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School of Mechanical and Industrial Engineering**

WHEEL/RAIL ADHESION UNDER PLASTIC BAGS CONTAMINATION CONDITION

**A Thesis Submitted to the School of Mechanical and Industrial
Engineering in Partial Fulfillment of the Requirements for the Degree
of Masters of Science in Mechanical Engineering**

(Rolling Stock Stream)

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Abstract

Railway vehicles require a certain level of adhesion between wheel and rail to operate efficiently, reliably, and economically. Different levels of adhesion are needed depending on the vehicle running conditions. In the wheel tread–railhead contact, the dominant problem is low adhesion, as low adhesion on the railhead negatively affects railway operation: on one hand, the vehicle will lose traction resulting in delay when driving on low-adhesion tracks; on the other hand, low adhesion during deceleration will extend the braking distance, which is a safety issue.

This thesis examines the influence of plastic bags contaminants on the adhesion in the wheel tread–railhead contact. This study will improve our knowledge of the low-adhesion mechanism and of how plastics contaminants influence adhesion.

In this thesis, the adhesion conditions of four groups of plastics ; group one, group two, group three and group four with corresponding thicknesses 0.00185mm, 0.0025mm, 0.0035mm and 0.007mm respectively were assessed using a twin disc test machine. Thus the research methodology used was a laboratory test. The test procedure and/or the test set up followed in this work was the set up described in [6] except the method of application of tested contaminants on the rail wheel due to the difference in contaminants considered. The aim of this work was to study the extent of adhesion coefficients in the contacts of wheel-rail rollers over a range of slip values with and without plastic bags contaminants. Thus the outcomes from lab test were the coefficients of adhesions of each contaminant within 0, 0.25, 0.5, 1, 2 to 10% slip values so as to sort out weather plastics contaminants will affect wheel-rail adhesion. The result of this experimental test shows that the adhesion coefficient due to plastic bags contaminated condition is much less than that of the dry test. The variation in wheel-rail adhesion ranges up to 88%. From the result it is concluded that plastics bags adversely reduce wheel-rail adhesion.

Keywords: Wheel tread–railhead contact; plastics contaminants; Adhesion; Slip; Twin disc.

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NOMENCLATURE

TOC	Train Operating Company
SPAD	Signals passed at dangers
ERC	Ethiopian Railway Corporation
F_f	Friction force
F_N	Normal force
f	Friction coefficient
F	Force
f_s	Coefficient of static friction
f_k	Kinetic friction coefficient
w	Angular velocity
v	Linear velocity
F_x	Traction force
μ	Adhesion coefficient
F_a	Adhesive force
S	Slip
$\vec{V}_1$	Speed of the contacting body one
$\vec{V}_2$	Speed of the contacting body two
v^{rel}	Relative velocity
v^{mean}	Mean velocity

q_x	Surface traction
p	Contact pressure
NS	Netherlands Spoorwegen
EMUs	Electrical Multiple Units
S_b	Distance to stop
V	Initial speed before brake stop
U	Final speed after brake stop
a	Deceleration
g	Gravitational acceleration
G	Gradient of the slope
N	Rotational speed of the wheel at contaminated condition
μ_d	Dry test adhesion
μ_c	Contaminated adhesion
UIC	International union of railways
E_a	Armature voltage
I_a	Armature current
N_r	Rotational speed of rail side motor
N_w	Rotational speed of wheel side motor

Chapter 1: Introduction

1.1. Transportation

Transport or transportation is the movement of people, animals and goods from one location to another. Modes of transport include air, rail, road, water, cable, pipeline and space. The field can be divided into infrastructure, vehicles and operations. Transport is important because it enables trade between persons, which is essential for the development of civilizations.

Transport infrastructure consists of the fixed installations including roads, railways, airways, waterways, canals and pipelines and terminals such as airports, railway stations, bus stations, warehouses, trucking terminals, refueling depots (including fueling docks and fuel stations) and seaports. Terminals may be used both for interchange of passengers and cargo and for maintenance.

Vehicles traveling on these networks may include automobiles, bicycles, buses, trains, trucks, people, helicopters, watercraft, spacecraft and aircraft. Operations deal with the way the vehicles are operated, and the procedures set for this purpose including financing, legalities and policies. In the transport industry, operations and ownership of infrastructure can be either public or private, depending on the country and mode.

Passenger transport may be public, where operators provide scheduled services, or private. Freight transport has become focused on containerization, although bulk transport is used for large volumes of durable items. Transport plays an important part in economic growth and globalization, but most types cause air pollution and use large amounts of land. While it is heavily subsidized by governments, good planning of transport is essential to make traffic flow and restrain urban sprawl.

1.2. Transportation subsystems

Transportation system is categorized into four major subsystems according to the medium on which the flow elements are supported. These subsystems are commonly referred to as modes,

but it should be understood that this term is also used to make finer distinctions between the various means of travel. Land transportation which includes high way or road transportation and railway transportation, air or flying service transportation water transportation, inland and pipe lines.

1.2.1. Air or flying service transportation

A fixed-wing aircraft, commonly called airplane, is a heavier-than-air craft where movement of the air in relation to the wings is used to generate lift. The term is used to distinguish this from rotary-wing aircraft, where the movement of the lift surfaces relative to the air generates lift. The aircraft is the second fastest method of transport, after the rocket.

1.2.2. Road transportation

A road is an identifiable route, way or path between two or more places. Roads are typically smoothed, paved, or otherwise prepared to allow easy travel; though they need not be, and historically many roads were simply recognizable routes without any formal construction or maintenance. In urban areas, roads may pass through a city or village and be named as streets, serving a dual function as urban space easement and route. The most common road vehicle is the automobile; a wheeled passenger vehicle that carries its own motor. Other users of roads include buses, trucks, motorcycles, bicycles and pedestrians.

1.2.3. Water transportation

Water transport is movement by means of a watercraft-such as a barge, boat, ship or sailboat-over a body of water, such as a sea, ocean, lake, canal or river. The need for buoyancy is common to watercraft, making the hull a dominant aspect of its construction, maintenance and appearance.

1.2.4. Railway transportation

Rail transport is where a train runs along a set of two parallel steel rails, known as a railway or railroad. The rails are anchored perpendicular to ties (or sleepers) of timber, concrete or steel, to maintain a consistent distance apart, or gauge. The rails and perpendicular beams are placed on a

foundation made of concrete or compressed earth and gravel in a bed of ballast. Alternative methods include monorail and maglev.

A train consists of one or more connected vehicles that operate on the rails. Propulsion is commonly provided by a locomotive, that hauls a series of unpowered cars, that can carry passengers or freight. The locomotive can be powered by steam, diesel or by electricity supplied by trackside systems. Alternatively, some or all the cars can be powered, known as a multiple unit. Also, a train can be powered by horses, cables, gravity, pneumatics and gas turbines. Railed vehicles move with much less friction than rubber tires on paved roads, making trains more energy efficient, though not as efficient as ships.

1.3. Background of the study

Since the beginning of railway transportation, wheel-rail adhesion has been limiting the acceleration and deceleration capabilities of rolling stocks. Sliding and slipping have always been major problem in the railway industry due to the low friction between wheel and rail. With increased speed, power and complexity of the modern railway vehicle, sliding and slipping phenomena have been seen to increase abruptly.

Railway is the safest form of transport. The chances of accidents and breakdown of railways are minima as compared to other modes of transport. But the loss of the required adhesion in the wheel rail contact due to contaminants will degrade the safety and performance of this transportation system. Different low adhesion related incidents have been occurred in different times at different railway infrastructures.

Six platform overruns had been reported in Texas, between 8 February and 3 March 2009. Another event at Ormond Railway Station on 25 February 2009 involved a train overrunning the platform by about 250 meters and entering the North Road level crossing before the boom barriers had fully lowered. Office of chief investigator had found that the predominant condition associated with the overrun events was the presence of low levels of adhesion between wheel and rail. [1]

On 24 Mar 2011 an X'Trapolis train collided with the end-of-track baulks at Macleod railway station and subsequently the station wire boundary fence. The train was fully loaded but there

was no injury to any occupant or other person. The leading car of the train sustained minor damage with the baulks being destroyed and the fencing damaged. The investigation determined that low-adhesion conditions were present at the wheel-rail interface, contributed to by vegetation matter from surrounding foliage and moss from the platform that had been washed onto the track during the platform cleaning process. The end-of-track baulks were poorly maintained and not fit for purpose. [1]

In U.K on 8 Nov 2010 A passenger train failed to stop at Stone gate station in East Sussex. The train ran for a further 3.94 km with the emergency brake applied, passing a level crossing before coming to a stop 5.18 km after first applying the brakes. No one was hurt and there was no damage to the train or to the track. The reason for this accident was rail adhesion conditions were poor on that day due to high winds causing fresh leaf fall, and the onset of rain. [1]

1.4. Problem statement

In metropolitan rail passenger services, loss of adhesion can cause problems in schedule reliability and can contribute to development of wheel flats. Wheel flats can be an expensive maintenance item and can make the system noisy. The initial loss of adhesion in such services results in excessive wheel slip, the proof of which can be seen as "rail burns" in stations at the point where train movement begins. Although schedules are significantly affected by the initial acceleration of the train, on the basis of its maximum adhesion capability, adhesion also affects braking. Insufficient adhesion can result in wheel slips and slides that can lead to wheel flats on wheel treads. Development of wheel flats leads to increased loss of adhesion, damage to the rail surface, increased damage to bearings and axles, and increased wheel noise. Extreme loss of adhesion may lead to collisions or derailments.

Light rail and commuter rail services may experience schedule delays during the year because of railhead contamination by moisture, ice, and leaves and other vegetation. These natural contaminants build up on the railhead, thereby causing slip and slide conditions, which affect the ability of light rail and commuter rail systems to safely maintain operating schedules. [2]

The adhesion force between rail and wheel is an essential factor for high speed railway systems, especially in braking, as deceleration for stopping the train within the specified distance is not obtained if the needed adhesion force cannot be assured. Moreover, most of surface damages on

wheel-treads such as flats, skidding marks and shelling will occur to give rise to noise and vibration of vehicle and deteriorate the riding quality. For these reasons, the technique to control adhesion force makes an important and fundamental research subject inherent to railways.

Addis Ababa LRT is a railway infrastructure which built in a city whose people has less awareness of how to use daily consumed products and habit of appropriate waste disposal.

The waste materials in the city are highland bottles, skin of banana, avocado and orange, and plastic bags. Among these, plastic bags are most consumed and highly disposable waste materials. The concentration of the plastic bags is as high as to create a visual pollution in the city.

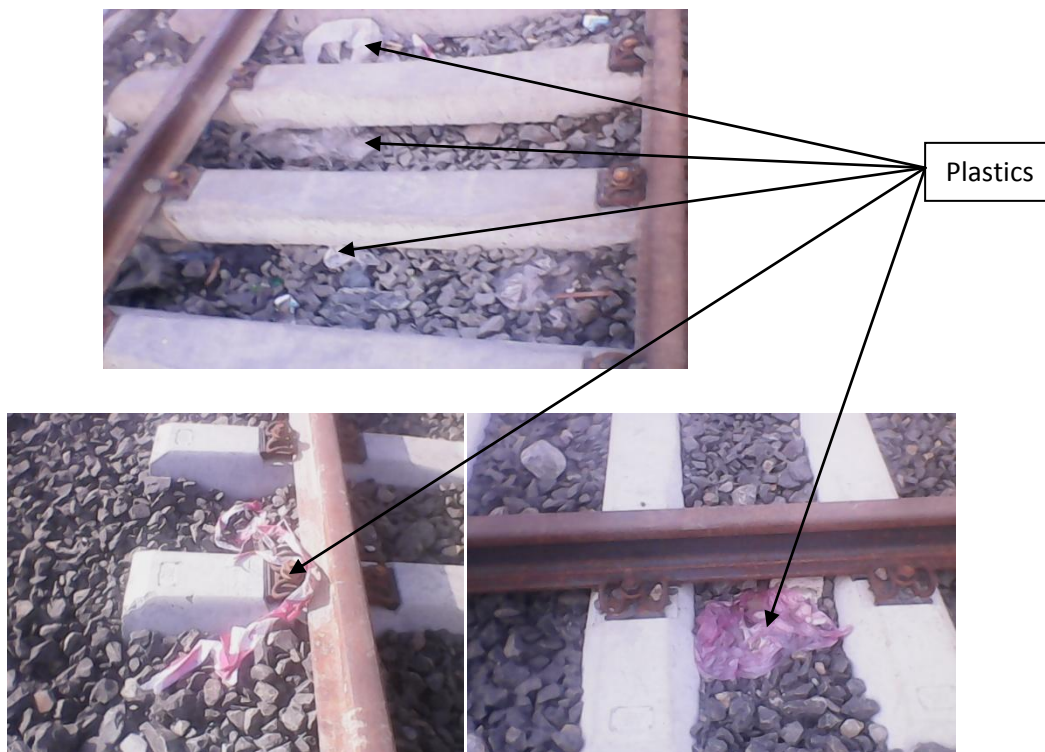


Figure 1.1: Plastics on the A. A. LRT rail line

These plastic bags are light in weight, floatable in the air and hence can be introduced into the railway line easily by the cross wind. The light weight and floatable in the air nature of these plastic bags play important role in increasing the extent of them to be on the rail head due to the turbulence effect of the pass by train.

The introduction of these plastic bags into the wheel rail contact will result a deviation in wheel rail adhesion required by the operating railway line. A deviation in wheel rail adhesion will result a performance issue of traction and braking on the running train and a safety issue on the passengers, goods and even on the train itself.

The friction between wheel and rail has a major impact on maintenance and logistics because it determines the wheel and rail wear, in case it is too high, and reduces the ability to brake and to accelerate properly, in case friction is too low. The wear and the traction are the most important aspects from an economic perspective.

Therefore, to understand the effect of plastic bags on wheel rail adhesion and mitigate their consequence on the performance of the railway line, experimental study on wheel/rail and plastic contact simulation is required.

Extremely low friction values between the wheel and the rail are reported worldwide, leading to severe delays and sometimes even to accidents.

Upon low adhesion, delays in the train service are the clearest consequence to the railway passengers. However, many other negative factors can arise because of low adhesion, such as defects on wheels and rails, signals passed at danger, station platform overruns and collisions. [3]

The immediate cause of the signals passed at dangers (SPAD) incidents that occurred at Esher on 25 November 2005 and Lewes on 30 November 2005 was poor adhesion between wheel and rail. Both trains involved had failed to stop within normally expected distances, despite the systems on the train performing in accordance with their specifications and the drivers correctly implementing the professional driving policy prevailing within the relevant Train Operating Company (TOC) at the time. Both trains had travelled a distance of approximately 3km from the time that the driver had first applied the brake. Stopping distances under normal circumstances would have been less than 2km. [4]

To attract more customers and compete with other modes of transportation, railway transport needs to ensure safety, punctuality, high comfort, and low cost; wheel–rail adhesion, i.e., the transmitted tangential force in the longitudinal direction during driving and braking, plays an important role in all these aspects. Adhesion needs to be kept at a certain level for railway

operation and maintenance. However, wheel–rail contact is an open system contact. Different contaminants can present between the wheel and rail surfaces, forming a third-body layer that affects the adhesion. Prediction of wheel–rail adhesion is important for railway operations and research into vehicle dynamics; however, this prediction is difficult because of the presence of contaminants. [8]

1.5. Objective of the research

1.5.1. General objective

The overall goal of this thesis was to investigate the influence of different group of plastic contaminants, according to their thickness, experimentally on the adhesion coefficient in the wheel tread–railhead contact and figuring out the extent of adhesion coefficients of each group under predetermined slip values and compared with that of dry test.

1.5.2. Specific objective

- Categorize plastic bags according to their thickness.
- Conduct the lab test.
- Collect test data and calculate adhesion coefficient.
- Compare the effects each group on adhesion, with each other and with that of the dry test.
- Calculate the braking distance with respect to the adhesion coefficient

1.6. Research methodology

In order to achieve the primary objective, experimental investigations have been performed .The experimental investigations have been carried out in the laboratory. The laboratory examination was performed with a twin disc roller rig which developed here by Mesfin G/Tsadik in which the actual wheel –rail contact was simulated by two identical discs that are pushed against each other as in fig 1.3 in rolling-sliding motion. The influences the different types of plastic groups simulating the wheel-rail adhesion conditions have been investigated by two contacting rollers with fixed slip mechanism.

The laboratory test approach has been chosen mainly for two reasons. The first one is field test which is impossible to carry out at this time. The other one is computer simulation is difficult to use them as a third layer.



Figure 1.2: contact mode of the twin disks [5]

The major problem in the laboratory test with this adhesion test machine is that the results may not be extrapolated to the actual condition due to the differences in geometry and operational conditions. Therefore the laboratory testing can provide a qualitative indication of what happens in the actual wheel-rail and to identify the more influencing contaminants on adhesion losses.

1.7. Scope and Limitations of the Research

1.7.1. Scope of the Research

As described in the problem statement there are many contaminants that affect the adhesion between wheel and rail. This thesis mainly investigates the adhesion coefficients of plastic bags only. Water, mud, leaves oil and grease which are believed in causing adhesion losses have been investigated in the context of Ethiopian railway system. [6]

1.7.2. Limitations of the Research

- Lack of appropriate motors, torque encoders and force measuring equipment on market were limiting factors to simulate the real contact conditions.
- It would have been possible to acquire all data on a PC which is also used for load and speed control if servo motors would have been fitted.
- Lack of information from Ethiopian Railway Corporation (ERC) about the technical specifications

1.8. Organization of the Thesis

This paper consists of five chapters. The first chapter deals with the introduction while the second chapter focuses on the review of literatures related to this paper. Chapter three addresses the methods, materials procedures used throughout this thesis. Chapter four comes with the test results and discussions. The next one, i.e. chapter five comprises conclusion, recommendation and future work of the research. The end of the paper will close up with sets of references used throughout the research and an appendix.

Chapter 2: Review of literature

2.1. Introduction

The friction available between wheel and rail during braking and traction operation is known in the railway terminology as adhesion. It is a crucial factor for the railway industry as a minimum level of adhesion is required for an appropriate braking and traction performance of the rail vehicles. Adhesion is influenced by many factors such as vehicle speed, wheel slip, contact pressure, environmental conditions and natural contaminants. The major cause of decreasing adhesion is the natural contamination; water, rust, oil, and leaves, have been identified as being mainly responsible. [8]

Railway vehicle operation depends on the adhesion between the wheel and rail. To run such vehicles efficiently and economically, the wheel–rail adhesion should be maintained at a certain level. According to the vehicle running conditions, wheel–rail contact is generally divided into two types, wheel tread–railhead contact on straight track and wheel flange–rail gauge contact on curved track. In most cases, flange contact requires a low adhesion coefficient to reduce wear and noise, while tread contact requires a comparatively high adhesion coefficient to obtain good accelerating and decelerating ability. [7]

2.2. Friction and adhesion

2.2.1. Friction

Friction is defined as the resistance force tangential to the common boundary between two bodies when, under the action of external force, one body moves or tends to move relative to the surface of the other fig 2.1. Friction is normally represented by the friction coefficient (f), which is defined as the ratio between the friction force (F_f) and normal force (F_N), as shown in Eq. 2.1

$$f = \frac{F_f}{F_N} \dots \dots \dots \text{Eq. (2.1)}$$

Figure 2.1 depicts a rectangular solid body of mass m that rests on a horizontal plane. If a force F , parallel to the plane and increasing in time, is applied to the center of mass, as displayed in fig 2.1, where k is an arbitrary constant and t is the time, there exist an instant, t_1 at which the body

starts sliding over the plane. The friction opposing the start of movement is referred to as static friction. The coefficient of static friction (f_s) is given by Eq. 2.2, g is acceleration due to gravity. From that movement onwards the body slides with an acceleration, a , and the force opposing the sliding movement of the body is referred to as kinetic (or dynamic) friction. The kinetic friction coefficient (f_k), at an instant t_2 given by Eq. 2.3, where a_2 is the body acceleration at instant t_2 .

$$f_s = f(t = t_1) = \frac{k \cdot t_1}{m \cdot g} \dots \dots \dots \text{Eq. (2.2)}$$

$$f_k = f(t = t_2) = \frac{k \cdot t_2 - m \cdot a_2}{m \cdot g} \dots \dots \dots \text{Eq. (2.3)}$$

In most tribological pairs, the static friction is higher than the kinetic friction, being the difference dependent on the materials and contact conditions. In the case of steel employed for railway wheels and rails, laboratory investigation has shown that the static friction coefficient can be up to almost twice of the kinetic friction coefficient.

