# ADDIS ABABA UNIVERSITY

# ADDIS ABABA INSTITUTE OF TECHNOLOGY

# SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

# Effects of Friction Modifiers (Sand-Based) in Wheel/Rail Contact

**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)**

**By: Gutanbar Debere**

**Advisor: Dr Daniel Tilahun**

**December, 2014**

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By

**Gutanbar Debere**

December, 2014

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# DECLARATION

I, the undersigned, declare that this thesis work is my original work, has not been presented for a degree in this or any other universities, and all sources of materials used for the thesis work have been fully acknowledged.

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Place: Addis Ababa

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This thesis has been submitted for examination with my approval as a university advisor.

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# ABSTRACT

The study of the effects of friction modifiers in wheel/rail contact is vital factor for the railway networks to examine and identify property of friction modifiers on adhesion, wear rates, etc. This work focused on the effects of sand particle sizes in wheel and rail contact. The laboratory investigations were carried out on the influence of sand particle sizes in between the wheel/rail interaction by using twin disc machine. The influence of sand was investigated by using four different sand particle size distributions to account the effect. The investigation results showed that sand with higher particle sizes yield a higher adhesion coefficient but higher wear rates and surface roughness. Adhesion coefficient value increased with the increase in slip with all sand particle size distributions.

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# LIST OF ABBREVIATIONS

a = acceleration

$a_2$ = body acceleration at the instant $t_2$

AAiT = Addis Ababa institute Technology

COF = Coefficient Of Friction

EMUs = Electrical Multiple Units

EN = European Standards

ERC = Ethiopian Railway Corporation

F = force

$f$ = the friction coefficient

FDRE = Federal Democratic Republic of Ethiopia

$F_f$ = the friction force

$f_k$ = kinetic friction coefficient

FMs = Friction Modifiers, FM = Friction Modifier

$F_N$ = the normal force

FR = Feed Rate

$f_s$ = static friction

g = the acceleration due to gravity

HM = Hardness Martens

HMMBI = Hibret Manufacturing and Machine Building Industry

HV = Hardness Vickers

HVT = Hardness Vickers from depth measurement

IEC = International Electro-technical Commission

ISO = International Organization for Standardization

K = arbitrary positive constant

L Sand = Large Sand

LLCC = Lower Life Cycle Cost

m = mass

M Sand = Medium Sand

METEC = Metals and Engineering corporation

PVC = Poly Vinyl Chloride

R Sand = Railway Sand

RCF = Rolling Contact Fatigue

RSSB = Rail Safety and Standards Board

S Sand = Small Sand

SMIE = School of Mechanical and Industrial Engineering

t = time

T = traction torque

$t_1$, $t_2$ = instant time

TC = Traction Control

UIC = International Union of Railways

$u_r$ = the rolling speed

$u_s$ = Sliding Velocity

$u_v$ = the vertical running speed

$u_w$ = the circumferential velocity of the wheel

$v$ = linear velocity

$w$ = angular velocity

WSP = Wheel Slide Protection

$\xi$ = Creepage

# CHAPTER -1: INTRODUCTION

## 1. Introduction

### 1.1 Background

The railway as a means of transport is a very old idea. The history of Mining and Railways are closely linked. At its beginning, it was mainly utilized in the central European mines with different means of traction being applied. But it did not come into general use until the invention of the steam engine. The rail as supporting and guiding element was first utilized in the 16th century to transport coal from mines. Around 1760, wooden rails were covered with cast iron plates. About 1800, free bearing rails were applied and flanged iron wheels took care of the guiding, as we still practice. Vehicles were moved forward by man-power or by horses. The use of railway (railroad) tracks started some 200 years ago. It evolved through trial and error. A continuous cycle of corrective measures (development of rail geometry, size and quality, train speeds for passenger and goods and development of wheel set and axle loads for passenger and goods train) was the unique characteristics of railway network. [1, 2]

The first passenger train started between Stockton and Darlington in 1825. Expansion and modernization of railway transportations was halted from 1930 onwards. The railway changed more in two decades from 1955-1975 than it did in the century from 1840 to 1940. [3]

