer During Rolling and Sliding'" Wear, 22, 109.

Hobbs A.E.W. (1967) "A Survey of Creep" B.R. Research Department Report No. DYN 52. Jenkins G.J. and Humphreys C.M.A. (1955) "Analysis of Lubricants and Additive Concentrates by using Spectroscopy and Physical Methods of Separation" J. Inst. Pet., <u>51</u>, 1.

Kalker J.J. (1966) "Rolling with Slip and Spin in the Presence of Dry Friction" Wear 9.

Kraft K. (1968) "Adhesion", Elektrische Bahnen, Vol. 39, Nos. 6,7,8 and 9.

Krause H. (1967) "Reaction Products Coating the Running Surface of Rails", Industrieanzeiger, <u>89</u>, 1935.

Markley R.S. (1960) "Fatty Acids, Their Chemical and Physical Properties", Part 1 Interscience Publications, New York.

Marta H.A. and Mels K.D. (1969) "Wheel - Rail Adhesion", Trans ASME.Jnl. Eng. for Industry. Aug. 1969.

Martin H.M. (1916) "Lubrication of Gear Teeth", Engineering Lond, 102, 199.

McEwen I.J. (1974) "Adhesion and Leaves. Experiments with High Pressure Water Jets", B.R. R & D Div. Technical Memo. ADH/SP12.

Murray C.L. (1973) "A Particular Example of very Low Adhesion and Wheelslide Behaviour of Hydrokinetic Brake", B.R. R & D Div. Internal Memo. IMPS 156/A.

Nayak P.R. (1972) "Surface-Roughness Effects in Rolling Contact", A.S.M.E. Paper No. 72 - APM - FF.

O'Connor T.L. and Uhlig H.H. (1957) "Absolute Areas of some Metallic Surfaces" J. Phys. Chem., 61, 402.

Pritchard C. and Tanvir M.A. (1973) "A Basic Study of Wheel/Rail Adhesion. 9 - Further Observations on Leaves", B.R. R & D Div. Technical Note TRIB.6.

Roberts A.S. (1962) "Measurement of the Dilatant Flow Properties of some Non - Newtonian Suspensions", Journal of Chemical and Engineering Data, Vol. 8, No.3.

S.N.C.F. (1971) Direction du Material de la Traction D.E.T.E. lg 43/443 M-1971. "Prevention du Patinage des Engins moteur par Traitment de la surface de Roulement du Rail".

Tabor D. (1951) "The Hardness of Metals", Oxford University Press, London.

Van Wazer, J.R., Lyons J.W., King K.Y. and Colwell R.E. (1963)" Viscos ty and Flow Measurements", Pub. J. Wiley.

Vermeulen P.J. and Johnson K.L. (1964) "Contact of Non-Spherical Elastic Bodies Transmitting Tangential Forces", J. Appl. Mech., <u>86</u>, 337.

Watkins D.J. (1975) "Exploring Adhesion with British Rail's Tribometer Train", To be published, Railway Eng. Journal.

Wichterle K. and Ulbrecht J. (1967) "Determination of the Parameters of the Ostwald-de-Waede Power Law from Rheometric Measurements on a Viscometer with a fast - rotating Disk", Rheol. Acta. 6. (4) October 1967.

Wickens A.H. (1973) "Stability of High Speed Trains", Physics in Technology, Vol. 4, No.1.

Wolveridge P.E., Baglin K.P. and Archard J.F. (1970-71) "The Starved Lubrication of Cylinders in Line Contact", Proc. Inst. Mech. Eng. Vol. 185, 81/71.

Yokose K. (1973) "On the Measuring Method of the Creep Forces Between Wheel and Rail", Railway Tech. Research Inst. (J.N.R.) Quart. Report Vol. 14, No.1, March 1973.

T.M.BEAGLEY Ph.D. THESIS 1975.

LABORATORY INVESTIGATION INTO WHEEL/RAIL ADHESION BY T.M. BEAGLEY

ABSTRACT:

Wheel/rail adhesion is affected by the contamination that is present on the railhead. This can be broadly divided into three categories oil, water and solid debris. The frictional phenomena associated with each of these groups were examined on a variety of laboratory simulation rigs. The interactions between each group were then explored so that a comprehensive description of wheel/rail adhesion could be established. Concepts of boundary lubrication can be used to describe the low friction of surfaces contaminated by oil and/or water. However these concepts are shown to have their limitations when solid debris is trapped in the contact area and either significantly lowers adhesion when mixed with small quantities of water under dynamic conditions, or increases the coefficient of friction by adsorbing the oil.

There is insufficient oil on most track to cause low adhesion even when the rails are wet. Under some specific circumstances debris helps form thin layers that cover the wear band and are weak enough in shear to reduce adhesion and cause wheel slip. Leaves readily form such films although the most common constituents are rust and water. Laboratory experiments have shown that low adhesion can be caused by mixtures of rust and water, and a theoretical explanation for this has been developed based on their rheological properties. It is concluded that low wheel/rail adhesion is usually caused by a viscous paste formed of solid debris and small quantities of water. It is because Britain has such a cold, damp climate that wheel/rail adhesion on BR is such a problem.