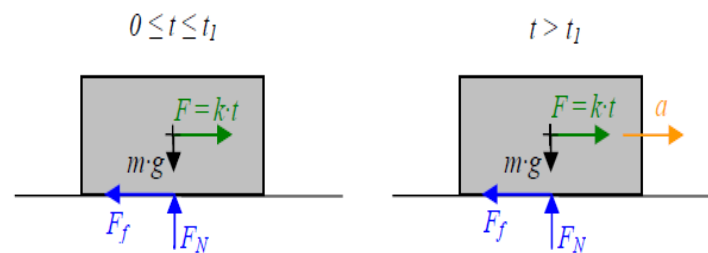


Figure 2.1: Rectangular solid body on a horizontal plane (force applied on the body)

2.2.2. Adhesion

Let us consider the railway wheel as a solid cylinder of mass m , and the rail as a horizontal plane, as shown in figure 2.2. According to the theory of hertz, the contact area formed between the cylinder and the plane has a rectangular shape of width equal to the length of the cylinder. If the tractive torque increasing in time is applied at the centre of mass of the cylinder around its axis of rotation, the wheel starts moving with a certain angular velocity (w) and linear velocity (v), as displayed in fig 2.2.

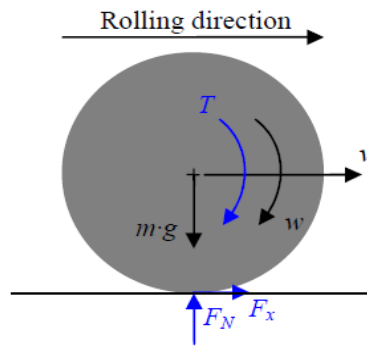


Figure 2.2: Schematic lateral view of the cylinder on the horizontal plane (force applied on the cylinder)

The application of a tractive torque causes a relative longitudinal tangential force at the contact interface with the plane, which is known as traction force (F_x). The ratio between traction force and the normal contact load is normally named the adhesion or adhesion coefficient (μ), as given below

$$\mu = \frac{F_x}{F_N} \dots\dots\dots \text{Eq. (2.4)}$$

2.3. Adhesive Force

A general scientific definition of the adhesive force is the force of attachment between two contacting objects. If this definition is translated into a railway definition, it will be the ability of the wheel to exert the maximum tractive force on the rail and still maintain persistence of contact without exceeding the optimal slip [9].

With these definitions it might seem like the adhesive force is equal to the friction force, but this is not the fact. The available adhesion is always lower than the friction between the rail and the track. Parts of the friction are consumed by other friction phenomena, such as heat.

Adhesion is the amount of force available between the rail and the wheel. Therefore, one can say that the adhesive force comes about as a result of the frictional forces. Further, the friction force is a resistance of motion, and as such an undesirable effect, while adhesion is a coupling force and therefore something desirable.

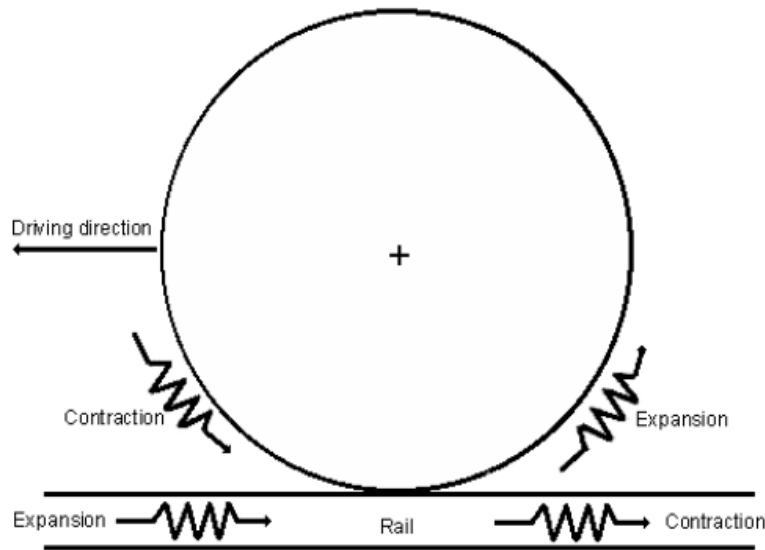


Figure 2.3: How slip occurs between the wheel and the rail

The adhesive force is given by

$$F_a = \mu F_N = \mu mg = ma \dots \dots \dots (2.5)$$

Where F_a is the adhesive force, μ the adhesion coefficient, F_N the normal force, m the adhesive mass of the vehicle and g is the gravitational acceleration. The adhesive mass is defined by the total mass on all the driven wheels. There may be differences in adhesive mass between wheel axis, depending on the specific load of the trailer et cetera.

The adhesive force changes in time, though the normal force is constant, which implies that the adhesion coefficient μ changes in time. There are several factors that can affect the value of the adhesion coefficient. Below, a few of them are listed:

Contaminants: Due to the very high stress at the wheel-rail contact point, high adhesion levels could be obtained. This is however not all good. Due to high stress, molecular levels of contaminants can lower the adhesion considerably. Also, larger amounts of contaminants like oil, leaves and moisture (snow, dew and rain) lead to major reductions in adhesion. These factors are random and are therefore hard to model but it is crucial to do so [9].

Vehicle velocity: As the wheels roll along the track, they bounce on surface irregularities. This reduces the normal force between the wheel and the track. Equation (2.4) shows that if the normal force decreases, so will the adhesive force. This phenomenon is difficult to model and would demand a great deal of computational power. In general it can be said that the adhesive force is reduced with increasing vehicle velocity, as shown in Figure 2.4 [9].

Slip velocity: The slip velocity, defined in Equation (2.6), is the most important factor influencing adhesion. The adhesion coefficient becomes higher if the slip velocity is controlled effectively [9].

This means that different reference slip velocities should be used depending on the current rail condition. Much experimental work has been done to derive a general relationship for how slip velocity affects the adhesion coefficient, and thereby the adhesive force [10, 11].

2.4. Slip-rolling motion

A tribological system under rolling motion and simultaneously solicited with sliding can be denominated as slip-rolling motioned. Sliding occurs when the speeds of the two contacting bodies differ, i.e. the speed vectors at the contacting point are not equal (direction, value).

Two different equations exist to express the slip-to-roll ratio:

$$S = \frac{\vec{V}_1 - \vec{V}_2}{\vec{V}_1} * 100\% \dots\dots\dots \text{Eq. (2.6)}$$

$$S = 2 * \frac{\vec{V}_1 - \vec{V}_2}{\vec{V}_1 + \vec{V}_2} * 100\% \dots\dots\dots \text{Eq. (2.7)}$$

Where $\vec{V}_1$ and $\vec{V}_2$ are the speeds of the contacting bodies. The first expression (Eq. 2.6) is the widely used and facilitates the understanding of the movement. The main specimen, the one of interest, is noted one, and the sign of its speed is always positive. The counter body (or counterpart) is indexed as two, and the sign of its speed is also positive to fulfill the basics of rolling. If this sign is positive then the counter body rolls in the opposite direction as the main body. And the speed vectors point in the same direction at the contacting point.

The condition of rolling motion is satisfied. The slip amount or slide-to-roll ratio then depends on the value of the speed of the counter body. Explicitly, for a higher speed of the counter body ($\vec{V}_2 > \vec{V}_1$), the slip ratio will be negative and in the case of a lower speed ($\vec{V}_2 < \vec{V}_1$), it will be positive. With a positive slip ratio, the resulting friction force F acts on the main specimen opposite to the rolling direction (*Fig. 2.4*).

For a negative sign of the counter body, it has the same motion of the main body and the resulting speed vector has an opposite direction at the contact point. However in this case, the slip is so high that it does not meet the fundamentals of rolling.

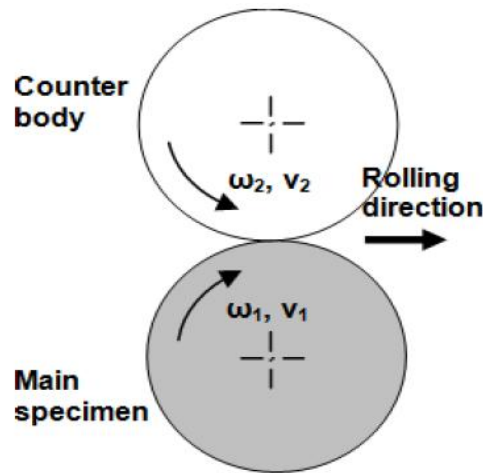


Figure 2.3: Slip-rolling motion

Due to the tractive, the circumferential velocity of the cylinder as a rigid body is higher than its linear velocity, causing the so-called creepage or slip (s). In general the slip can be expressed as the quotient between the relative velocity (v^{rel}) and the mean velocity (v^{mean}) of the cylinder along the plane, as shown in Eq. 5, where r is the radius of the cylinder.

$$S = \frac{v^{rel}}{v^{mean}} = \frac{w.r - v}{0.5.(w.r + v)} \dots\dots\dots \text{Eq. (2.8)}$$

In 1926, Carter presented the first relationship between the traction force and the slip. The representation of this relationship is known as traction curve. Fig 3 depicts the theoretical traction curve of Carter, together with the contact area and the traction distribution along it (in blue color), for three representative points of the traction curve, namely A, B, and C. Point A represents the situation of null traction, i.e. $\mu = 0$, which is known as the free rolling condition, the whole contact patch is in stick.

As the traction force increases, an increasing part in the rear of the contact patch becomes in slip. The surface traction (q_x) distribution for point B increases for stick area until reaching the slip

area, where the surface traction given by the product of the friction coefficient (f) and the contact pressure (p), as shown in fig 2.5.

As the point C of the traction curve is reached, the whole contact patch becomes in slip, and the adhesion coefficient is equal to the friction coefficient. From point C on wards, the contact is said to be in full sliding condition, and the slip may be referred to as macro-slip. On the other hand, between point A and C the contact is in partial slip conditions, and the slip may be referred to as micro-slip.

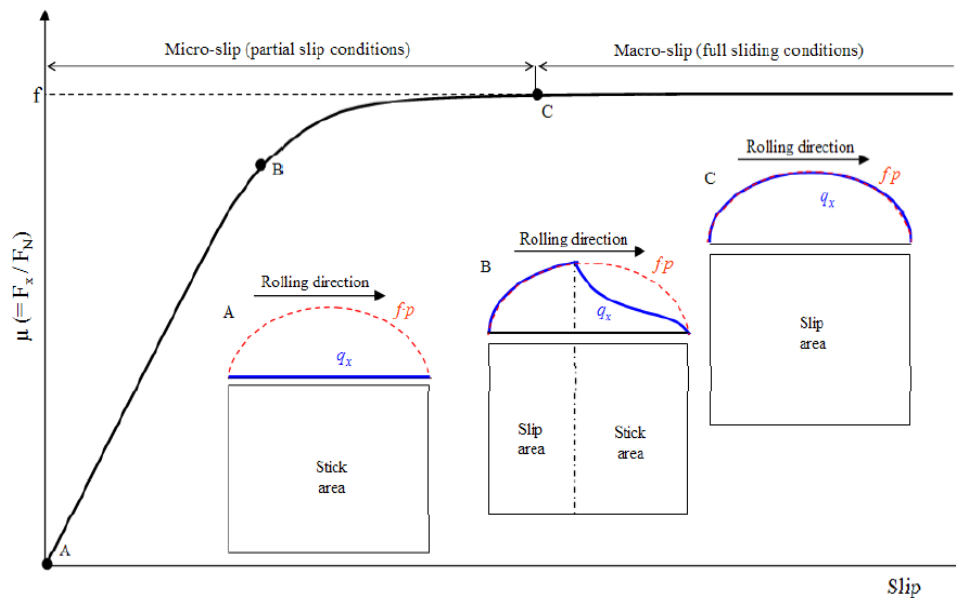


Figure 2.4: Representation of the theoretical traction curve of Carter. [26]

Although the explanation of adhesion has been given to traction, the same holds for braking. The major difference is that the braking torque causes the circumferential velocity to be lower than its linear velocity, and Eq. 2.8 changes to Eq. 2.9. In addition, the wheel slips in full sliding conditions during braking is normally referred to as wheel slide.

$$S = \frac{v^{rel}}{v^{mean}} = \frac{v - w.r}{0.5.(w.r + v)} \dots\dots\dots \text{Eq. (2.9)}$$

2.5. Wheel–rail adhesion under contaminated conditions

As a rolling–sliding contact, a wheel–rail contact is similar to a rolling ball bearing or gears [12], though these are mostly closed systems with comparatively good lubricating conditions. The wheel–rail contact is an open system, which makes it extremely difficult to transfer knowledge from other well-studied but closed systems. For example, the friction coefficient on the railhead is high on a sunny day but decreases on a rainy day. Even on a sunny day, the friction coefficient can differ depending on the humidity and temperature. In addition, foreign substances, such as sand, dust, leaves, oil or grease, can also be present on the rail. All these factors will influence the friction coefficient, resulting in excessive or insufficient wheel–rail adhesion. Table 2.1 shows the friction coefficient measured using a hand-push tribometer [12]. The friction coefficient varies depending on the conditions, and is generally reduced by water, oil/grease, and wet leaves. Moreover, temperature and humidity can also change the friction coefficient [13]. Moore [14] presented the typical available friction, i.e., adhesion coefficient, under various conditions as shown in Table 2.11. Note that sand can increase the adhesion coefficient and moisture can reduce it, compared with outright wet conditions.

Table 2.1 : Friction coefficients measured using a hand-push tribometer [12].

Conditions	Temperature (°C)	Friction coefficient
Sunshine dry rail	19	0.6–0.7
Recent rain	5	0.2–0.3
Substantial grease on rail	8	0.05–0.1
Damp leaf film on rail	8	0.05–0.1

Table 2.2: Examples of wheel–rail adhesion coefficients [14].

Rail conditions	Adhesion coefficient	Rail conditions	Adhesion coefficient
Dry and clean	0.25–0.3	Moisture	0.09–0.15
Dry with sand	0.25–0.33	Light snow	0.10
Wet and clean	0.18–0.20	Light snow with sand	0.15
Wet with sand	0.22–0.25	Wet leaves	0.07
greasy	0.15–0.18		

In the context of the railway track, contamination refers to any material that is present on the rail and becomes entrained in the wheel–rail contact. The contamination can be divided into solid contamination, such as sand, dust, leaves, and debris, and liquid contamination, such as water, oil or grease. Of these contaminants, sand is usually used to increase adhesion and remove surface layer contamination, since modern power cars and locomotives require a higher friction coefficient on the railhead [12]. Liquid contaminants and leaves can reduce adhesion, especially when the rolling speed is increasing. Dust or debris could reduce the adhesion by mixing with liquids [15]–[16]. As a result, the dominant problem is too low adhesion in the wheel tread–railhead contact. This thesis focuses mainly on low adhesion in the wheel–rail contact caused by plastics contaminants.

2.6. Adhesion requirements in railway transportation

In railway transportations there are normally three different types of adhesion requirements, namely given by tractive/braking capacity of the rolling stock, timetable regulation and safety during operation.

The first requirement, adhesion for tractive/braking, corresponds to the adhesion needed to accelerate or brake the rolling stock at a given full capacity, which may be employed by the driver under certain circumstances. This adhesion requirement varies according to rolling stock types, depending mostly on characteristics of the traction or braking systems, the number of driven or braked wheel axles, the diameter of the wheels, and the axle load. For the sake of illustration, in the fleet of the major train operation company (TOC), in the Netherlands, i.e. Netherlands Spoorwegen (NS), the maximum adhesion required in traction by Electrical Multiple Units (EMUs) of the VIRM double-decker series is 0.23, while electrical locomotives of series 1700 may require up to 0.24. Furthermore, the tractive/braking capacity of rolling stock can vary with the traveling velocity due to limitation in motor power. For example, in traction operations VIRM trains may require a maximum adhesion of 0.23 up on start, whereas it does not require more than 0.09 at 100km/h. Moreover, the adhesion requirement largely differs for traction and braking operations mainly due to the fact that a considerably lower number of wheel axles is employed to accelerate a train than to brake it, e.g. only 25 % the wheel axles are used

for traction in the VIRM trains. In the passenger rolling stock of NS the maximum adhesion requirements are up to 0.25 in traction and 0.14 in braking.

The second adhesion requirement is given by the time table that strongly influences the traction and braking behavior of the driver. In the Netherlands, an average value of 0.07 is employed for traction operations to establish the time table of commuter train. For traction operation, different values of adhesion are employed depending on the rolling stock, 0.17 being the maximum value employed.

The third type of adhesion requirement is indispensable to guarantee the safety in the railway transportation and is only applicable to braking operation. In most countries the railway track is divided into blocks, in which the trains are allocated for safe control of the traffic flow. Railway signaling aims at giving instructions to the drivers to avoid a train enters a block already occupied by another train so that no collision can occur. The minimum distance between fixed signals or blocks is normally determined based on the braking tables at the disposal of the railway network managers. Note that the braking tables have been calculated by considering the characteristics of the rolling stock and the tracks.

[17] Figure 2.6 schematically shows the required adhesion coefficients according to these three categories. It should also be noted that the adhesion coefficient requirements also depend on the type of rolling stock, traction and braking systems, number of powered/braking axles, etc. [17]. For example, a metro vehicle or a commuter train usually requires relatively high acceleration and deceleration due to the short intervals between stops [19]. An acceleration of 1.5 m/s^2 measured in a metro vehicle [18] requires an adhesion coefficient of at least 0.15.