Since the 18th century it has developed faster and faster until in the 21th century. It has become the most efficient means of transport for medium distances thanks to the development of high speed railway system. But the main factors that have been driven the enormous development of railway, as any other means of transport, have been and continue to be safety, speed and economy. On top of all this, as every day passes, its environmental impact is minimum if not zero. In the case of the railway, one of the determining factors behind its development was the type of track used, either because of its gauge or the materials used in its construction. At the start, these were made of cast iron, but they turned out to be lacking in safety as they easily broke due to their fragility. Towards the end of the 19th century steel began to be used as it was a less fragile and much stronger material. Nowadays, plate track is a key element in the development of High Speed trains making wooden sleepers a thing of the past. The rubber track mountings which are currently used to support the tracks have led to enormous reductions in vibration and noise both in the track and the rolling stock. Moreover, each country had a different track gauge due to strategic reasons of commerce and defence. Today's global markets leave no other option but to standardise track gauges or failing that, to produce rolling stock that can be adapted to the different gauges quickly and automatically. [1, 2, 3]

The birth of the railway is linked to the birth of the steam engine, while the tremendous development of the railway in the 20th century was linked to the electrification of the railway lines. In addition, the diesel locomotive played a very important role because of its autonomy, particularly on those lines where electrification was unviable. The rivalry between these three types of locomotive was long and hard with each competing to see which was the safest, fastest and cheapest. The first electric locomotives appeared in the last third of the 19th century, while the first Diesel locomotive was built at the beginning of the 20th century (Faure, 2004) [1]. Diesel locomotives never reached the speeds of electric locomotives; however, the latter require a greater investment in infrastructure to electrify the line. As we all know, it is electric locomotives that are at the forefront of railway traction, while the Diesel locomotive is kept for some very specific uses. The final decade of the 20th century and the first decade of the 21st century were marked by the enormous rise in High Speed due to the huge leaps forward in electric locomotive technology [1, 2, 3].

According to [4] the railway network construction in Ethiopia was first started in October 1897 from Djibouti. The first commercial service began in July 1901, from Djibouti to Dire Dewa. In 1906 firm went bankrupt and construction halted. By 1908, compagnie de chemin de Fer Franco-Ethiopien de Jibuti à Addis Ababa took over and began reconstruction. By 1915, the railway line reached Akaki and two years later came all the way to Addis Ababa itself. In 2006, agreement with Italian company costa to rehabilitation the line was reached and by 2007, National Railway Dev launched by CoM regulation Ne 141/2007 and ERC established. Transportation infrastructure in Ethiopia has been neglected for more than decades but it is a priority of the government of Ethiopia now.

The railway transport system is one of the most crucial transport systems in the world with higher speed and higher axle loads, higher reliability and safety, large carrying capacity (volume), lower life cycle cost (LLCC), satisfy environmental demands and higher availability and fewer disturbances comparing with roadway. Now days, there is high demand of railway transportation system in the world including Ethiopia for a long and medium distance transportation of passenger and goods (freight). To satisfy such demands, it needs to have a railway transportation system with standard safety, comfort, speed, economy and reliability of the network. At the top of every system safety comes and has no compromise. Among many complex analyses of the railway network, this paper focuses on the effects of sand-based friction modifier in wheel-rail contact which is safety issue. This study mainly concentrates on the effectiveness and side effects of sand-based friction modifier in wheel/rail contact.

The wheel-rail contact is a safety critical interface for railway network. Different researchers, institutes, companies, etc have been worked and continue their work on wheel-rail contact for safety and others. The network (railway vehicle) operation depends on the adhesion between the wheel and rail. To run such vehicles efficiently and economically in addition to safety, the wheel-rail adhesion should be maintained at a certain level. The adhesion (or available traction) in the wheel-rail contact is the most important parameter in braking and traction operation of rail vehicles. The increasing demands in railway transportation have led to faster trains with higher accelerations and decelerations; however, the wheel–rail adhesion still remains limited by the available friction between the steel wheels and rails. Since the beginning of railway transportation, sanding from locomotive has been the common practice to enhance wheel-rail adhesion in most of the railway networks. Sand-based friction modifiers are another practical measure that some railway organizations have been using to overcome low adhesion incidents caused by natural contaminants like autumn leaves. Although sand has widely been accepted as an effective adhesion improver in the most of the natural contamination conditions, this seems to be a lack of understanding on the influence of the sand particle size. This hinders not only a possible optimum sanding practice, but also the development of suitable sand-based friction modifiers.

Furthermore, the wheel slip at which sanding is activated represents another relevant parameter that may help to optimize sanding practice. In the railway network, sanding can be activated manually by the driver or automatically by the Wheel Slide Protection (WSP) and Traction Control (TC) systems. The activation by the WSP/TC systems is triggered with a certain wheel slip (or slip) threshold.

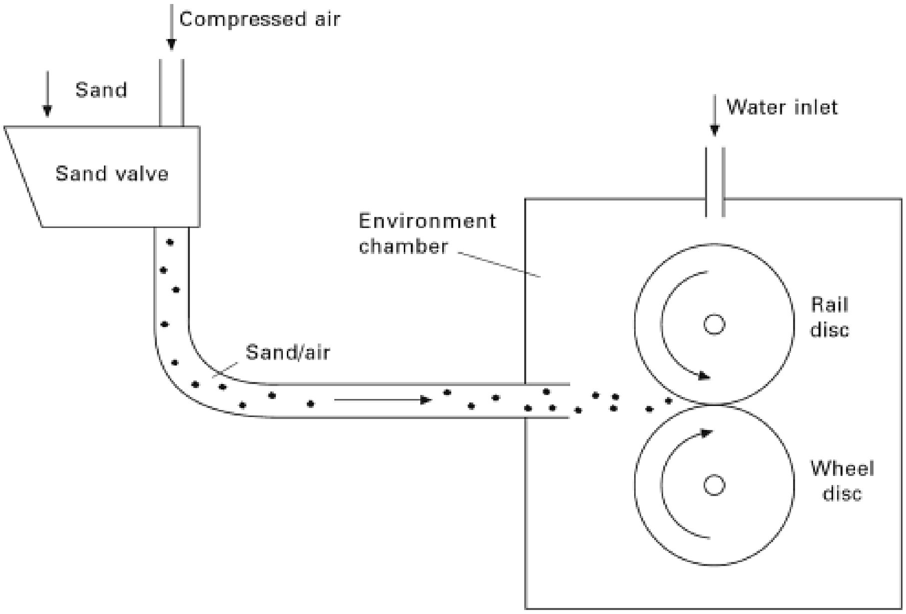


Figure 1. 1: Sand application to the wheel /rail contact

This study describes the influence of particle size distribution at different slips on adhesion and wear. The wheel-rail contact is simulated by means of a twin-disk test machine under closely controlled laboratory conditions. The adhesion coefficient during sanding at four particle size distributions has been analyzed. The wheel and rail disks have also been examined after each test to analyze the wear, not only in terms of mass loss, but also the surface damage, surface work-hardening and subsurface deformation caused by sanding at different sizes. The analysis of effects of sand-based FMs in wheel/rail contact requires the detail analysis of the contacting surface conditions and factors affecting the contacting surface behavior of the two interacting surfaces (rail-wheel). Therefore, to understand the general functions and properties of the two interacting surfaces (wheel/rail), it is preferable to see each sub components separately as follows.

### 1.1.1. Rails

Rails are one of the railway system components arranged in parallel to provide a continuous and level surface for train movement, provide lateral guidance to the train wheels, bear the wheel load. All modern railways use steel rails which are specifically rolled for the purpose from steel which has the required qualities of strength, fatigue endurance and wear and corrosion resistance. The shape of the rail has now become generally standardized as the Flat Bottom (FB) rail. The head of the rail has an almost flat top with curves at the outer edges designed to fit the shape of the wheel tyre. One of the features of a well matched rail head and wheel tyre is that, when the axis of the wheel coincides with the longitudinal axis of the track and the rail is set at its correct inclination of 1 in 20 to the vertical, the point of contact between the two is very close to the centre line of the rail. This is very desirable since it minimises the twisting effect on the rail which a concentrically applied wheel load would produce, and by keeping the contact area away from the gauge corner, reduces both corner 'shelling' and fatigue damage. [2, 5]