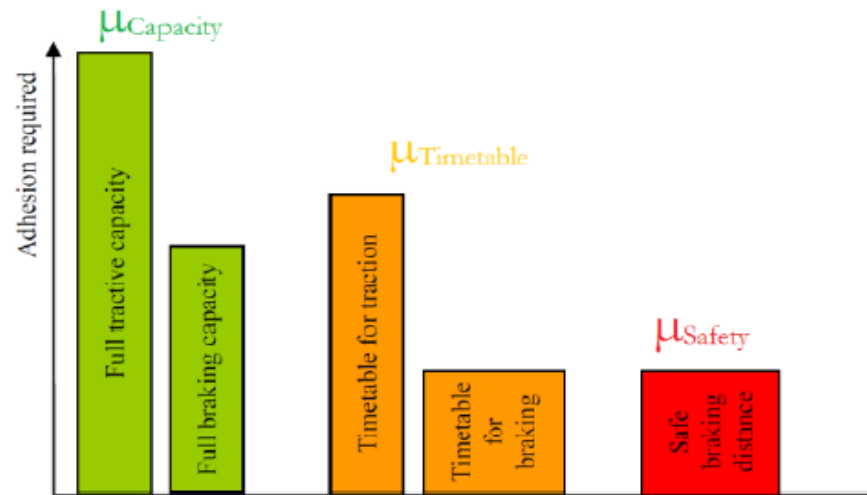


Figure 2.5: Common adhesion requirements in railway transportation [17]; the bar height is proportional to the maximum required adhesion coefficient in the Netherlands.

2.7. Wheel–rail contact conditions

Unlike road vehicles, such as the automobile, railway vehicles have some unique behaviors and properties, such as hunting motion, self-steering capability, and lateral dynamics. These unique features originate from the wheel–rail guidance system depending on wheel and rail geometry. First, the rail has a specific profile [20], governed by rules, and is mounted at a small inwards inclination (1:30 in Sweden) (indicated by no. 3 in Fig. 2.7) for better fit to the wheel profile and better load transfer to the sleepers and ballast. Second, the wheel is of a special design, including a wheel tread (where contact point 1 is located on the wheel in Fig. 2.7) and wheel flange (where contact point 2 is located on the wheel in Fig. 2.7). Moreover, the wheel profiles are usually conical (indicated by no. 4 in Fig. 2.7), leading to the difference in rolling radius in a curve for the two wheels in the same wheel set. Compared with tire–road interaction, the wheel–rail contact is very small at approximately 1 cm^2 [12]. As a result, the heavy axle load is transferred through a small patch generating high contact pressure.

Due to the above-mentioned factors, the wheel–rail contact area changes when running under different conditions. Generally, when the vehicle is running on a straight track, the contact area is usually between the wheel tread and railhead, as shown by contact point 1 in Fig. 2.7. When the vehicle is running on a curve, the contact area moves to between the wheel flange and rail gauge,

as shown by contact point 2 in Fig. 2.7, or both of contact point 1 and 2. However, in real operation, the wheel rail contact varies constantly in terms of area and type, even starting from the same profile. In railway maintenance, wheels need to be changed and rails need to be re-ground after a certain time, depending on the contact conditions and wear.

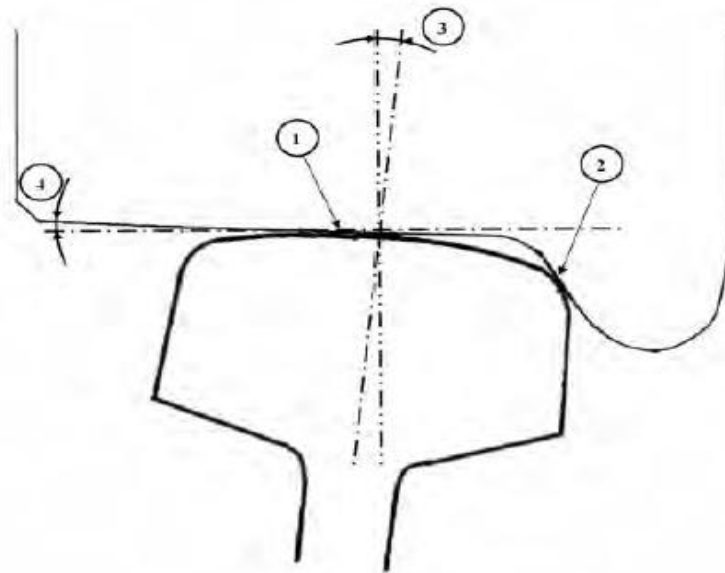


Figure 2.7: schematic view of two types of wheel-rail contact: 1. wheel tread-railhead contact; 2. wheel flange-rail gauge contact; 3. rail inclination; 4. conical wheel profile. [7]

The two basic types of wheel-rail contact differ in many respects. Lewis and Olofsson [21] presented the operating conditions in a wheel tread-railhead contact and a wheel flange-rail gauge contact, as shown in Fig. 2.8. As the contact area changes from wheel tread with railhead to wheel flange with rail gauge, both contact pressure and sliding velocity increase significantly. According to Olofsson and Telliskivi [22], rail hardness also has clear dependence on the contact type. In addition, the wear rate at the rail gauge is 10 times greater than the wear rate at the railhead [21]. In the present work, we will discuss only the wheel tread-railhead contact, which assumes that the vehicle is running on a straight track, and only longitudinal creep is considered. In the following sections, all discussions are based on this assumption.

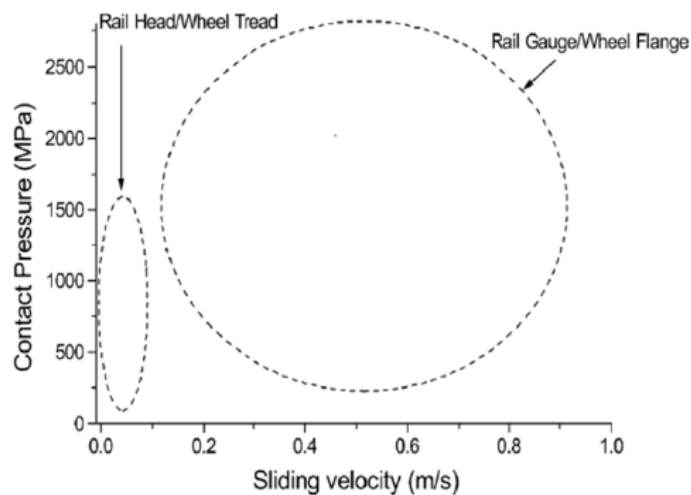


Figure 2.8: Contact conditions in a wheel rail contact [21].

The wheel–rail contact is a rolling–sliding contact. It is easy to imagine wheels rolling on tracks. On the other hand, wheels will also spin if the tracks are very slippery, for example, if there is ice on the track, in what is known as sliding motion. The combination of the two motions is called rolling–sliding contact. The difference between the circumferential velocity of a driven wheel and the translational velocity of the wheel over the track is usually a non-zero value, which is known as sliding velocity, U_s . The ratio of sliding velocity to rolling velocity is called creep or creepage [23], which is the main source of creep force.

Many sources treating railway dynamics define creep as the ratio of sliding velocity to vehicle speed, assuming very small creep. In wheel flange–rail gauge contact, creep is high, resulting in high sliding velocity, while in wheel tread–railhead contact, creep is usually relatively small.

When creep is zero (here we only consider longitudinal creep), which is a pure rolling case, no tangential force is transmitted and the contact area sticks. As soon as tangential force starts to be transmitted, a slip region appears in the trailing edge of the contact patch, while the rest of the contact patch remains stick. This stick-slip region results in rolling-sliding contact. The slip region increases and the stick region decreases in size with increasing creep. When the creep is high enough, the stick region disappears leading to gross slip. The relationship between tangential force and creep is shown below [24], [17].

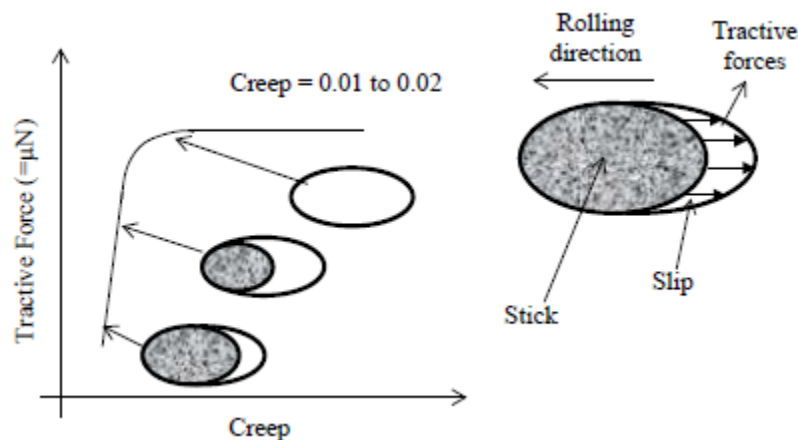


Figure 2. 9: Relationship between tangential force and creep at the wheel-rail contact [5]

2.8. Consequences of low adhesion

The consequences of low adhesion differ depending on whether they are encountered during traction or braking. It is generally said that in traction operation affects punctuality, whereas it can threaten the safety during braking. But, there may be some other consequences due to low adhesion, as presented below in more details.

2.8.1. During traction

Low adhesion during traction may affect the railway track capacity, reduce the punctuality of the railway transportation, and in some extreme cases damage the rails more rarely the wheels. The track capacity can be a limiting factor to satisfy the increasing demand on railway transportation in densely populated country. Reduced accelerations in rolling stock lead longer occupation the track, which could ultimately force the construction of new infrastructure to accommodate the increase of freight and passenger transportation. [25]

The punctuality of passenger transportation in past year in the Netherlands is given below in table 2.3. Note that the calculation of delays in the Netherlands only considers trains that arrive at least three minutes later than scheduled. It can be seen that the average punctuality decreases in autumn, which can be attributed to the likelihood of presence of contaminants, such as leaves and water. The loss of punctuality generates a double to the train operating companies (TOCs). On the other hand, the TOCs may need to pay the government as compensation for inadequate

performance. The payment is normally in proportion to the percentage loss, e.g. the costs of each punctuality loss percentage were around 3 m€ in 2004 for NS [25]. On the other hand, delays in commuter service generally cause dissatisfaction to the passengers, which may promote in some case the preference of to use other forms of transportation. This situation may not only increase the costs of TOCs, have an indirect impact on the environment.

Table 2.3: Average punctuality of railway transportation in the Netherlands between 1999 and 2003 [25]

	1999	2000	2001	2002	2003
Whole year	86.8%	84.7%	79.9%	81.2%	83.1%
autumn	82.5%	78.6%	76.4%	76.5%	77.5%

Furthermore, slipping wheels could occasionally cause damage to rails and wheels, especially in the particular case of rolling stock unequipped with an adequate traction control (TC) system. Low adhesion upon start of traction can imply spinning wheels (i.e. spinning wheels that do not move forward), which can generate high temperatures on the rail surfaces, leading the formation of the so called rail burns.

Additionally spalling of the brittle material formed on the surface of the rail may also occur, as pointed out in [25]. Moreover, the high level of slip at low rolling velocities could cause fatigue crack growth on the wheel tread [26]. On the other hand, at high rolling velocities thermal effects due to large wheel slip could lead martensite on the tread following to spalling of the martensite in the worst cases [26].

2.8.2. During braking

Low adhesion condition during braking can affect track capacity and punctuality (equal to the case of low adhesion during traction), threaten the safety of the railway transportation, and cause damage to wheels. If a train is requested to stop at a signal, the adhesion at the wheel-rail is critical to the rate at which to the train can decelerate. Signals passed at danger (SPADs) can occur due to low adhesion conditions, e.g. nine low adhesions related SPADs were registered in 2005 in the UK [27]. In most detrimental cases, a SPAD may lead to a collision if the invaded

track is occupied by another train. This type incident was presumably encountered in accident that recently occurred in the metro system of Amsterdam in Netherlands.

Furthermore, damage to wheel due to braking under low adhesion conditions can occur, particularly in rolling stock equipped with an adequate wheel slide protection (WSP) system. The blockage or partial blockage of a wheel set during a braking maneuver leads to a high level of slide, causing part of the wheel tread to wear off forming a wheel flat. The high temperature in the contact patch, exceeding 800-850 °C due to the dissipated energy, transforms the pearlitic wheel steel into austenite [26]. The subsequent rapid cooling of the thermal affected zone as the wheel starts rotating again causes a transformation of the austenitic phase into martensite. Furthermore, the initial wheel flat with sharp edges transforms into a longer flat with rounded edges the plastic deformation of the wheel material upon subsequent impacts with the rail. [28]

The high impact forces in the wheel-rail associated with wheel flat lead to damage on the rail, concrete sleepers and some part of the wheelset [29]. They can also produce excessive noise and vibration level, affecting the passenger comfort. In order to remove the wheel flats, the wheels are normally re-profiled, which increase the maintenances of the TOCs. In Netherlands annual re-profiling costs associated with low adhesion were on average 1 m€ between 1997 and 2007 [25, 17].

2.9. Related literatures

Since the beginning of the railway transportation, adhesion between rail and wheel has been identified as a crucial factor. It may limit the acceleration and braking capabilities of a train. The increasing demands in railway transportation have led to faster trains with higher accelerations and decelerations. But the adhesion depends on the available friction between steel wheel and rail was not enough for faster trains.

Poor / low adhesion leads in wheel/rail contact to:

- ✓ Extended stopping distances which is a safety issue
- ✓ Performance issue as it affects traction (delays and disturbance with timetable)
- ✓ High energy requirements
- ✓ High noise and vibration

- ✓ Wear and RCF

As it has been presented on different papers, the causes of low adhesion observed in the studies are:

- ✓ Slippery coatings formed by leaves
- ✓ Humidity and
- ✓ Oil and wear particles

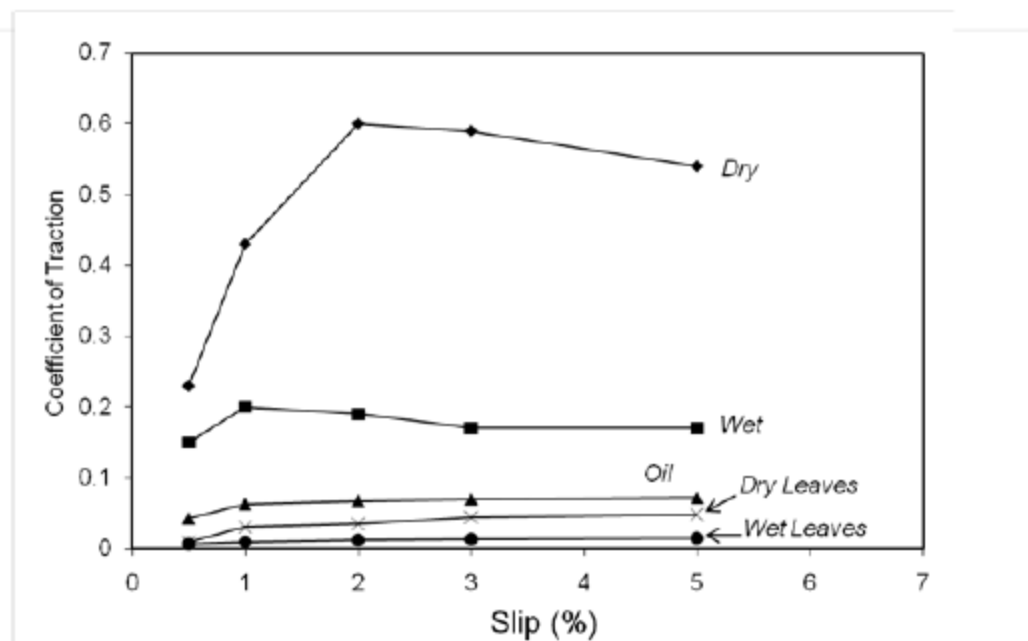


Figure 2.10: Comparison of coefficient traction with slip at different contaminants [30]

Yi Zhu (2013) under Adhesion in wheel-rail contact conducted experiment on wheel rail contaminated or lubricated with oil and water using a mini-traction machine (MTM). The MTM test rig consists of a steel ball and a steel disc, both of which can be rotated independently by two motors to generate a rolling-sliding contact.

The result of this work shows that both water and oil are known to reduce adhesion between the wheel and rail. Moreover, oil could reduce the adhesion coefficient much more than water could when the speed was increased within a low speed range. The fluid load capacity is inversely proportional to the adhesion coefficient.

Tranergy Corporation (1997) under Improved Methods for Increasing Wheel/Rail Adhesion in the Presence of Natural Contaminants developed a theoretical analysis of adhesion, including the factors affecting adhesion and the mechanisms by which adhesion is reduced. A survey was then taken of two dozen commuter and light rail systems regarding their experiences and observations. A laboratory investigation of adhesion, an intensive search and review of literature, and a study of the properties of rail contaminants were then completed. A field investigation of rail contaminants was then done in two parts. The first part was a study of rail contaminants conducted by the Association of American Railroads (AAR). The second part was the analysis and experimentation with rail contaminants collected with the help of three commuter and light rail systems. The results of this work show that rail surface contamination is the primary reason for loss of adhesion.

Fallen leaves (especially leaves with oil [e.g., pine and cedar leaves]); a little water, frost, or light drizzle; and morning hours produce the worst conditions for maintenance of adhesion. Rust, dry dirt, and other dry contaminants on top of the rail, by themselves, do not affect adhesion much; however, the presence of small amounts of water and oil results in the formation of a thin slurry or paste that reduces adhesion. Heavy rains do not reduce adhesion as much because they tend to wash the rail and remove the slurry.

[Lewis] The application of friction modifiers to increase the adhesion level between wheel and rail under different contamination conditions is popular practice. O. Arias-Cuevas*¹, Z. Li*, R. Lewis# and E.A. Gallardo-Hernández# investigated the adhesion characteristic of two friction modifiers contaminated with water and leaves with the help test roller rig . This work shown that when water is applied to the disks contact, the adhesion coefficient drops between 30 and 65% depending on the slip and the FM used even though the recovery time for the two friction modifiers are different due to the difference in the particle size distribution of the components of the friction modifies.

2.10. Braking Distance

For trains to safely travel on a railway, trains must be provided with sufficient distance in which to stop. Allowing too long a distance reduces the capacity of the line and hence the return on rail infrastructure investment. Too short a distance and collisions would occur, because the train would not be able to stop within the available distance and would therefore occupy a section of

track that could be allocated to another train. Consequently it is important that the distance be adequate, but not overly so.

Braking Distance is the distance the train travels from when the train driver makes a full-service brake application to when the train stops. Coefficient of adhesion between wheel and rail plays to either elongate or shorten the braking distance of a train set to stop.

Braking Distance Influencing Factors

Braking distance depends on:

- the speed of the train when the brakes are applied;
- the deceleration rate available with a full-service brake application, which varies according to the coefficient of friction between wheel and rail;
- the delay from when the brakes are commanded by the train driver to when they are actually become effective (brake delay time);
- the state of the wear of the brake pads and the air pressure available in the brake cylinders;
- the geography of the track, in particular the track gradient the train travels over from when the brakes are commanded to where the front of the train stops.
- The mass distribution of the train.

2.11. Calculating braking distance with available level of adhesion

Braking distance can be calculated using the vehicle entry speed and level of low adhesion that is to be generated in the wheel-rail contact interface. The distance to stop from the point of braking for level track can be calculated by using the equation:

$$S_b = \frac{v^2 - u^2}{2a} \dots\dots\dots \text{Eq. (2.10)}$$

Where:

S_b = distance to stop

v = initial speed before brake stop

u = final speed after brake stop (zero)

a = deceleration

The maximum braking deceleration can be calculated by using the equation:

$$a = \frac{\mu}{100} \times g \dots\dots\dots \text{Eq. (2.11)}$$

Where:

μ = adhesion level (coefficient of friction), expressed as a percentage

g = gravitational acceleration

Contaminants will not be concentrated in a given section of the track instead they will be displaced some distance along the track which is called contaminant limit distance. So additional length of track based upon the contaminant limit distance, which will allow for a safe run out, is included in the brake distance calculation. It should take into account that the vehicle may spread the contaminant, the brake build up time, errors on the entry speed (allow 25% for these factors) plus an overall safety factor of 10%.