The rail head sides slope is at 1 in 20. This is to compensate for the 1 in 20 inwards slope of the rails and not only makes it simpler to check the gauge but ensures that when side wear takes place the associated gauge widening is minimized. [2, 5]

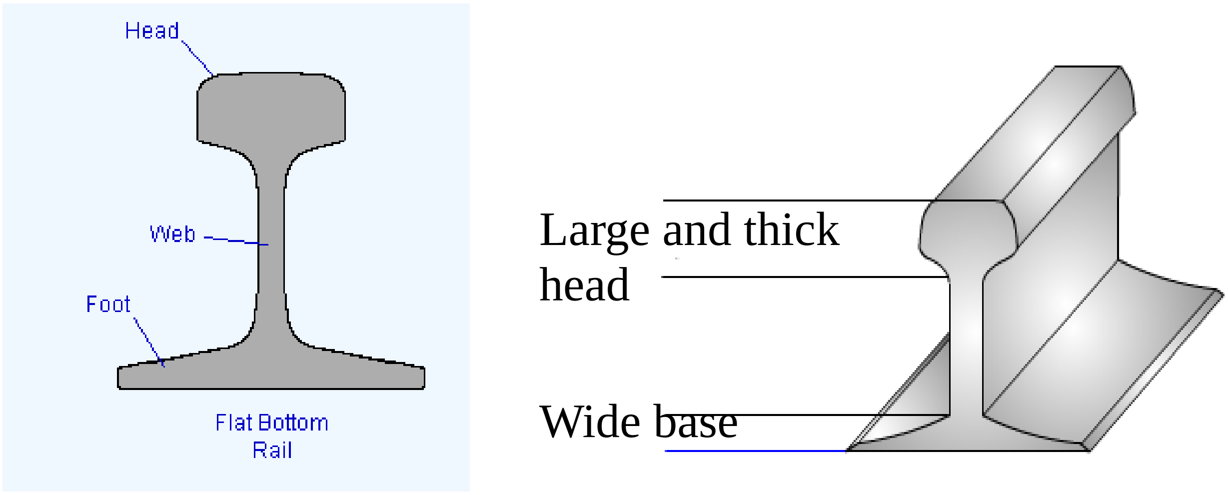


Figure 1. 2: Rail profile

### 1.1.2. Train wheel

A train wheel or rail wheel is a type of wheel specially designed for use on rail tracks. A rolling component is typically pressed onto an axle and mounted directly on a rail car or locomotive or indirectly on a bogie, also called a truck. Wheels are cast or forged (wrought) and are heat treated to have a specific hardness. New wheels are turned, using a lathe, to a specific profile before being pressed onto an axle. All wheels profiles need to be periodically monitored to insure proper wheel-rail interface. Improperly turned wheels increase rolling resistance, reduce energy efficiency and may create unsafe operation. A railroad wheel typically consists of two main parts: the wheel itself and the tire (or tyre) around the outside. A rail tire is usually made from steel, and is typically heated and pressed onto the wheel, where it remains firmly as it shrinks and cools. [2], [5]