2.12. Braking distance considering gradient

Track gradient at the test will have an effect on the stopping distance. If the train is moving in the down gradient direction then the required run out stopping distance will be increased (and up gradient will be reduced). This should be taken into account when calculating the deceleration.

The change in stopping distance due to a down gradient can be worked out as follows:

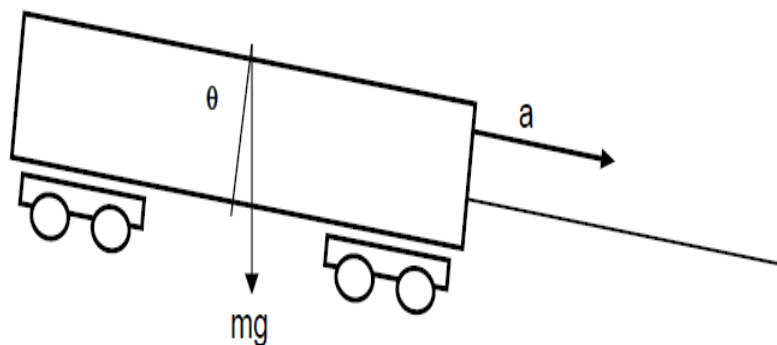


Figure 2.11: free body diagram of a vehicle along a gradient

With no braking force, the force (F) acting on the train can be calculated as:

$$F = mg \sin \theta = ma \dots \dots \dots \text{Eq. (2.12)}$$

Where:

m = mass of train

$G = \sin \theta$ = gradient of the slope

Therefore, the acceleration of the train, due to the gradient, can be calculated as:

$$a = g \sin \theta = g \times G \dots \dots \dots \text{Eq. (2.13)}$$

The overall vehicle deceleration is the deceleration due to braking, less the acceleration due to the gradient:

$$a = \frac{\mu}{100} \times g - g \times G \dots \dots \dots \text{Eq. (2.14)}$$

Chapter 3: Experimental methods, procedure, and conditions

3.1. Wheel-rail Material

As investigated in different literature, there are several wheel and rail standards but closely similar in their properties. In the entire standards wheel steel material is a little softer than that of the rail differing slightly in the amounts of carbon, silica, and manganese in the steels used.

For Addis Ababa light rail transit (AA LRT), the rail standard used is China National Railways standard of 50 kg/m while the national is 60kg/m. Table 3.1 represents the chemical compositions and table 3.2 .mechanical property of wheel and rail specimens which suits to the standards that of Chinese and UIC900A .

Table 3.1: Material composition of steel wheel and rail steel discs which suit to UIC standard (UIC 900A rail and R7 wheel) and Chinese standard

Chemical composition (wt %)	C	Si	Mn	P	Ni	Cr
CSN 12071(rail) (AISI/SAE 1070)	0.6-0.7	0.37	0.6-,8			
CSN 12071(wheel) (AISI/SAE 1050)	0.47-.55	0.17-0.37	0.5-0.8	0.035	0.3	0.25

The rail material designated by CSN 12051 in table 3.2 which represents the wheel material does have a hardness of 270-286HB (28-30HRC) and a tensile strength of 700- 850 N/mm². The rail wheel material is a little harder, in the hardness range of 282–330 HB, with tensile strength in the ranging 750–900 N/mm². These specimens prepared for this thesis are types of materials close to wheel/rail material of UIC and Chinese standard. As shown in the table 3.1 the percentage composition of each material is a little bit lower than the percentage compassion of the standard but is within the range assuring nothing is wrong with the selection.

Table 3.2: Mechanical properties of the selected materials for both the wheel and rail disc samples

Material Type	Brinell hardness (HRC)	Yield strength (M Pa)	Tensile strength (M Pa)
CSN 12051(wheel) (AISI/SAE 1050)	270-286 (28-30)	460	700-850
CSN 12071(rail) (AISI/SAE 1070)	282-330 (30-35)	470	750-900

3.2. Feature and dimension of the test rigs specimen

As discussed in most research papers, the maximum outer diameter of the specimens are limited by the maximum diameter that can be extracted from the section of the rail head; the contact width being 10mm to represent the wheel thread and rail top contact. Thus the specimen feature prepared from the specimens with material composition close to the standard wheel rail material, CSN 12051(in Czech standard) for wheel disc and CSN 12071 for rail as depicted in table 3.1. The composition of each material is depicted in the table 3.1 comparing with UIC and Chinese National Railway standard. The dimensions of the twin discs for this thesis are indicated in figure 3.2., because there is no dimension limitation as it would have been taken from the rail section. As the name implies, Twin Discs, both the wheel disc and the rail disc have the same dimensions and shape. The effective diameter of both rigs are made 100 mm while the contact width remained to be 10 mm to represent the contact area of the wheel thread and rail top of the real contact .

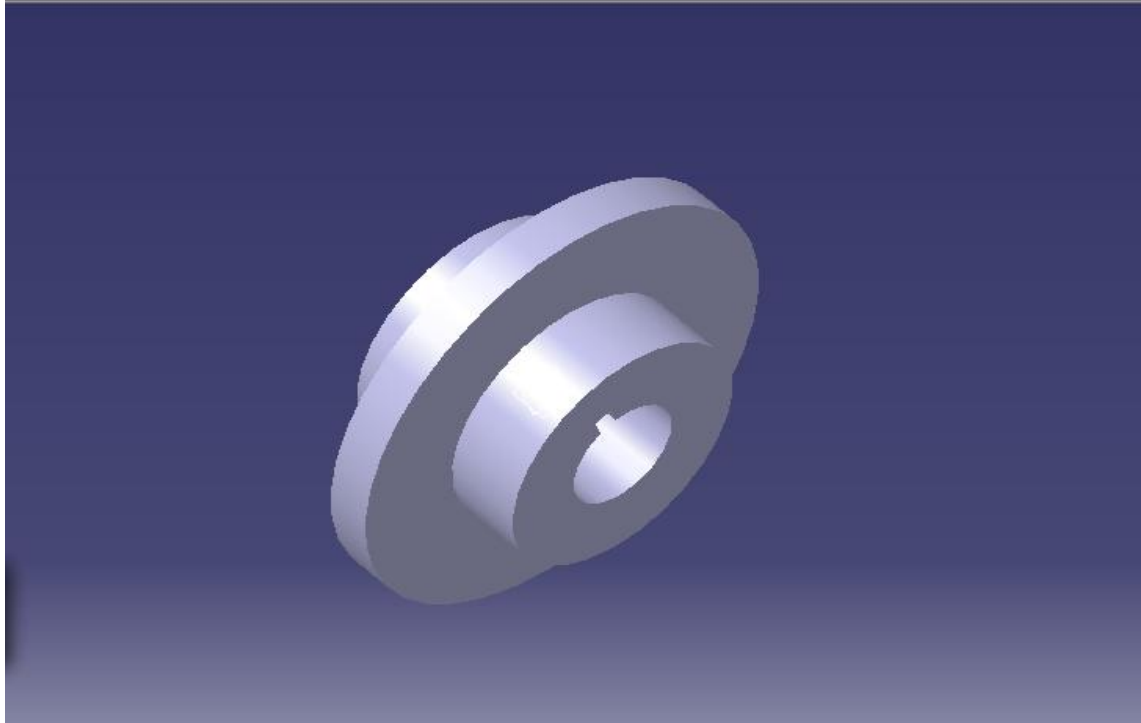


Figure 3.1: Feature of the test rig specimen in CATIA V5



Figure 3.3: Photograph of the test disks used

3.3. Method and Test Description

The most common approach used to perform adhesion tests on materials is the use of pin-on-disk [31, 32] or twin-disk systems. The concept of the twin-disk system is very similar to the use of a roller rig and can be used for adhesion studies [33]. The twin-disk system is simple and efficient;

it consists in the use of two cylindrical rollers pressed into contact and rotating with different peripheral speeds. The variation of the relative velocity and of the contact pressure allows performing the test under different conditions.

The tests performed with this system cannot be directly compared with a railway vehicle, since contact geometry and slip conditions are different at the contact interface. For this reason the optimal method to validate an adhesion, representing a real railway vehicle, is the use of tests on the track. This method, however, requires a large investment in order to perform the tests due to track occupation, vehicle parameterization and instrumentation, use of a track geometry measurement vehicle to identify the track quality before the passage of the train, and all of these for a long mileage. Furthermore, the twin-disk method applies conveniently only in cases of wheel wear [34, 35] or adhesion studies [36, 37], where it is adopted especially to test anti slip or antiskid systems.

An alternative to the test on the track consists of the use of a full scale roller rig. This approach, already adopted by Carter at the beginning of the 19th century to perform adhesion tests on locomotives [38], gives substantial benefits, since the tests are performed on a test stand in a laboratory environment, without the requirement for line occupation. The tests can be performed on real vehicles [39] or real wheel sets [40], and the instrumentation of the test rig allows the achievement of repeatable and reliable measurements.

However, the tests performed on full scale roller rigs are rather expensive in terms of time and direct costs. Therefore, the use of a scaled roller rig, already used by several authors to perform dynamic tests and other studies on railway vehicles [41], can be a useful alternative. The test description for this thesis comprises two main components; mechanical arrangement and, control and data acquisition.

3.3.1. Mechanical arrangement

The mechanical component of the test machine is mainly composed of two rail and wheel rollers, each one supported by parallel shafts which are fixed at their ends by bearing. One end of each roller's shaft is connected to independent electrical motors. The wheel side roller is connected to

the shunt motor and the rail side roller is connected to the DC motor by means of couplings. A spring is used as a normal contact load application mechanism with the help of a T-bolt.

3.3.2. Control and data acquisition

The main experimental output variables required for the determination of wheel rail adhesion at each contaminant and slip conditions are angular speed, the armature current and armature voltage of the wheel side shunt motor. The angular speed of the motor is controlled by the variable resistor and is measured by a tachometer and or sensor speedometer. The armature current and armature voltage are directly read from ammeter and voltmeter respectively.

The twin disc test approach has been used to produce creep curves for a number of different contact conditions. This method, while not having the scale or geometry of the actual contact, provides a good simulation of the rolling-sliding motion and allows close control of operating parameters not available in more complex test methods. Tests have been carried out over a range of preset slip values with in Eq. 3.3 and creep curves have been generated.



Figure 3.4: motor speed readers

3.4. Test set-up and Conditions

Determination of Applied Force and contact pressure of the Interaction

Contact force determination

The required force applied to the disc was calculated as shown below.

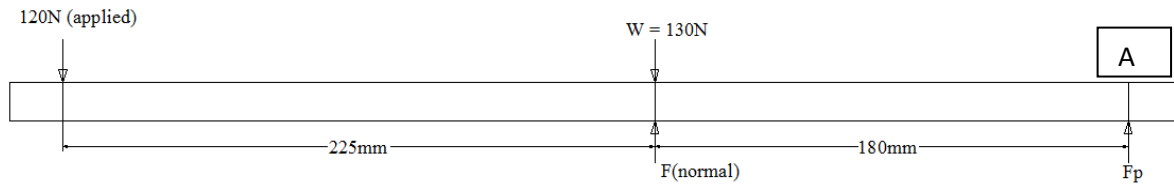


Figure 3.5: schematic representation of the rail side wheel carrier arm

$$\Sigma M_A = 0$$

$$\Rightarrow F_N = \frac{FA \times 405mm + W \times 180mm}{180mm} = \frac{120N \times 405mm + 130N \times 180mm}{180mm}$$

$$F_N = 400N$$

Contact pressure distribution determination

$$P = \frac{2 \cdot F_N}{\pi \cdot b}, \text{ Where}$$

b-is the half width of the contact rectangle = 5mm

F_N – is the normal load per unit length (N/m) = 400N

$$P = (2 \cdot 400) / (3.14 \cdot 0.005) = 800 / 0.0157 = 50,955 \text{ N/m}^2 = 51 \text{ kPa}$$

The adhesion test was carried out under the conditions of different wheel/rail contacts, such as various speeds of the wheel disc while rail disc made constant throughout the tests, contact load of 400N, and dry and contamination situation. In order to generate slip, we adapt a method by presetting the two motors' speeds which the rotation speed of the part of the braking motor i.e. the rail disc motor made 400rpm throughout while wheel disc motor speeds are varied from 400rpm to 442rpm so as to create slip values of 0 to 10% calculated from Eq.2.7.

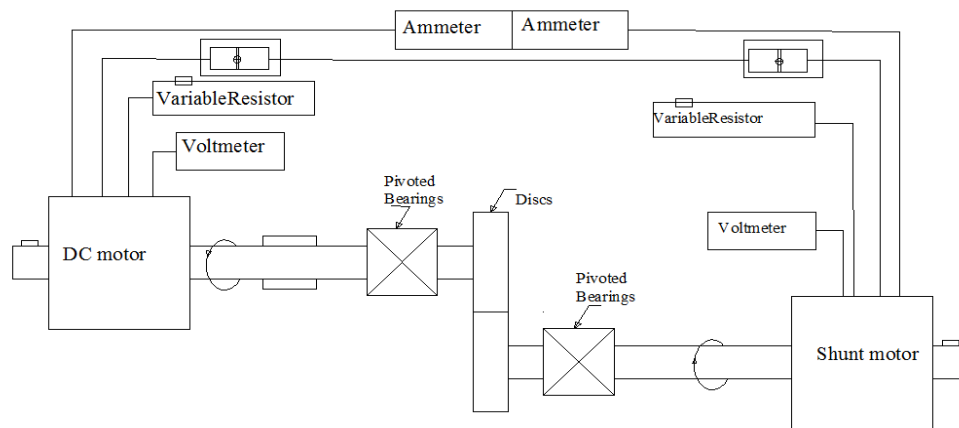


Figure 3.6: Schematic representation of the setup

For determination of adhesion coefficients at each application of the contaminant, the friction characteristics of contact bodies should be considered by taking into account the roll mode with a slip. For this purpose, a friction machine was used with a set-up as in figure 3.7

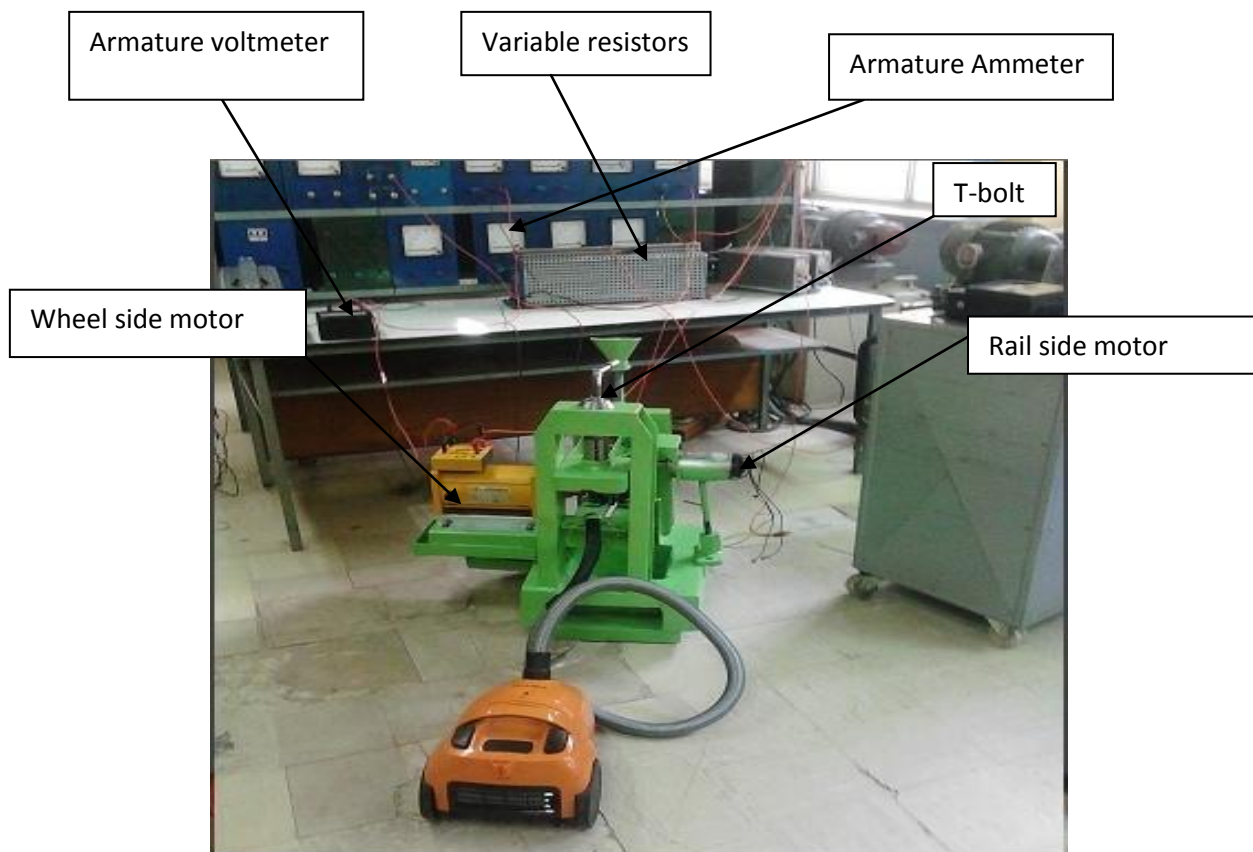


Figure 3.7: photograph of the set-up

The test settings for this test case were as follows:

- (a) Normal contact load of 400 N due to the applied load of 120N through the T-bolt;
- (b) Different steel materials to represent wheel and rail of rail vehicle as described in section3.1;
- (c) Diameter of each wheel roller is 100mm as in figure3.2;
- (d) The wheel disc is a little softer than the rail disc to represent the real situation as depicted in table 3.2;
- (e) Angular speeds of the wheel roller were preset 400 to 442 rpm using eq. 2.7 or the corresponding one eq. 3.3 so as to create slip value/relative slips of 0, 0.25, 0.5, 1, 2 up to 10%. In this case the rail velocity was taken as 400 rpm which is constant throughout the test for all slip conditions the wheel velocity was varied according to the respective slips.

Consider 0 percent slip condition

Slip = 0 %, $N_r = 400$ rpm

Since both wheel and rail are equal in radius, the equation corresponding to eq. 3.3 becomes

$$Slip = \frac{N_w - N_r}{N_w + N_r} * 200\%$$

$$0\% = \frac{N_w - 400}{N_w + 400} * 200\%$$

$$\Rightarrow N_w = 400 \text{ rpm}$$

Similarly the wheel side rotational speed for other slips are predetermined and indicated in the appendix tables.

- (f) Torques due to the influences of the contaminants could have been read directly from a torque transducers had it been fitted on the shaft of the motor but it was calculated from the induced armature volts currents and the corresponding as,

$$T_i = \frac{60(E_a I_a)_i}{2\pi N_i} \dots \dots \dots \text{Eq.3.1}$$

Where T_i , E_a , I_a and N_i are Torques armature voltage, armature current and rotational speeds from 0 to 10% slips at each contaminant application Armature voltage, armature current and rotational speeds respectively.

(g) The corresponding adhesion coefficients are calculated as

$$\mu_i = \frac{T_i}{r_w \times F_N} \dots \dots \dots \text{Eq.3.2}$$

Where μ_i and T_i are adhesion coefficients at each slip values and constant torque due to the applied load respectively.

(g) Preset slip values are calculated with formula

$$\text{Slip} = \frac{\omega_{\text{wheel}} \times r_{\text{wheel}} - \omega_{\text{rail}} \times r_{\text{rail}}}{\omega_{\text{wheel}} \times r_{\text{wheel}} + \omega_{\text{rail}} \times r_{\text{rail}}} * 200\% \dots \dots \dots \text{Eq.3.3}$$

3.5. Tested contaminants

In different researches the influence of contaminants on the level of wheel-rail adhesion has been studied with respect to the thickness of the contaminant adhered on the surface of the rail. Among contaminants, the friction properties related to their thickness tried to be investigated were leaves and oxide layers on the rail.

In [42] unanswered question of how much leaf is necessary on the rails before the lowest friction is encountered was raised. [43] Identified that higher average thickness values were found with fresh leaves. In [44 and 45] contaminant thickness was higher at the initial crushing of leaf on to rail and decreased as the train further rolled due to the spread of the individual leaf patches along the line.

In this thesis wheel-rail adhesion under plastics contamination was investigated with respect to a single plastic sheet thickness. Different plastics were measured with micro meter and most of their thickness fallen into four main groups as depicted in the table 3.3

Table 3.3: tested plastics groups and their thickness

Plastics group	Thickness (mm)
Group one	0.00185
Group two	0.0025
Group three	0.0035
Group four	0.007

As shown in figure 3.8, four plastics contaminants were considered to simulate adhesion conditions of wheel rail contact with twin disc test machine.

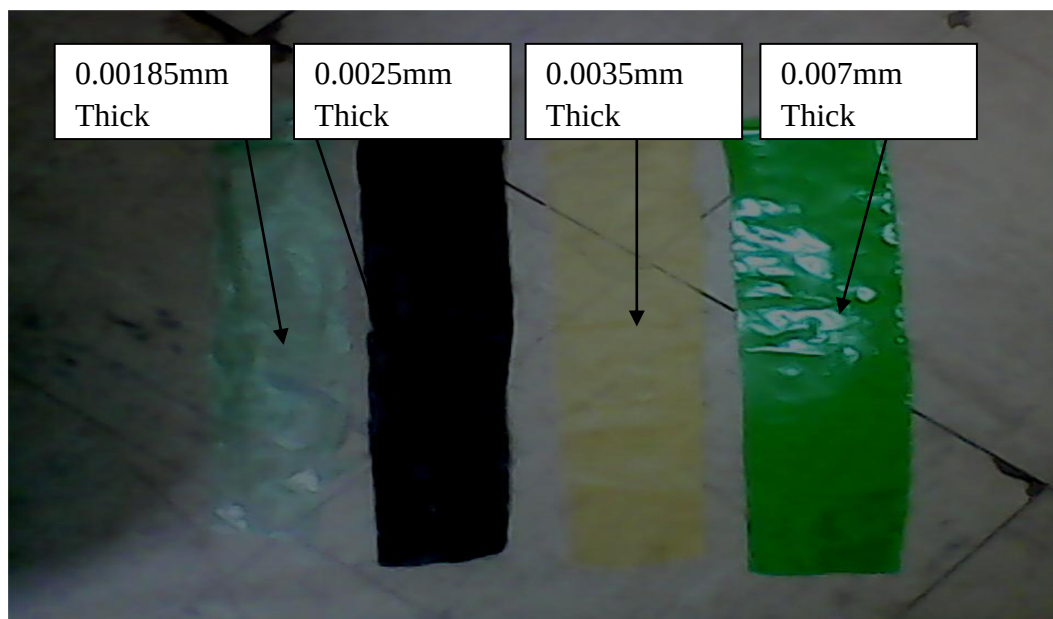


Figure 3.8: Photographs of the plastic contaminant strips considered for adhesion testing

3.6. Test Procedure

In the tests the wheel disk made to rotate faster than the rail disk; the rail disc rotational speed was maintained at 400rpm, equivalent to 4.2 m/s of rolling speed. Since cylindrical disks were used, a line contact of 10 mm width was present in the test. The speed of the wheel disk was adjusted from 400 to 442 rpm to create slip conditions of 0, 0.25, 0.5%, 1%, 2%, 3% up to 10% representing values typical of wheel tread and rail head contacts. Strips of each plastic with length equal to the perimeter of the rail disk and wider than the width of the rail disk prepared as

shown in fig3.8. The strips were wrapped around the rail disk and stack against it with the help of a sticky jelly fluid called alardite witch painted on side face of the rail wheel as shown in figure 3.10. A contact force of 400N was applied.



Figure 3.9: Alardites



Figure 3.10: Method of plastics application on the rail side wheel surface

3.6.1. Dry test

Tests were initially run dry with no contamination i.e. dry test. This test was performed from zero slip to ten percent. Test one of the dry test, at 0% slip, the rotational speed of each motor was adjusted to 400rpm prior to loading each disks together. Then the upper disk was lowered by releasing the load arm lock from its rest pivot and made to meet to the lower disk. Insuring the two discs are perfectly aligned at their 10mm contact width and seen run smooth, a force of 120

N is applied through T- bolt compressing the spring 6mm through the guide and the required force of 400N at the disks contact. The disks were run until stable and data were collected i.e. speed by speed sensor (speedometer), armature voltage from the voltmeter and current from ammeter. In the same manner the corresponding data were collected for the rest of slip values of the dry test.

3.6.2. Contaminated test

Plastics contaminated test was performed from zero to ten percent as in dry test. At 0 % slip the rotational speed of each motor was adjusted to 400 rpm prior to loading each disk together. Then the motors turned off and the rollers came to rest. This time the strip of 0.00185 thick plastics is wrapped around the rail disk and both motors turned on. Then the rail disk was lowered by releasing the load arm lock from its rest pivot and made to meet to the lower wheel disk. Insuring the two discs are perfectly aligned at their 10mm contact width and seen run smooth, a force of 120 N is applied through T- bolt compressing the spring 6mm through the guide and the required force of 400N at the disks contact. The disks were run until stable and data were collected i.e. speed by speed sensor (speedometer), armature voltage from the voltmeter and current from ammeter. After data collected for this test motors were turned off and the rail disk was raised and the two rollers cleaned with the help of ethanol. The same procedure is followed for 0.0025, 0.0035 and 0.007 mm thick plastics at the same slip condition. After test for each plastics group is conducted and data collected at 0 % slip, the motors speed was adjusted so as to provide the next slip condition. In a similar way data is collected at 0.25, 0.5, 1, 2, up to 10% for each plastics group.

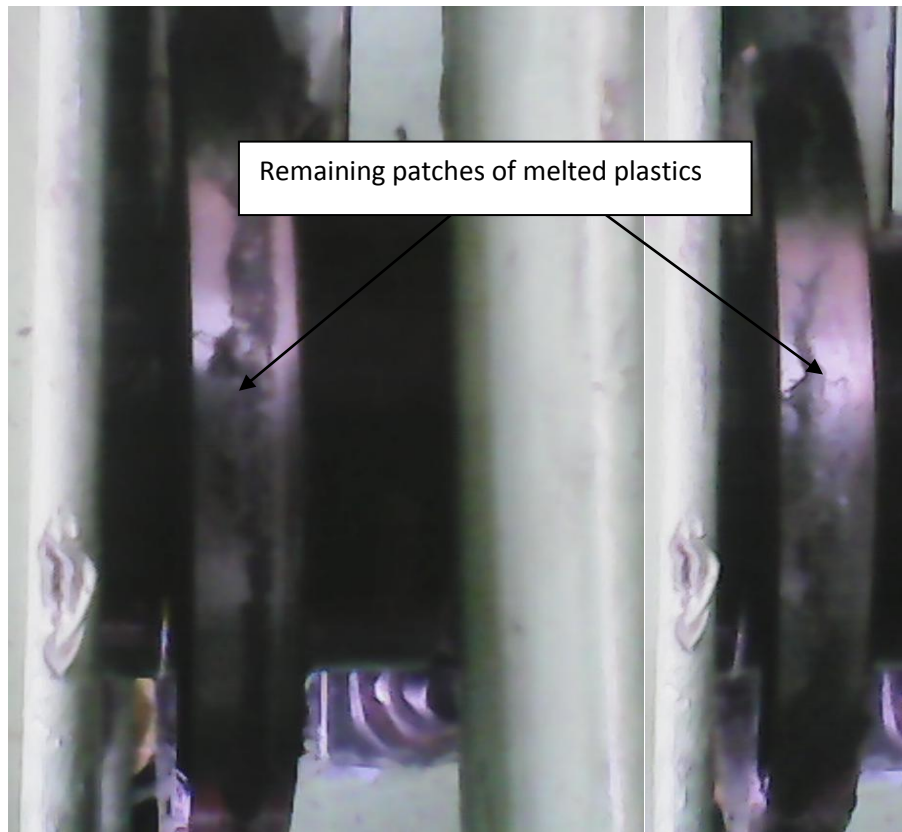


Figure 3.11: Rail and wheel disks after plastics test with blackish layer

Chapter 4: Result and discussion

4.1 Experimental Results

4.1.1 Dry tests

The adhesions results for 0, 0.25, 0.5, 1, and 2 to 10% slip in dry conditions are given in Figure. 4.1. The dry test gave the largest adhesion, with adhesion coefficients at 0.578 for the slip value of 3%. The adhesion results as seen in the curve, the maximum adhesion coefficient was observed at 3% slip while in most researches was found to be 0.6 at 2-3% slip. However, this is closely in good agreement with previous researches [3, 14, 17 and 6] carried out with this roller rigs. Furthermore, in all researches the test investigated with dry test at zero slip was seen to be almost zero adhesion i.e. indication of pure rolling but in this particular test it has come to be 0.099. This could be due to the resistance torque of bearing and some misalignment of couplings due imprecision of the test machine and other factors.

Table 4.1: Slip values Vs adhesion coefficient of dry test

Slip (%)	Coefficient of adhesion
0	0.099
0.25	0.109
0.5	0.148
1	0.246
2	0.480
3	0.578
4	0.560
5	0.558
6	0.568
7	0.570
8	0.520
9	0.550
10	0.532

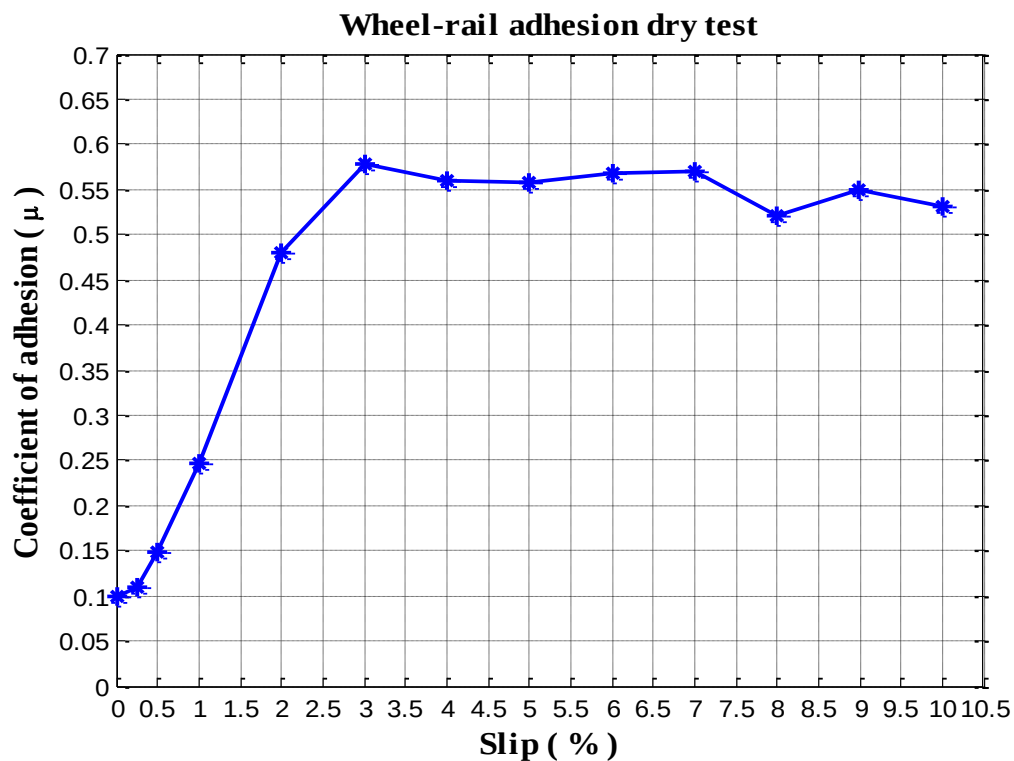


Figure 4.1: graph of dry test slip versus adhesion coefficient

4.1.2. Group one plastics test

Table 4.2: slip versus adhesion coefficient of group one plastics test

Slip (%)	Coefficient of adhesion (μ)
0	0.064
0.25	0.069
0.5	0.073
1	0.125
2	0.142
3	0.145
4	0.141
5	0.139
6	0.136
7	0.132
8	0.131
9	0.138
10	0.125

Figure 4.2 shows adhesion results obtained for test with plastics having 0.00185 mm. the adhesion coefficient has risen from 0.064 at zero slip to pick point 0.145 at three percent slip and after wards started to decrease smoothly with regular pastern as further slip increased.

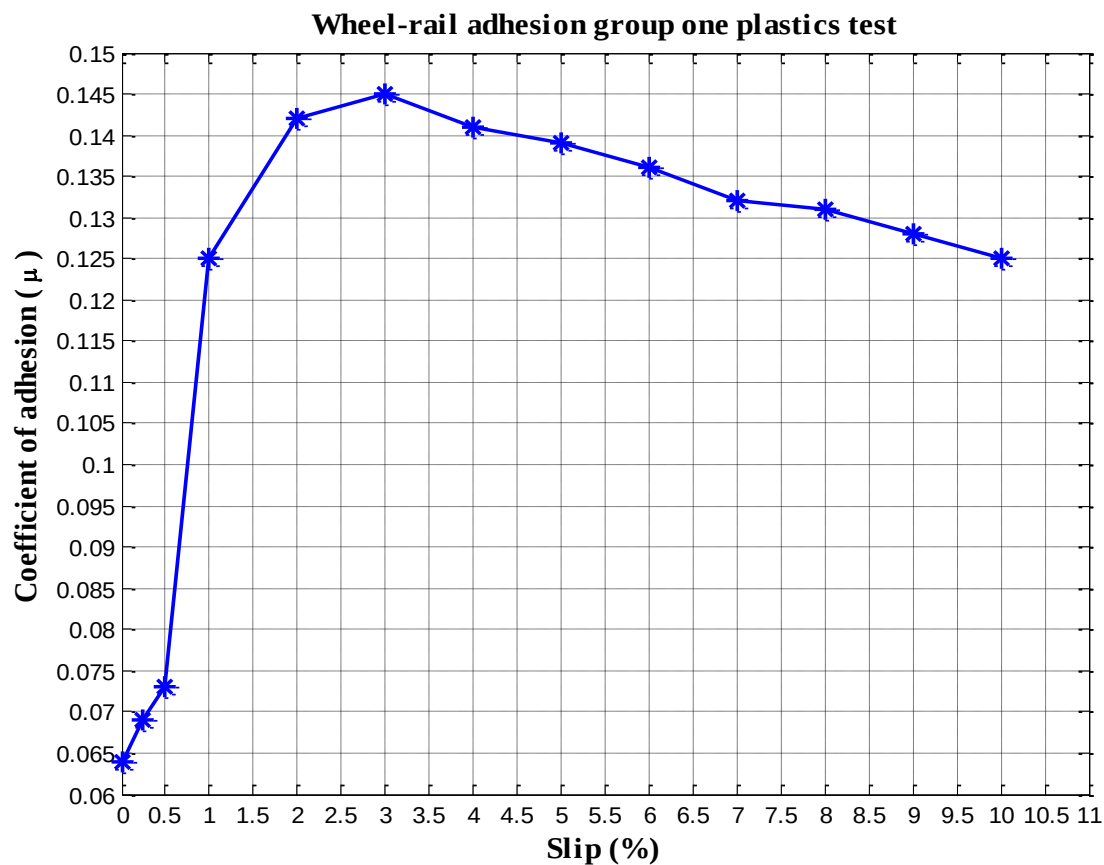


Figure 4.2: graph of group one plastics test slip versus adhesion coefficient

4.1.3. Group two plastics test

Figure 4.3 shows the adhesion coefficient obtained for test with 0.0025 mm. the adhesion level was registered 0.068 for zero percent slip value and with increasing pattern it reached pick at three percent slip. After wards it steeply decreased for the next two slip conditions and finally decreased smoothly for the remaining slip values.

Table 4.3: slip versus adhesion coefficient of group two plastics test

Slip (%)	Coefficient of adhesion (μ)
0	0.068
0.25	0.081
0.5	0.088
1	0.165
2	0.187
3	0.210
4	0.200
5	0.185
6	0.180
7	0.176
8	0.169
9	0.166
10	0.165

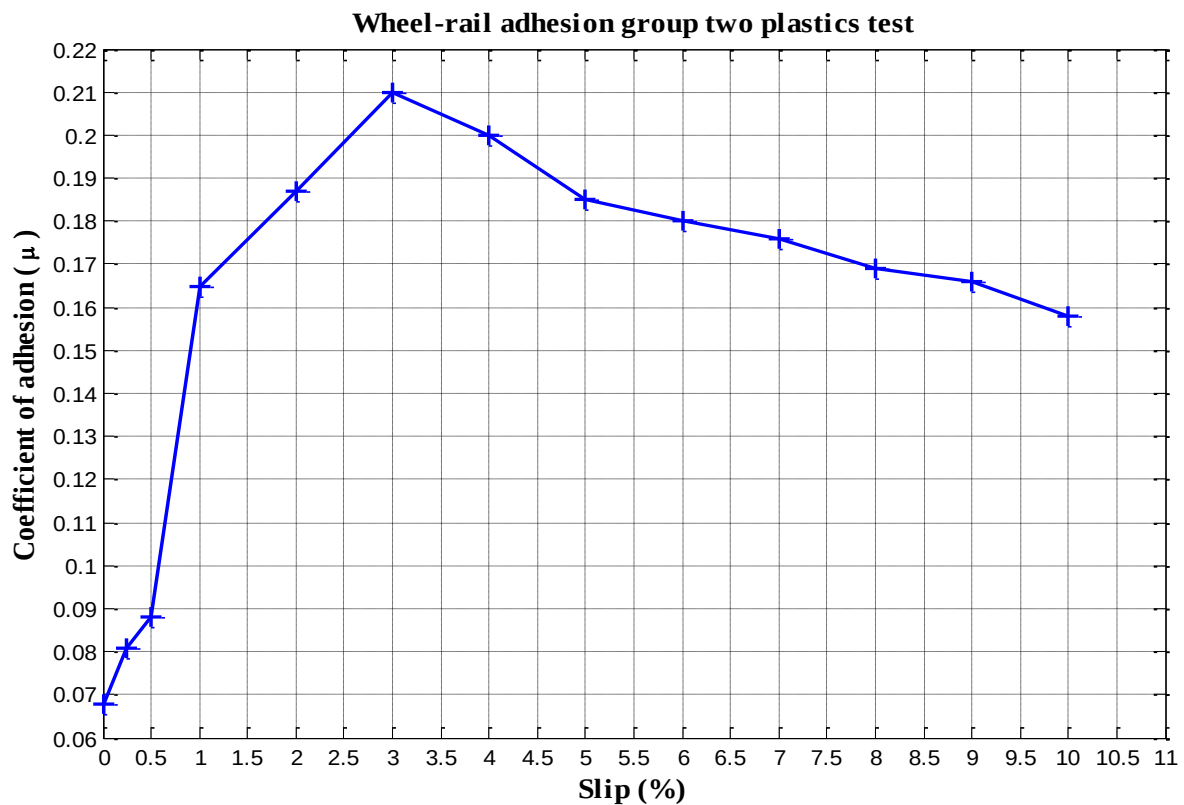


Figure 4.3: graph of group two plastics test slip versus adhesion coefficient

4.1.4. Group three plastics test

The characteristics of adhesion obtained for test with 0.0035 thick plastics (group three) is shown in the figure. In this test 0.072 adhesion level was registered for zero percent slip condition. An increasing nature of adhesion level was shown up to four percent slip condition where the adhesion is 0.249 and a decreasing pattern of adhesion coefficient graph was depicted for the rest of slip values.