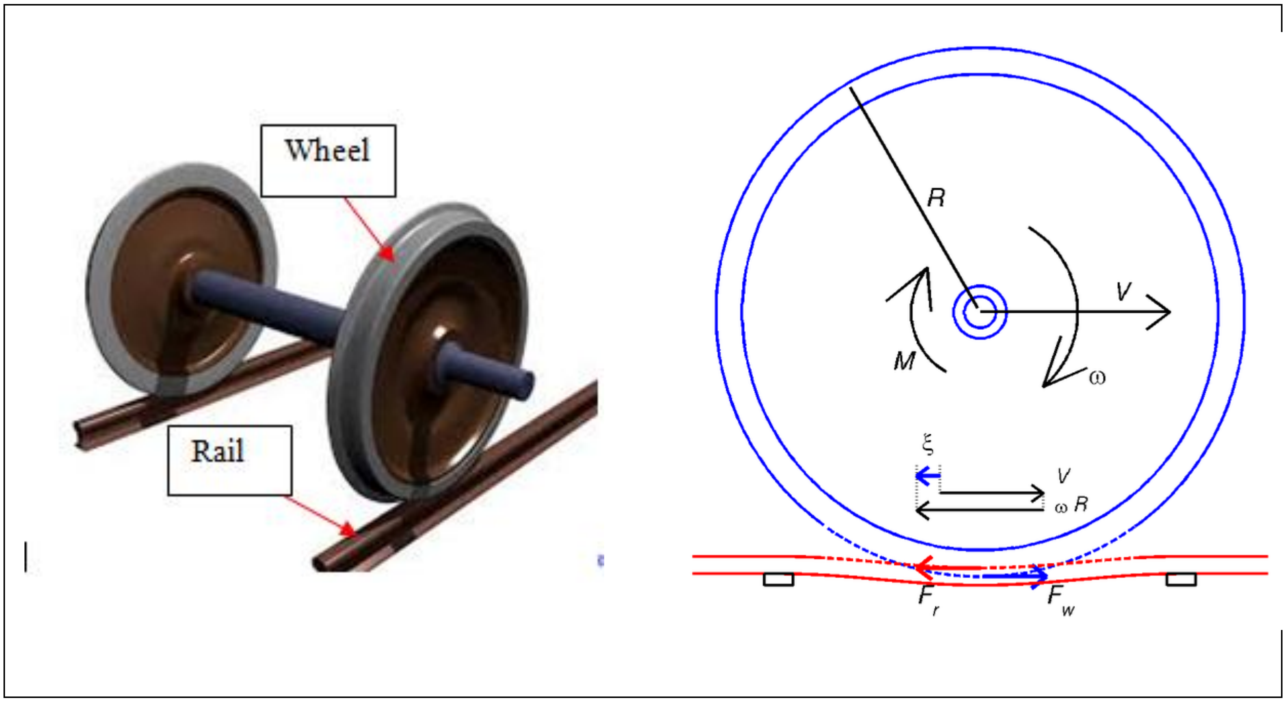


Figure 1. 3: Wheel and rail arrangement [2]

### 1.1.3. Wheel-set

A wheel-set is the wheel-axle assembly of a railroad car. The frame assembly beneath each end of a car, railcar or locomotive that holds the wheel-sets is called the bogie (or truck in North

America). Most North American freight cars have two bogies with two or three wheel-sets, depending on the type of car; short freight cars generally have no bogies but instead have two wheel-sets [2].

A wheel-set comprises of two wheels rigidly coupled by an axle as shown below in Fig. 1.4.

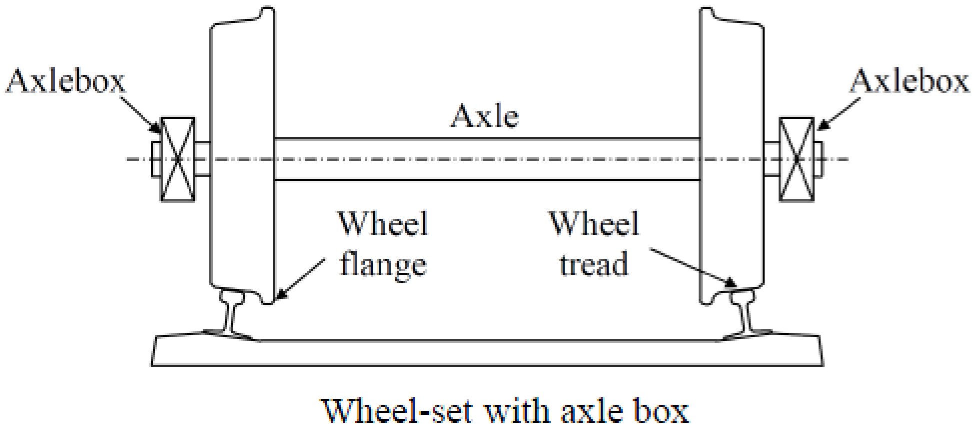


Figure 1. 4: Wheelset configuration

The wheel-set:

- provides the necessary distance between the vehicle and the track
- provides the guidance
- transmit traction and braking to the rails