Table 4.4: slip versus adhesion coefficient of group three plastics test

Slip (%)	Coefficient of adhesion (μ)
0	0.072
0.25	0.082
0.5	0.085
1	0.178
2	0.219
3	0.228
4	0.249
5	0.246
6	0.242
7	0.239
8	0.237
9	0.232
10	0.228

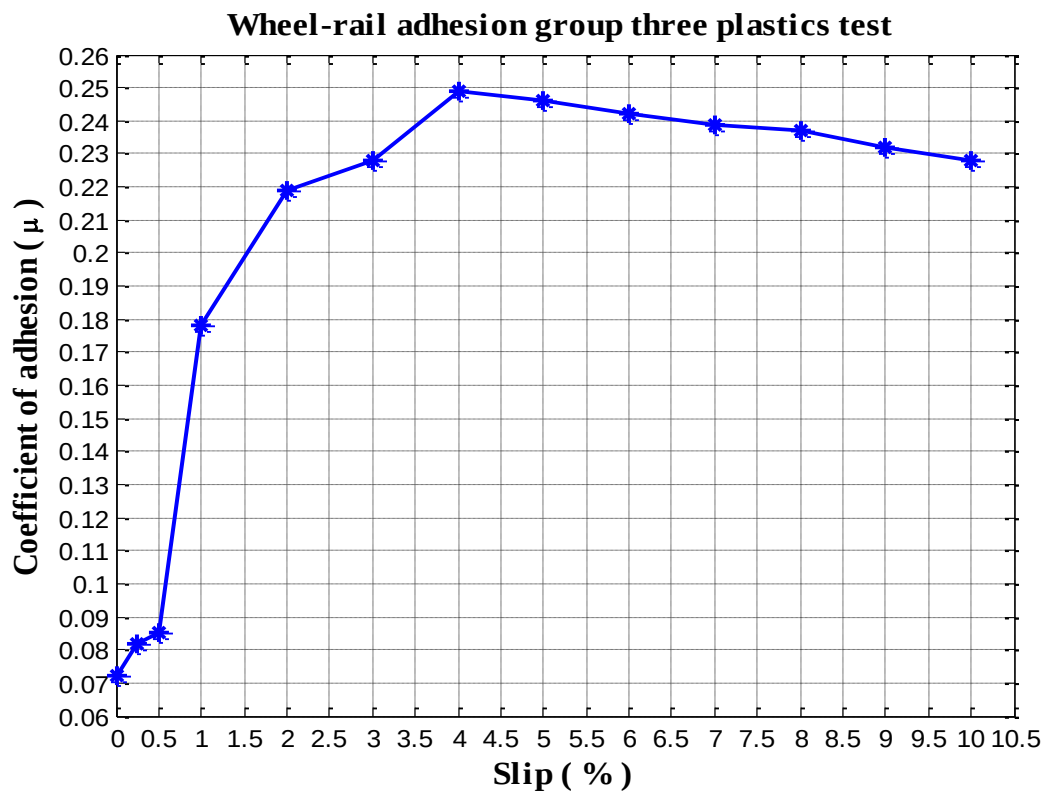


Figure 4.4: graph of group three plastics test slip versus adhesion coefficient

4.1.5. Group four plastics test

The experimental results of adhesion for this test are shown in table 4.5 and graphical represented in figure 4.5. In this test 0.083 coefficient of adhesion at zero percent slip and a peak value of 0.290 adhesion coefficient at three percent slip value were observed. The adhesion profile observed in this test was an increasing from 0 to 3% slip conditions and a slight decrease for 4 and 5 percent slip values then increased at 6 % slip. Finally from 6% slip and the rest considered slips the adhesion decreased gently.

Table 4.5: slip versus adhesion coefficient of group four plastics test

Slip (%)	Coefficient of adhesion (μ)
0	0.083
0.25	0.091
0.5	0.096
1	0.199
2	0.268
3	0.290
4	0.275
5	0.270
6	0.282
7	0.278
8	0.274
9	0.271
10	0.266

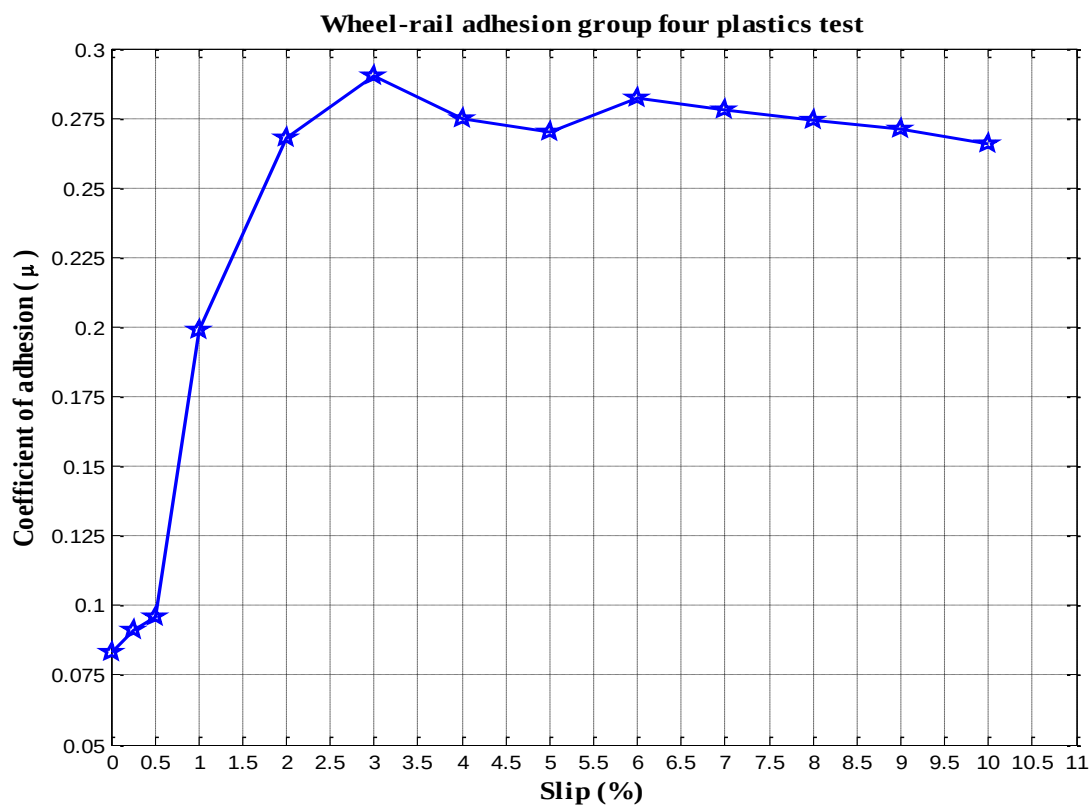


Figure 4.5: graph of group four plastics test slip versus adhesion coefficient

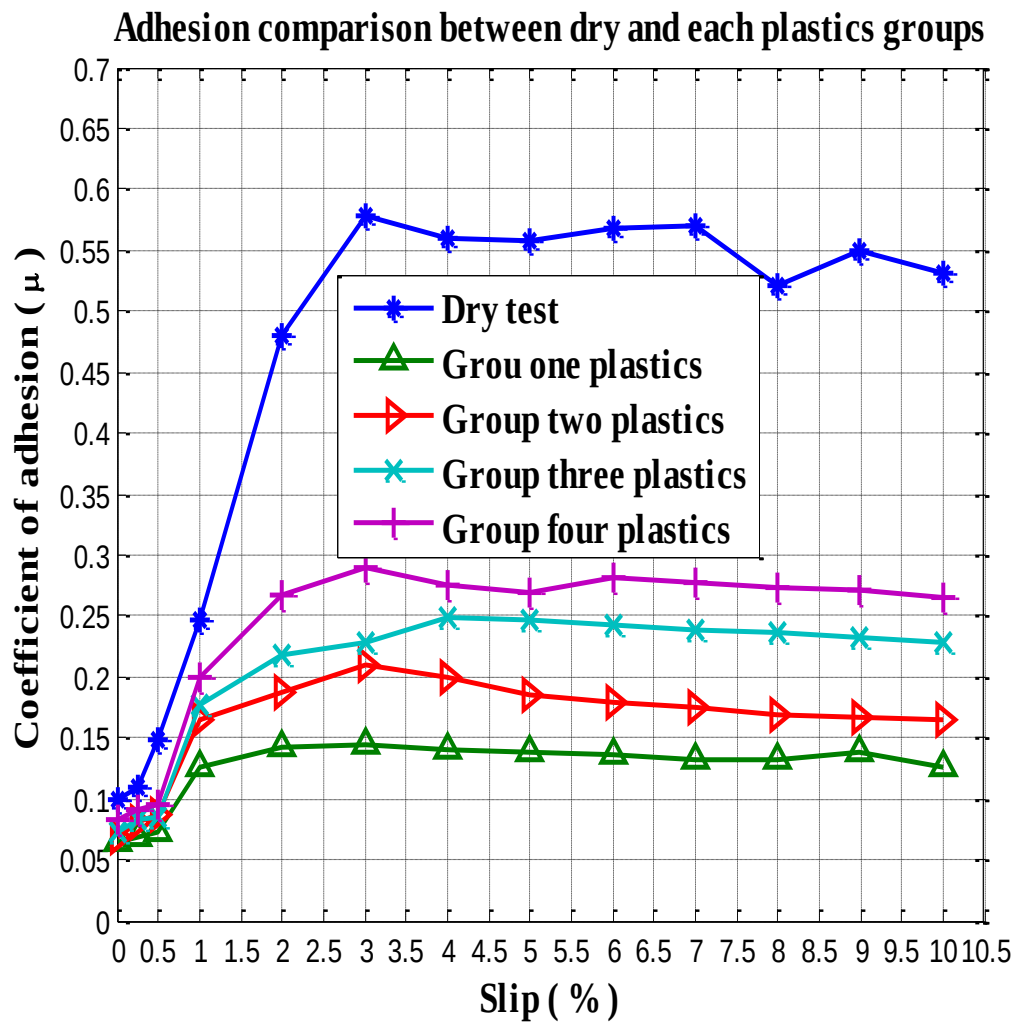


Figure 4.6: adhesion comparison between dry and each plastics group

4.2. Braking distance result and discussion

The optimal method to validate an adhesion, representing a real railway vehicle, is the use of tests on the track. This method, however, requires a large investment in order to perform the tests due to track occupation, vehicle parameterization and instrumentation as explained. However, the behavior of the railway vehicle under lower adhesion condition can be examined by observing the characteristics of the braking distance with respect to the adhesion results at each slip conditions. The braking distance calculated according to two track conditions: on straight level track and along grade.

To calculate the braking distance of the two track conditions, the necessary parameters such as vehicle running speed and the wheel- rail adhesion condition considered are the experimental results. This is because the results presented in this work can only be taken as qualitative of the actual wheel-rail situation to be used for comparison between the plastics contaminants tested and the dry test.

The initial speeds of the vehicle are determined from the rotation speed of the wheel side motor at each slip conditions where corresponding adhesion levels are determined, and the radius of the wheel using the equation below

$$V = \frac{2\pi N}{60} \times r_w$$

Where, V is running speed of the vehicle

N is rotational speed of the wheel at contaminated condition

4.2.1. Braking distance on level track

The braking distance for level track can be calculated analytically using the following equations

$$S_b = \frac{v^2 - U^2}{2a} \dots\dots\dots \text{Eq. (2.10) and}$$

$$a = \frac{\mu}{100} \times g \dots\dots\dots \text{Eq. (2.11)}$$

The adhesion percentage is calculated using the following equation

Adhesion percentage (μ %) = $\frac{\mu_c}{\mu_d} \times 100$, where

μ_d is dry test adhesion

μ_c is contaminated adhesion

The vehicle speed is obtained from the rotational speed of the wheel side motor using the following equation

$$V = \frac{2\pi N}{60} \times r_w$$

Using the above formula and with the help of excel tool the braking distance for adhesion percentage at each slip conditions for all plastics groups calculated. The results are tabulated and graphically represented from fig 4.7 to fig 4.10.

4.2.1.1. Group one plastics braking distance

The braking distance along level straight track and the adhesion level with respect to slip conditions from 0, 0.25, 0.5, 1, 2 up to 10% group one plastics is shown in the figure 4.7. For these plastics group a minimum of 2.437 m and a maximum of 6.607 m braking distance were observed at 0.25 and 10 % slip conditions respectively. The graph demonstrated that for the first two slips the braking distance seen to be almost constant. Generally the braking distance increased from 1% and after wards but rapidly increased from 1 to 3 % slip conditions.

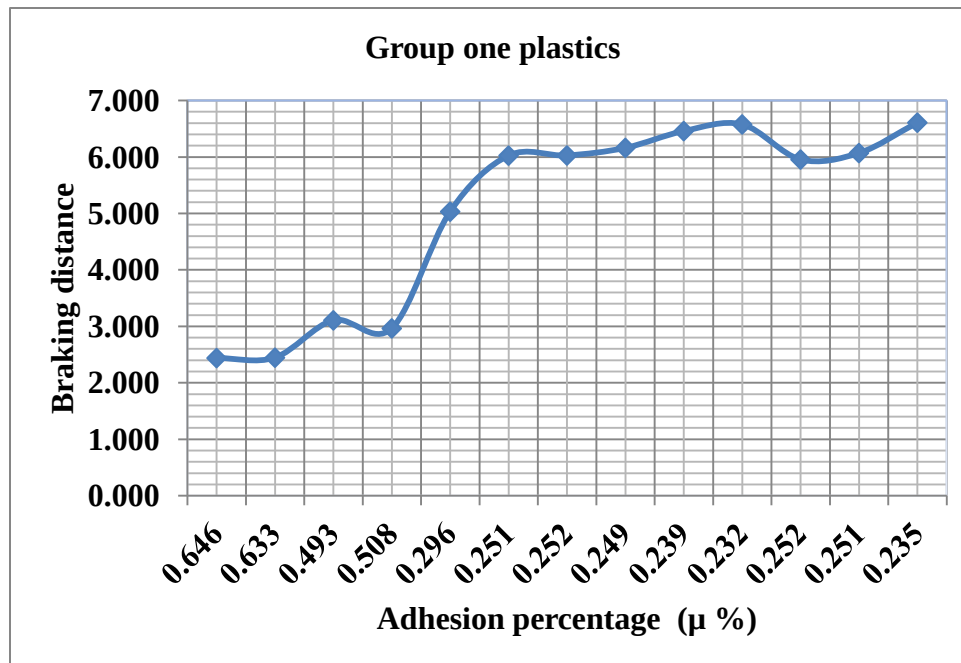


Figure 4.7: graph of group one plastics adhesion percentage versus braking distance

4.2.1.2. Group two plastics braking distance

Figure 4.8 shows the braking distance along level straight track versus the adhesion level with respect to slip conditions 0, 0.25, 0.5, 1, 2 up to 10% group two plastics. For these plastics group a minimum of 1.843 m and a maximum of 4.595 m braking distance were seen at 0.25 and 10 % slips respectively. The braking distance is almost constant with small sinusoidal variation for the first four slips. But it increased rapidly from 1 to 2% slips. Afterwards it continued increasing with gentle slope.

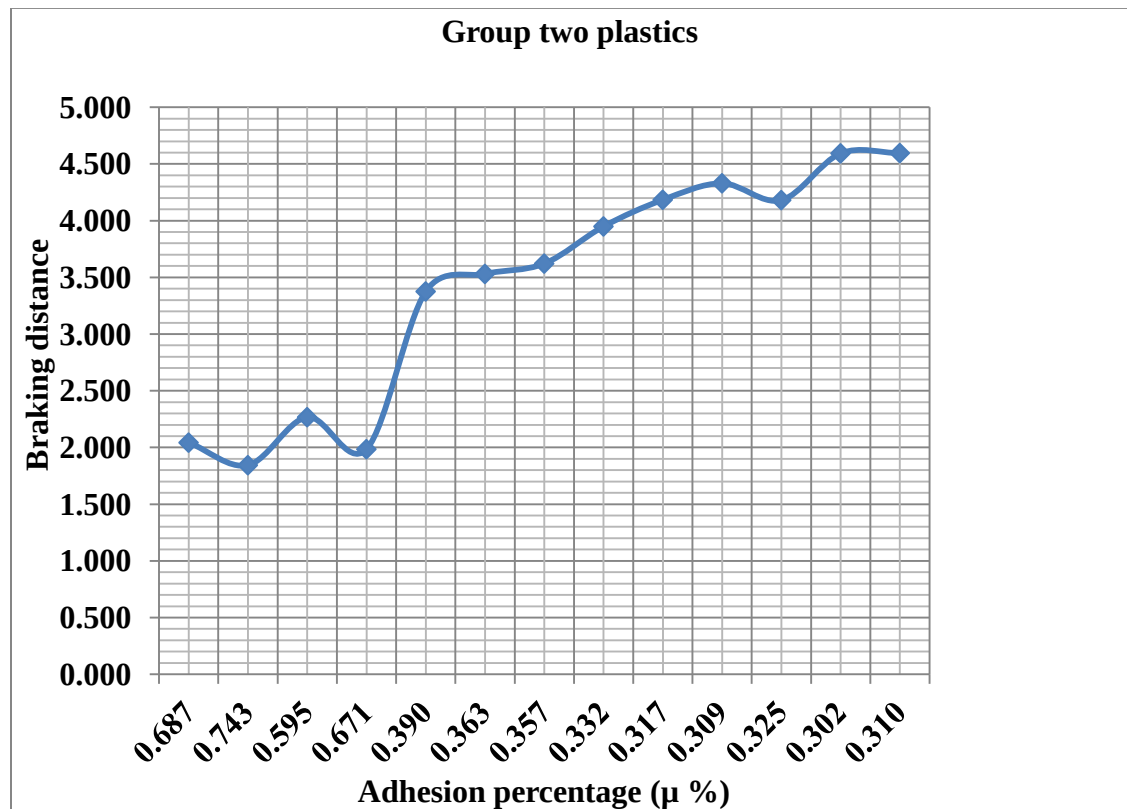


Figure 4.8: graph of group two plastics adhesion percentage versus braking distance

4.2.1.3. Group three plastics braking distance

The characteristics of braking distance versus coefficient of adhesion for group three with respect to the slip conditions on level straight track are depicted in figure 4.9. For these group a 1.676 m minimum and 3.063 m maximum braking distance registered at 0.25 and 3 % slips respectively. In these test results from 0.25 to 0.5 % slips shorter braking distance increment and from 1 to 3 % slips longer braking distance increment is observed.