## 1.2. Railway transport advantages and disadvantages

### 1.2.1. Advantages [3]

- Limited use of space compared to large transport capacity
- Better reliability and safest mode of land transport with the lowest accident rate

- High degree of automation and management
- Most efficient energy consumption (minimum friction and minimum air resistance)
- Environmentally friendly (mostly electric powered)
- It offers comfortable ride options such as meal, sleeping and entertainment
- Dense city agglomerations and mixed land use developments instead of sub-urban sprawl

### 1.2.2. Disadvantages [3]

- Cost of railway infrastructure is expensive; *(ca. $ 4 - 20 million US/km)*
- High speed railway lines are more expensive; *(ca. $ 20 - 45 million US/km)*
- Out of the total cost, 50% of the cost is for track construction such as track superstructure including switches and crossings, electrification, tele, etc.
- The remaining cost is for track substructure, such as bridges, tunnels, embankments, subgrade improvement, etc.;
- Very difficult terrains requires many special civil structures (tunnels and bridges) which increase the cost rapidly
- Railway construction in tunnels can cost up to $ 40 million US/km
- The cost for a double track is about twice that of a single track
- Cannot support severe alignments such as steep slopes and sharp curves
- Severity of accidents is high
- Security threat as it is prone to attacks
- Low flexibility in terms of network operations

Railway companies are often unprofitable, government have to support financially to operate trains (high operation and maintenance cost).

## 1.3. Statement of the problem

In our country Ethiopia, the railway networks are upon construction and in the near future, its service will begin. Because of this, different factors which limit the optimal use of the railway networks and the countermeasures taken with their effects must be studied. Therefore, railway vehicle operation mainly depends on the adhesion/friction between the wheel and rail. To run such vehicles safely, efficiently and economically, the wheel–rail adhesion should be maintained at a certain level. An adhesion between wheel and rail is a crucial factor in the railway transportation, as it may limit the acceleration and braking capabilities of a train. But the increasing demands in railway transportation have led to faster trains with higher accelerations and decelerations. This competitive importance of railway transportation network has been achieved by the discovery of FMs. Hence, an adhesion level in between the wheel and rail interface has been maintained by the application of friction modifiers. Since the beginning of railways, sanding has been a common practice among different types FMs to increase the adhesion of locomotives. The Ethiopian railway network also will use sand for adhesion improvement. The fundamental understanding of the effects of sanding parameters on its effectiveness and side effects on possible optimization in the use of sand is very important for the new railway network beginners like Ethiopia. In general, the wheel-rail contact is a key area of the railway system as a whole. Being able to manage the interaction between the wheel and rail is a solution to the reliability of a modern cost effective resilient rail network.

In wheel/rail contact, the study of effects of sand-based friction modifiers, the main problem is identifying the effects of the sand particle size distribution, sand feed rate and for the case Ethiopia as it is new, adopting own resource instead of importing from overseas. Thus, the design of effective and appropriate friction modifiers for the interaction by minimizing damage to wheel and rail with increased demands of railway transportation is a common objective in the network. The influence of particle size and wheel slip on adhesion and wear is the main idea for optimum use of sand. Different countries using railway networks have also different standards on sanding practice but Ethiopia has no such standards and going to use sand supplied from China according to the operation and service department of ERC. Therefore, the experimental investigation of effects of sand particle sizes in between the contact (wheel and rail) using the materials found in Ethiopia and to compare the results obtained from the tests, with different researches conducted on this area at different times.

## 1.4. Significance of the Research

This research has a great impact on future analysis, applications and understandings of effects of friction modifiers in wheel/rail contact in general and in particular in the Ethiopian context. Especially, it will contributes a lot for future analysis of effects of friction modifiers in wheel/rail contact regarding adhesion, wear and safety. The problems related to effects of FMs, especially sand-based FMs have to a large extent not been solved yet, despite the countermeasures adopted by the affected railways. Understanding the effectiveness and side effects of friction modifiers (sand-based FMs) is a critical for the longivety, reliability and smooth running of the railway network. I hope this research put wakefulness on our resource potential and neglect the necessity of import this and other materials from abroad.