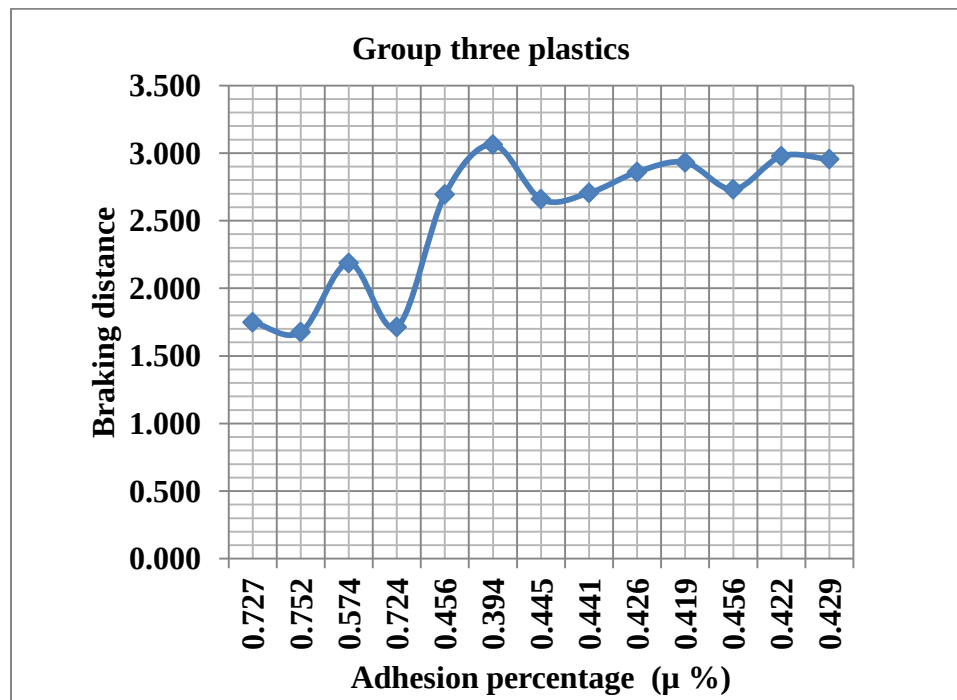


Figure 4.9: graph of group three plastics adhesion percentage versus braking distance

4.2.1.4. Group four plastics braking distance

The relation between braking distance on straight level track and adhesion level for group four plastics according to the considered slip conditions is shown in figure 4.10. The minimum distance is 1.368 m and the maximum braking distance is 2.284 m at 0 and 10% slips respectively. Generally for the first four slip conditions the braking distance seems to be short and constant then increased from 1% slip and after wards.

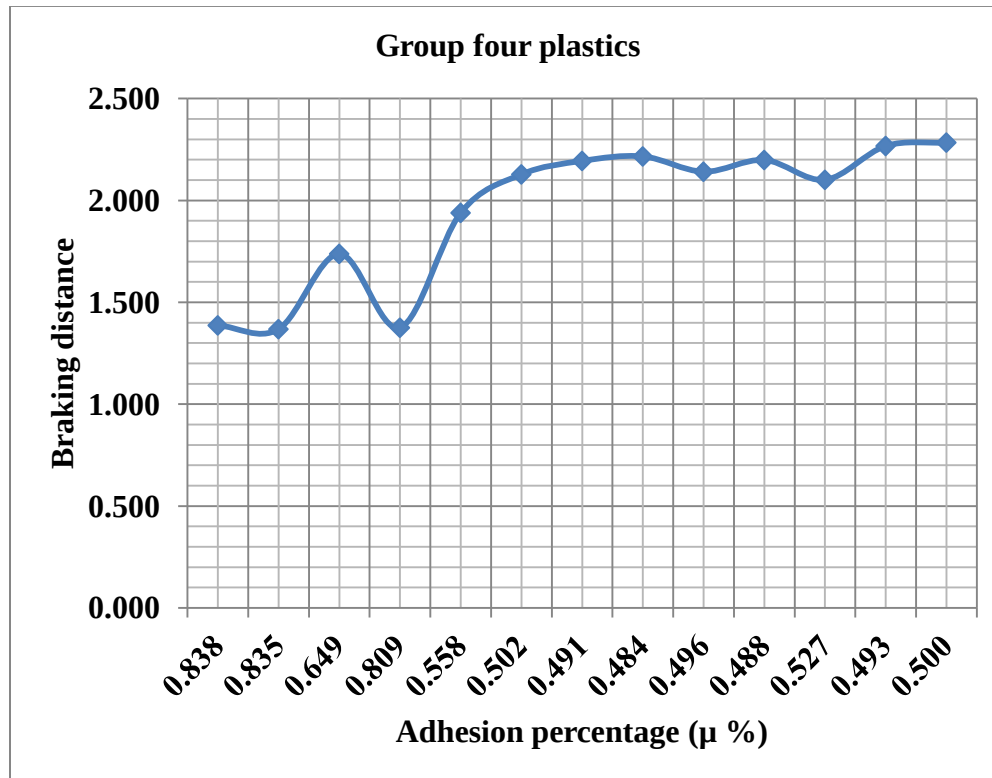


Figure 4.10: graph of group four plastics adhesion percentage versus braking distance

4.2.2. Braking distance along grade

The braking distance for gradient track can be calculated analytically using the following equations.

$$S_b = \frac{v^2 - U^2}{2a} \dots\dots\dots \text{Eq. (2.10)}$$

$$a = \frac{\mu}{100} \times g \dots\dots\dots \text{Eq. (2.11) and}$$

$$a = \frac{\mu}{100} \times g - g \times G \dots\dots\dots \text{Eq. (2.14) where}$$

G is Maximum gradient for LRT which is 0.055

Using the above formula and with the help of excel tool the braking distance along a grade at each slip conditions for all plastics groups calculated. The results are tabulated and graphically represented below.

4.2.2.1. Group one plastics braking distance along grade

The braking distance along gradient straight track and the adhesion level with respect to slip conditions 0, 0.25, 0.5, 1, 2 up to 10% for group one plastics is shown in the figure 4.11. For these plastics group with the specified grade condition, a minimum of 2.664 m and a maximum of 8.627 m braking distance were observed at 0.25 and 10 % slip conditions respectively. Generally the graph profile is the same as that of the same plastics groups on straight level track except the braking distance is higher at each slip values.

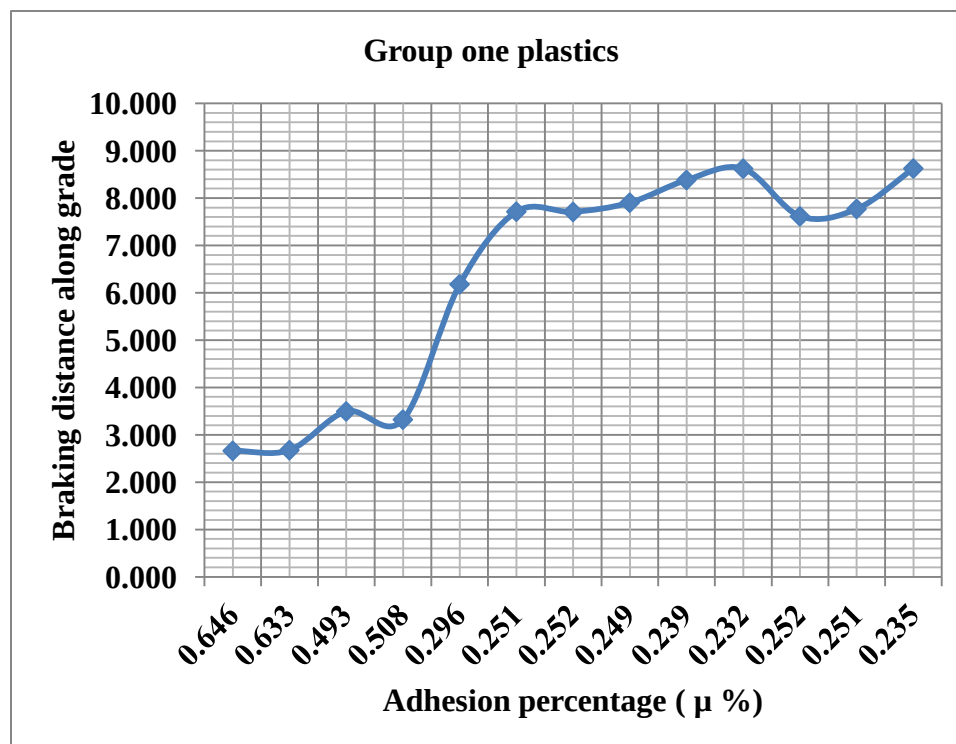


Figure 4.11: graph of group one plastics adhesion percentage versus braking distance along grade.

4.2.2.2. Group two plastics braking distance along grade

Figure 4.12 shows the braking distance along gradient straight track versus the adhesion level with respect to slip conditions 0, 0.25, 0.5, 1, 2 up to 10% for group two plastics. For these

plastics group a minimum of 1.991 m and a maximum of 5.615 m braking distance were seen at 0.25 and 10 % slips respectively. Generally the graph profile is the same as that of the same plastics groups on straight level track except the braking distance is higher at each slip values.

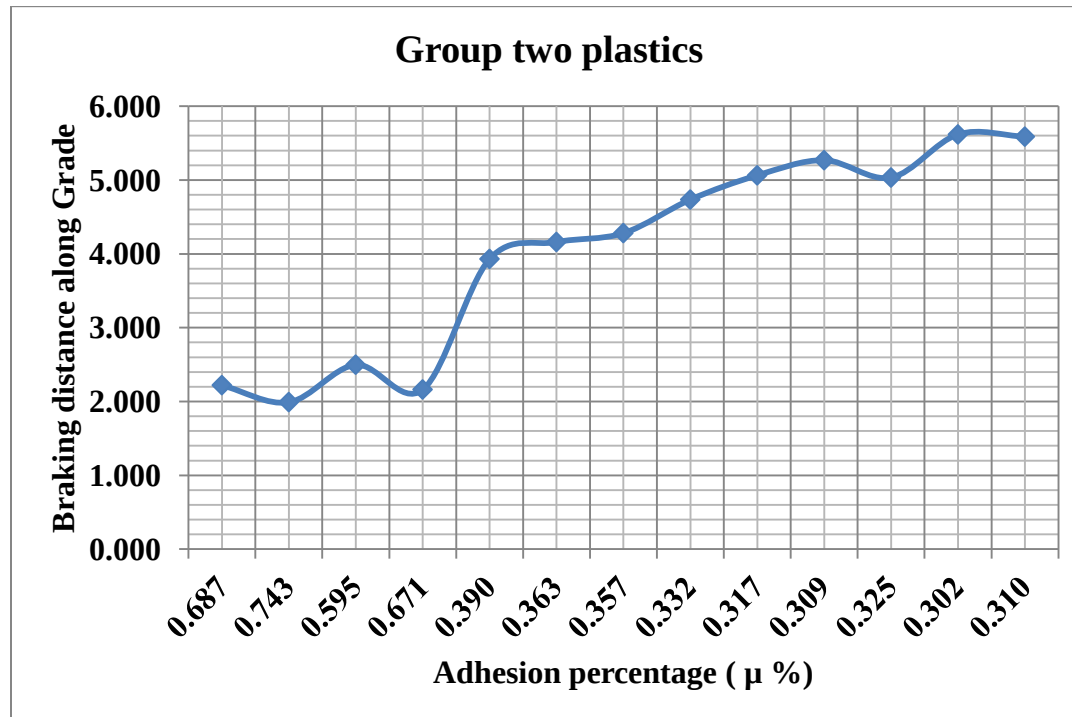


Figure 4.12: graph of group two plastics adhesion percentage versus braking distance along grade.

4.2.2.3. Group three plastics braking distance along grade

The characteristics of braking distance versus coefficient of adhesion for group three with respect to the slip conditions for gradient track are depicted in figure 4.13. For these group a 1.808 m minimum and 3.559 m maximum braking distance registered at 0.25 and 3 % slips respectively. Generally the graph profile is the same as that of the same plastics groups on straight level track except the braking distance is higher at each slip values.

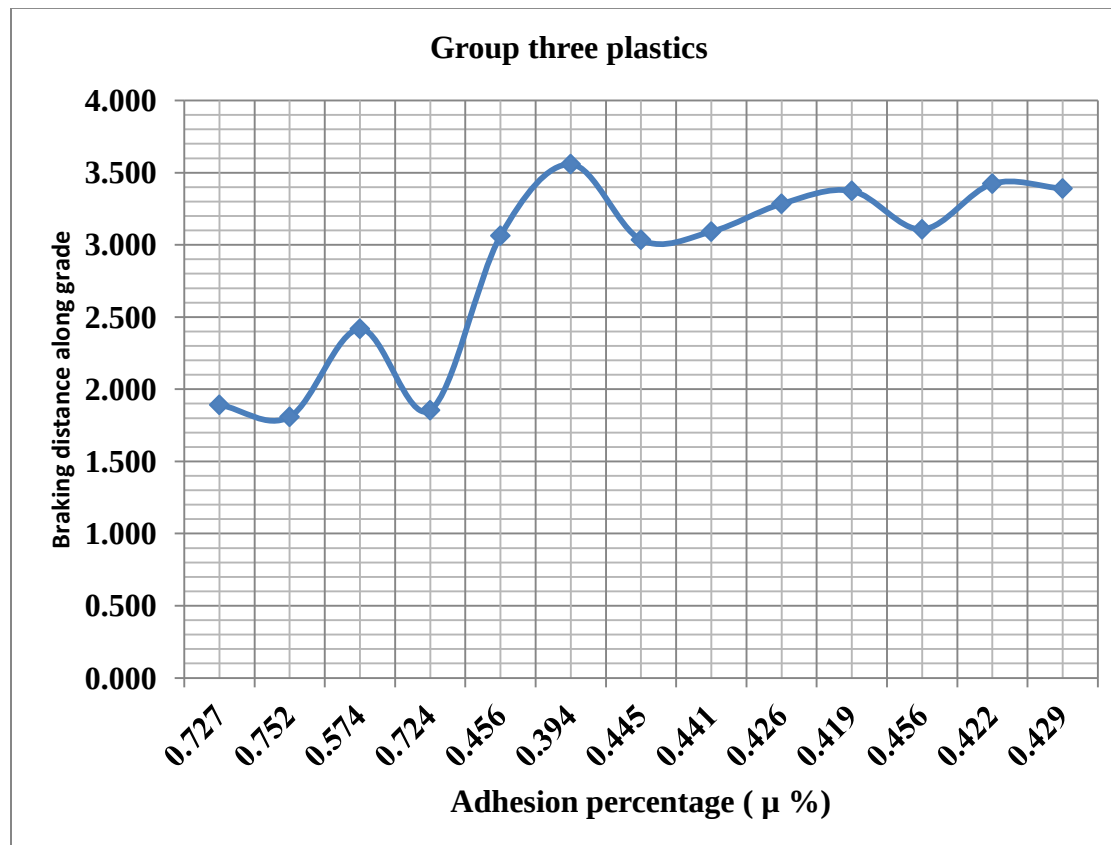


Figure 4.13: graph of group three plastics adhesion percentage versus braking distance along grade.

4.2.2.4. Group four plastics braking distance along grade

The relation between braking distance and adhesion level for group four plastics according to the considered slip conditions on gradient track is shown in figure 4.14. The minimum distance is 1.464 m and the maximum braking distance is 2.566 m at 0.25 and 10% slips respectively. Generally the graph profile is the same as that of the same plastics groups on straight level track except the braking distance is higher at each slip values.

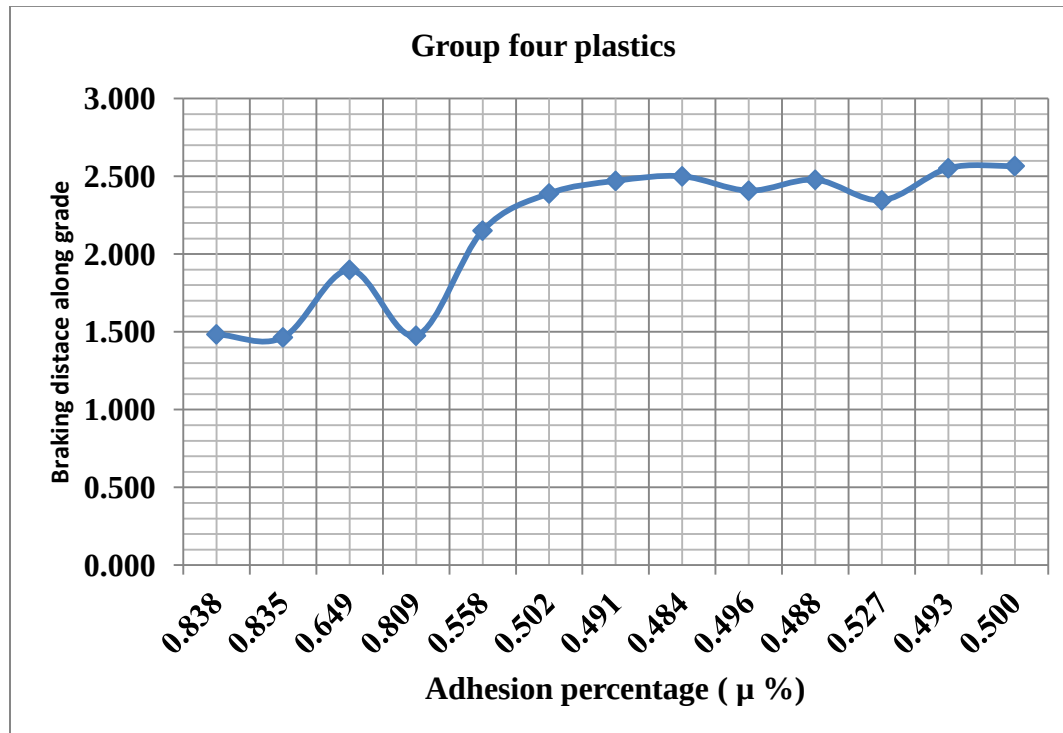


Figure 4.14: graph of group four plastics adhesion percentage versus braking distance along grade.