Literatue has shown that different standards on sanding practice appear to be used by different railways. In particular, different particle size distributions are employed in european countries. In addition, different application rates may also be used depending on the railways and the characteristics of the sanders. The benefit of sanding on adhesion improvement is observed in railway transportation systems. But the influence of the particle sizes and feed rate, as well as other sanding parameters, on the effectiveness of sanding should be identified.

## 1.5. Objective of the research

### 1.5.1. Main objective

The main objective of the study is to assess the effects of friction modifiers, especially sand-based FMs in wheel/rail contact using sand materials found in Ethiopia with experimental investigation.

### 1.5.2. Specific objective

Specifically, the research tries to address the following objectives:

- Developing twin disc test machine for simulation of the interaction

- Preparing test specimen discs to simulate wheel and rail contact
- Collecting and preparing test materials samples used for test in laboratory
- Investigating or testing the influence of the sand particle size distribution on adhesion and wear in between wheel and rail contact.
- Investigating the influence of sand particle size distribution on surface roughness or surface topography
- Investigating mass loss due to the third body incorporated to the wheel and rail contact
- To compare and contrast the result obtained with the practically in use in European countries.

## 1.6. General methodologies

In order to find the effects of FMs (sand-based friction modifiers) presented in significance of research, experimental investigations have been performed. Experimental investigations have been carried out using twin disc test machine. Test discs with twin disc machine were prepared in METEC, HMMBI whereas test material was collected from different areas of East Shoa, Oromia Region, Ethiopia. This test material was tested and prepared for thesis work in Materials Laboratory of Oromia Water Works Design and Supervision Enterprise (OWWDSE). In the laboratory investigations, the wheel-rail contact adhesion and other effects of FMs has been examined with a twin-disk test machine, in which the actual wheel-rail contact is simulated by the two disks in rolling-sliding motion. The influence of particle size distribution in wheel/rail contact has been investigated with constant sand feed rate.

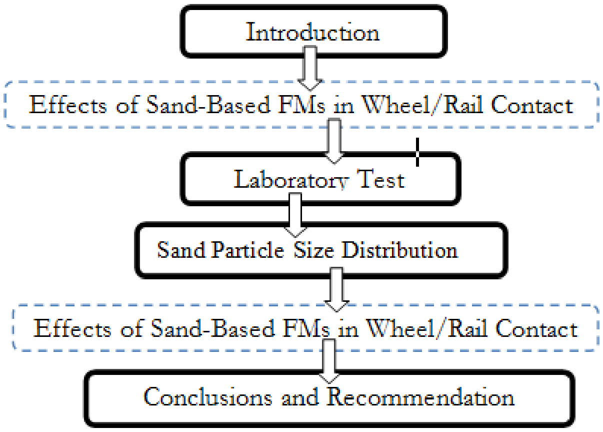


Figure 1. 5: Schematic of the methodology of the thesis

## 1.7. General conditions

The test disks will be mounted on independent shafts. By means of screw a controlled load of a 400N will be applied on the disks producing a maximum Hertzian pressure of 51Pa in the contact zone which is representative of the contact between wheel tread for passenger train. Since cylindrical disks are used in the experiments, a line contact of 10mm is present. In the tests, the wheel disk rotated faster than the rail disk to realize the slip; the rotational speed of the rail is maintained at 400rpm, equivalent to 0.98m/s of rolling speed.

## 1.8. General parameters

During the analysis of effects of sand-based FMs in wheel/rail contact, there are different types of external and internal parameters affecting the interactions. These parameters can be broadly classified as:

- Vehicle parameters: sand type (silica sand and filter sand), vehicle type, operating speed, axle load, contact pressure, wheel slip, rail & wheel profile, conicity, etc.
- Environmental parameters: Wheel /rail coefficient of friction conditions (dry, wet, contaminant etc.)
- Sand parameters: sand particle size distribution, feed rate, etc

- Track parameters: Track geometry (gauge, cant, alignment and curve), Rail head profile and shape etc.
- In this paper, all the above parameters are not taken into consideration due to its broad applications.