4.3 Comparison of dry and contaminated braking distance

The braking distance calculation of each contaminated condition both on the level track and along grade described in section 4.2 was to show the braking distance profile due to the adhesion percentage level of each plastic contaminant group according to the slip considered. The characteristics and comparison of dry and contaminated braking distances with respective adhesion at each considered slips for both is shown below

For level track

Consider dry test at zero percent slip condition

Dry test adhesion (μ_d) = 0.099

The wheel side motor rotational speed at this slip, $N = 400$ rpm

$$V = \frac{2\pi N}{60} \times r_w = 4.189 \text{ m/s}$$

From Eq. 2.5 the braking deceleration becomes

$$a = \mu \times g = 0.099 \times 9.81 = 0.971 \text{ m/s}^2$$

$$\text{The braking distance } (S_b) = \frac{V^2 - U^2}{2a} = \frac{4.189^2 - 0^2}{2 \times 0.971} = 9.026 \text{ m}$$

Group one plastics at zero percent

$$\text{Adhesion } (\mu) = 0.064$$

The wheel side motor rotational speed at this slip, $N = 531 \text{ rpm}$

$$V = \frac{2\pi N}{60} \times r_w = 5.56 \text{ m/s}$$

$$a = \mu \times g = 0.064 \times 9.81 = 0.628 \text{ m/s}^2$$

$$\text{The braking distance } (S_b) = \frac{V^2 - U^2}{2a} = \frac{5.56^2 - 0^2}{2 \times 0.628} = 24.619 \text{ m}$$

Similarly the braking distance at zero slip for group 2, 3 and 4 are 20.630, 17.662 and 14.001 m respectively. Using the above formulas and an Excel tool the braking distance for dry and all plastics groups tabulated in table and plotted against the slips considered in graph

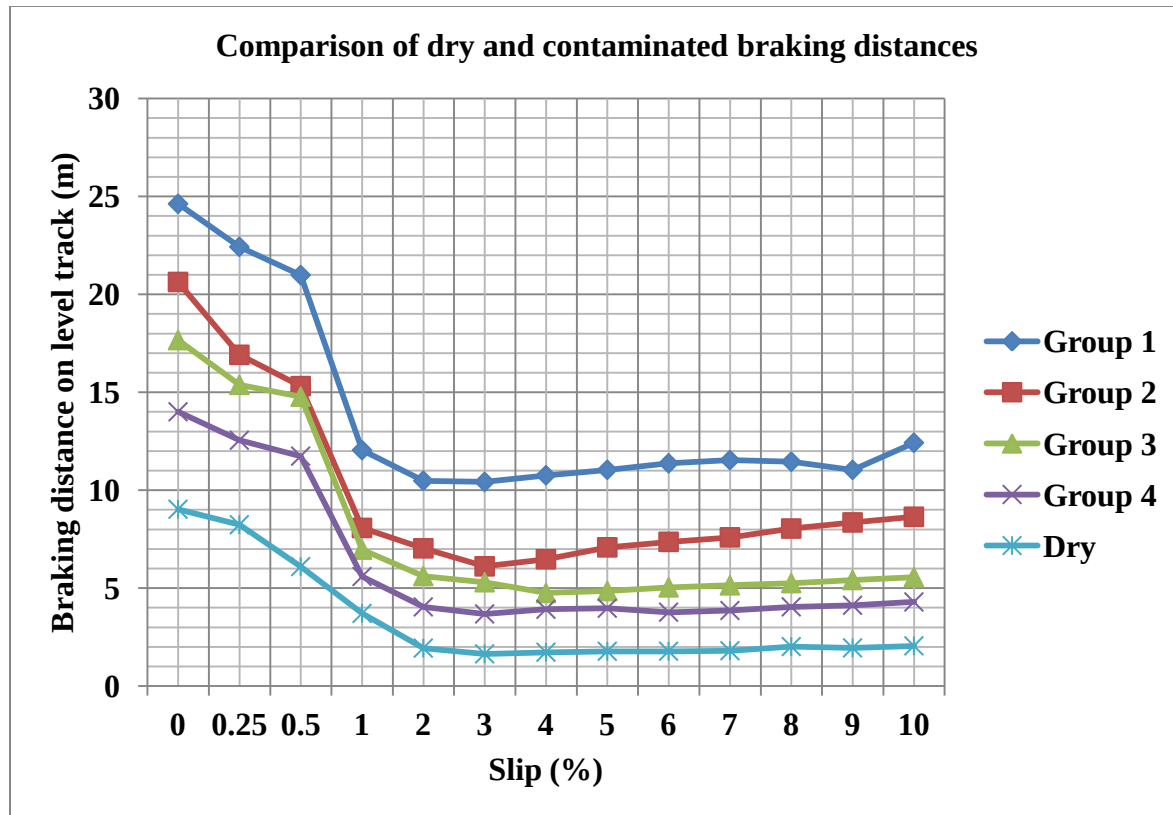


Figure 4.15: Comparison of braking distance at dry and contaminated condition on level track

For gradient track

Consider dry test at zero percent slip condition

Dry test adhesion (μ_d) = 0.099

Grade, $G = 0.055$

The wheel side motor rotational speed at this slip, $N = 400$ rpm

$$V = \frac{2\pi N}{60} \times r_w = 4.189 \text{ m/s}$$

From Eq. 2.14 the braking deceleration becomes

$$a = (\mu - G) \times g = (0.099 - 0.055) \times 9.81 = 0.432 \text{ m/s}^2$$

$$\text{The braking distance } (S_b) = \frac{V^2 - U^2}{2a} = \frac{4.189^2 - 0^2}{2 \times 0.432} = 20.307 \text{ m}$$

Group one plastics at zero percent

$$\text{Adhesion } (\mu) = 0.064$$

The wheel side motor rotational speed at this slip, $N = 531$ rpm

$$V = \frac{2\pi N}{60} \times r_w = 5.56 \text{ m/s}$$

$$a = (\mu - G) \times g = (0.064 - 0.055) \times 9.81 = 0.088 \text{ m/s}^2$$

$$\text{The braking distance } (S_b) = \frac{V^2 - U^2}{2a} = \frac{5.56^2 - 0^2}{2 \times 0.088} = 175.069 \text{ m}$$

Similarly the braking distance along grade at zero slip for group 2, 3 and 4 are 107.898, and 41.504 m respectively. Using the above formulas and an Excel tool the braking distance along grade for dry and all plastics groups tabulated in table and plotted against the slips considered in graph

Figures 4.15 and 4.16 show the braking distances comparison of dry and contaminated condition for both level and grade tracks respectively against the slips considered. In both cases the braking distance is longer for lower coefficient of adhesion specifically for the first four slip conditions and shorter for higher coefficient of adhesion. Moreover the braking distance for dry case, at all slip conditions, is shorter than that of plastic contaminated, and braking distance for contaminated case decreases as plastic thickness increases this is due to adhesion increases with plastics thickness.

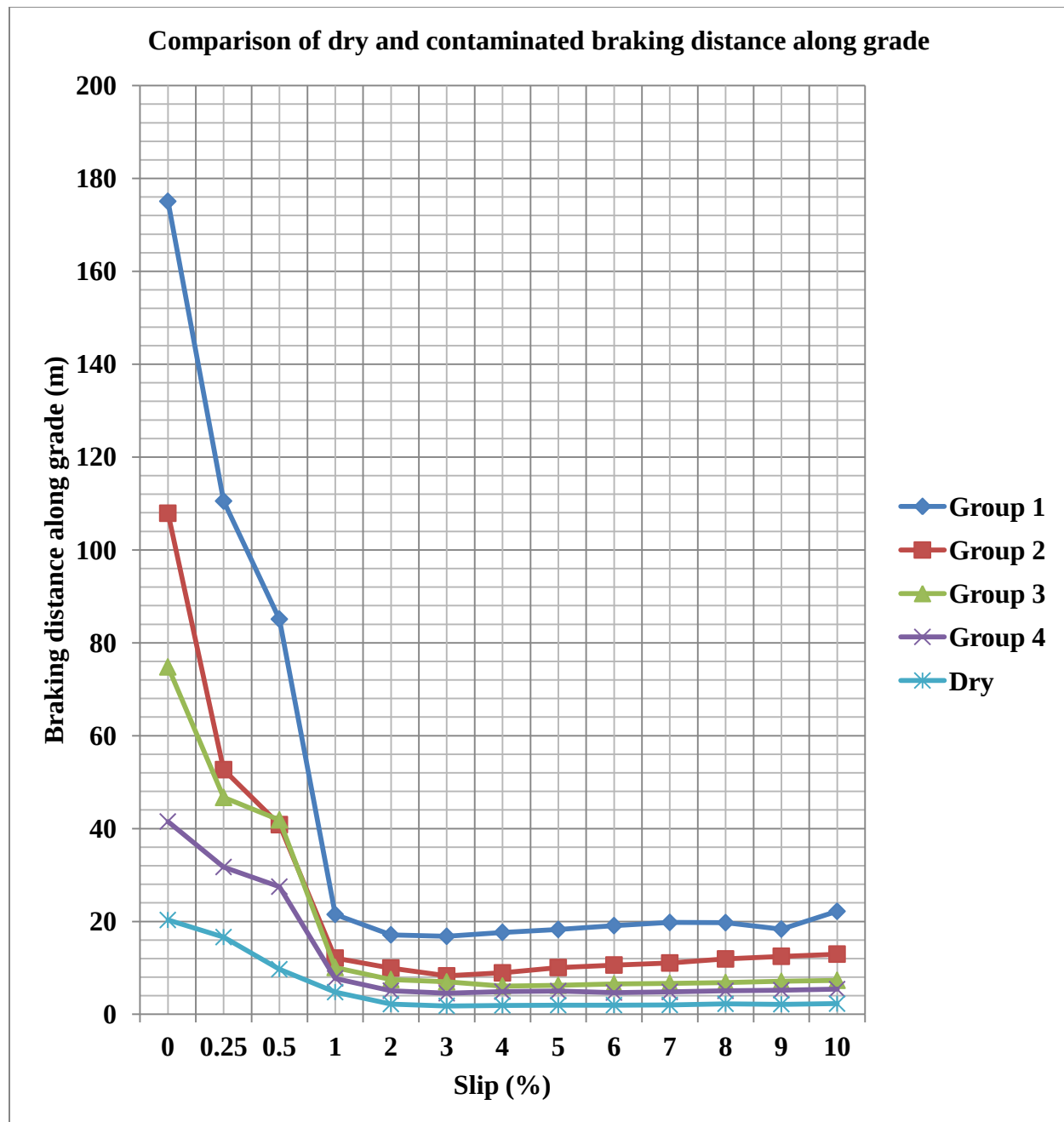


Figure 4.16: Comparison of braking distance at dry and contaminated condition along grade.

Chapter 5: Conclusion, recommendation and future work

5.1. Conclusion

A plastic contaminated wheel-rail contact has been simulated in rolling-sliding conditions with a twin-disk roller rig in closely controlled laboratory test. Four main groups of plastics, according to their thickness 0.00185, 0.0025, 0.0035 and 0.007mm have been tested in order to evaluate their influence on the wheel-rail adhesion with respect to thickness. In order to compare the test results of with the untreated condition (i.e. without contamination), a dry test has been conducted. This work came up with the following concluding points.

- Throughout the test and slip conditions the untreated condition that is the dry test coefficient of adhesions is higher than that of plastic contaminated test. The adhesion results of the dry test ranges from 0.099 to 0.578 which is in a good agreement with the previous work, [6]. The maximum adhesion at this test was at 3% slip value.
- Plastic contamination adversely reduced coefficient of adhesion in the wheel-rail contact. The coefficient of adhesion range for 0.00185 mm thick plastics was from 0.064 to 0.142, for 0.0025mm thick plastics was from 0.068 to 0.210, for 0.0035 mm thick plastics was from 0.072 to 0.249 and for 0.007 mm thick plastics was from 0.083 to 0.290. Furthermore the wheel-rail adhesion degrading characteristics of plastics become worst as the speed or slip increased.
- The adhesion level plastics contaminated condition, when compared that of the dry test, is described to be about 88 % lesser on average. In addition adhesion level related to such contaminants as water, mud, leaf, oil and grease was tested [6] with the same test machine and test conditions. The comparison of plastics bags adhesion level with that of those contaminants is shown to be lesser with about 50% from water, 47% from mud, 66% from leaf, 69% from oil and 72% from grease.
- To examine the behavior of the railway vehicle under plastics contaminated condition, the braking distance along a straight level track and along a grade was calculated for each plastics group based on the adhesion level obtained at each considered slip conditions. Obviously, since the adhesion level of all plastics groups is lower than that the dry test,

the braking distance on the plastics contaminated condition longer than that of the untreated or dry one. The result of the braking distance calculation show that at 0, 0.25% slips for group one plastics and at 0, 0.25, and 1% slips for group two, three and four plastics seen to be shorter. But after 1% slip values it increases with the thinner the thickness of the plastics is the longer the braking distance.

- Different literatures have put a remark on adhesion requirement. In [24] pointed out that for steel-steel contact under dry clean condition, the coefficient of friction is approximately 0.6 which obviously fulfils all adhesion requirements. In [4] it is stated that the value of adhesion for dry rail should be at least 0.2. Even the technical specification of vehicles for LRT East-West line says that the emergency brake deceleration should be at least 2 m/s which is corresponding to a coefficient of adhesion at least 0.2. The dry test adhesion result of this work is in agreement of with the requirements but the plastic contaminated test results are less than that of the dry test. Thus, plastic contamination decreases wheel-rail adhesion.
- The braking distance calculation has clearly shown that low level of adhesion due to plastics contamination affects negatively the safety of passengers and the train itself. The same holds for punctuality because delay time will increase due to traction problem.

5.2. Recommendation

- Even though the test results of plastics contaminants better to indicate the extent of their effect on the wheel-rail adhesion, the result would be even best if shaft encoders and torque transducers were fitted on the simulating machine, and data was acquired and both speed and load were controlled by personal computers.
- The load to simulate the experimental contact condition was much less than that of the actual wheel-rail contacts condition. But a contact pressure close to the real situation the railway line would be achieved if the motors capacities have been better.
- The experimental result of this work exhibits that plastic contaminants were seen to reduce the wheel-rail adhesion and their consequences are serious. Thus, the Ethiopian Railway Corporation has to give emphasis in creating awareness on Addis Ababa residents that inappropriate disposal of the plastics will negatively affects the operational condition of the LRT. In addition, the corporation, the Addis Ababa municipality and the

Environmental Hygiene Departments have to be hand in hand to create plastics and other contaminants free LRT line.

5.3 Future work

Finally, some suggestions are listed below for future work as extension and continuity of this paper.

- ✓ The wheel-rail adhesion characteristics due to plastics contamination investigated in this thesis was only by assuming the wheel-rail rollers contact temperature to be the ambient temperature. Considering the actual wheel-rail contact temperature will be parameter to extend this work further.
- ✓ Load application was limited to 120N because of the capacity of the shunt type motor availed.
- ✓ Due to unavailability of DC servo motors, data feeding and collection were made manually. Had these motors been found all data feeding and collection would have been well controlled through personal computer. The data collected also could have been directly presented graphically. For the future this machine will be equipped with these mentioned types of motors and adhesion experiments will be performed so that the results will be in best agreement with the tests made so far by different researchers.

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Appendix

Table A: experimental inputs and outputs for group one (0.00185mm) plastics test

Experimental inputs			Experimental outputs		
Slip (%)	Nw (rpm)	Nr (rpm)	Ea (V)	Ia (A)	Nout (rpm)
0	400	400	101.5	0.7	531
0.25	401	400	95	0.8	526
0.5	402	400	94	0.85	523.5
1	404	400	143	0.95	519
2	408	400	188.5	0.825	516
3	412	400	126	1.25	520
4	416	400	118	1.3	521
5	421	400	116.5	1.4	524
6	425	400	100	1.5	526
7	429	400	99	1.45	522
8	433	400	105	1.35	518
9	438	400	110.5	1.25	522
10	442	400	115	1.2	527

Table B: experimental inputs and outputs for group two (0.0025mm) plastics test

Experimental inputs			Experimental outputs		
Slip (%)	Nw (rpm)	Nr (rpm)	Ea (V)	Ia (A)	Nout (rpm)
0	400	400	142.5	0.50	501
0.25	401	400	140.0	0.60	495
0.5	402	400	139.0	0.65	491
1	404	400	198.5	0.85	488
2	408	400	196.0	0.95	485
3	412	400	210.0	1.00	479
4	416	400	168.0	1.20	481
5	421	400	170.0	1.10	484
6	425	400	146.5	1.25	487
7	429	400	124.5	1.45	489
8	433	400	126.0	1.40	493
9	438	400	130.5	1.35	498
10	442	400	134.5	1.25	505

Table C: experimental inputs and outputs for group three (0.0035mm) plastics test

Experimental inputs			Experimental outputs		
Slip (%)	Nw (rpm)	Nr (rpm)	Ea (V)	Ia (A)	Nout (rpm)
0	400	400	179.5	0.40	477
0.25	401	400	186.5	0.60	441
0.5	402	400	129.5	0.65	474
1	404	400	195.0	0.90	471
2	408	400	187.0	1.15	469
3	412	400	202.5	1.10	465
4	416	400	184.5	1.30	460
5	421	400	185.5	1.28	462
6	425	400	166.5	1.42	467
7	429	400	160.5	1.46	469
8	433	400	169.5	1.38	472
9	438	400	172.5	1.34	474
10	442	400	187.0	1.27	476

Table D: experimental inputs and outputs for group four (0.007mm) plastics test

Experimental inputs			Experimental outputs		
Slip (%)	Nw (rpm)	Nr (rpm)	Ea (V)	Ia (A)	Nout (rpm)
0	400	400	113.0	0.70	456
0.25	401	400	108.5	0.80	452
0.5	402	400	106.0	0.85	449
1	404	400	186.0	1.00	446
2	408	400	192.5	1.28	440
3	412	400	189.5	1.40	437
4	416	400	178.5	1.30	439
5	421	400	212.0	1.20	438
6	425	400	171.5	1.50	436
7	429	400	176.0	1.45	438
8	433	400	183.5	1.39	445
9	438	400	195.0	1.30	447
10	442	400	198.5	1.28	452

Table E: experimental inputs and outputs for dry test

Experimental inputs			Experimental outputs	
Slip (%)	Nw (rpm)	Nr (rpm)	Ea (V)	Ia (A)
0	400	400	208.5	0.90
0.25	401	400	216.5	0.95
0.5	402	400	213.0	1.30
1	404	400	210.0	2.20
2	408	400	215.0	3.75
3	412	400	213.5	4.65
4	416	400	205.5	4.75
5	421	400	205.0	4.80
6	425	400	198.5	5.10
7	429	400	183.0	5.60
8	433	400	174.0	5.40
9	438	400	162.0	6.20
10	442	400	170.0	5.90

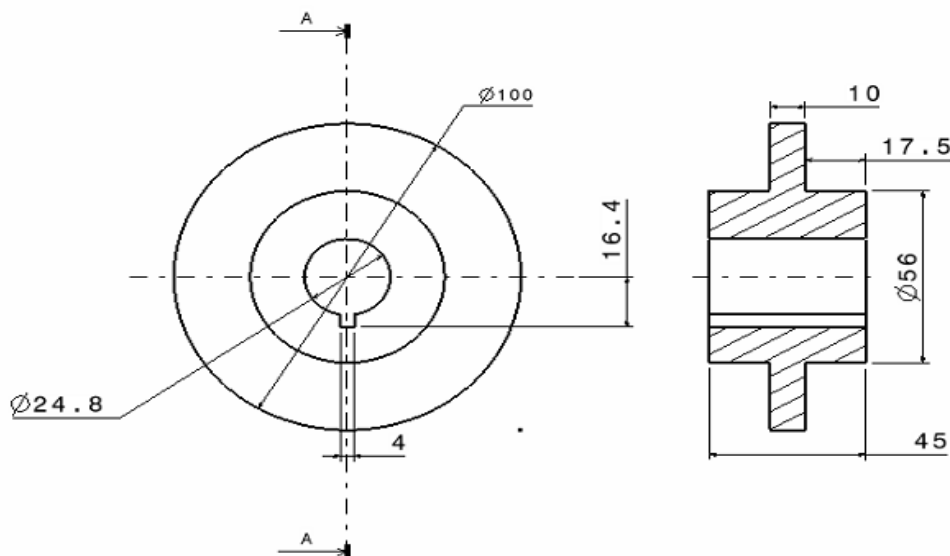


Figure 3.2: Dimension of the test rig specimens