# CHAPTER 2: LITERATURE REVIEWS

## 2. Literature Reviews

### 2.1. Introduction

This portion reviews the previous related and relevant literature works on the case under investigation or test, which are basic guide for the introduction of the current work. Generally, there are many journals, conference papers, proceedings, books, etc related to the railway technology, wheel/rail contacts and interactions and others. This part intensifies the deep analysis of the previous related works and selection of appropriate conditions, approaches, and methodologies for the successful accomplishment of the paper.

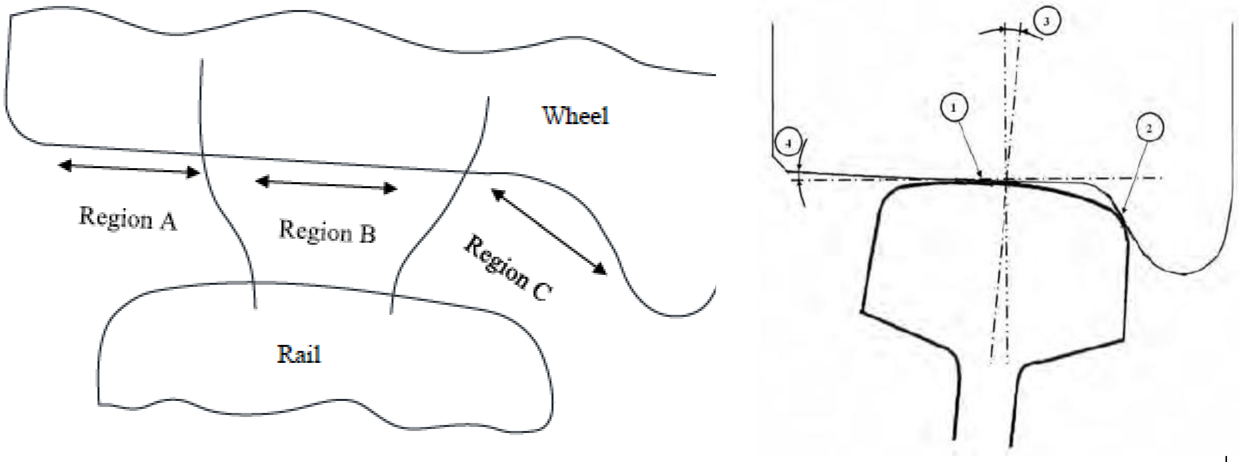
The history of wheel/rail contact mechanics is an integrated part of contact mechanics, which goes back to the middle of the 19th century. Problems of wheel/rail contact (damage phenomena and influence of contact mechanics on vehicle dynamics, especially on vehicle stability) have been investigated since the middle of the 19th Century. Since the early 1970's many measures have been undertaken in order to mitigate the problem. One of the measures adopted by many railway networks is the use of friction modifiers. However, the low adhesion problem still persists. Furthermore, the effectiveness of these friction modifiers has not well proven yet due to the lack of research in controlled conditions up to the last decades. Consequently, the rolling stock operators and infrastructure managers do not clearly understand the performance and side effects of the friction modifiers used on their networks. [6, 7, 8]

### 2.2. Wheel-rail contact conditions

Unlike road vehicles, such as the automobile, railway vehicles have some unique behaviours and properties, such as hunting motion, self-steering capacity 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, governed by rules, and is mounted at a small inwards inclination 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 and wheel flange.

Moreover, the wheel profiles are usually conical, leading to the difference in roolling raduis in a curve for the two wheels in the same wheelset. Comperared with tire-road interaction, the wheel-rail contact is very small at approximately 1cm$^2$. As a result, the heavy axle load is transferred through a small patch generating high contact pressure.[9, 10]

Due to the above mentioned factors, the wheel-rail contact changes wheen 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. When the vehicle is running on a curve, the contact area moves to between the wheel flange and rail gauge. 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 conditios and wear. [9], [10]



1. Wheel tread–railhead contact and

2. Wheel flange–rail gauge contact;

3. Rail inclination;

4. Conical wheel profile

Figure 2. 1: Schematic of two types of wheel–rail contact [9]

The two basic types of wheel-rail contact differ in many respects. Lewis and Olofsson presented the operating conditions in a wheel tread-railhead contact and a wheel flange-rail gauge contact, as shown in Fig. 2.1. 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, 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 [5], [9], [10].

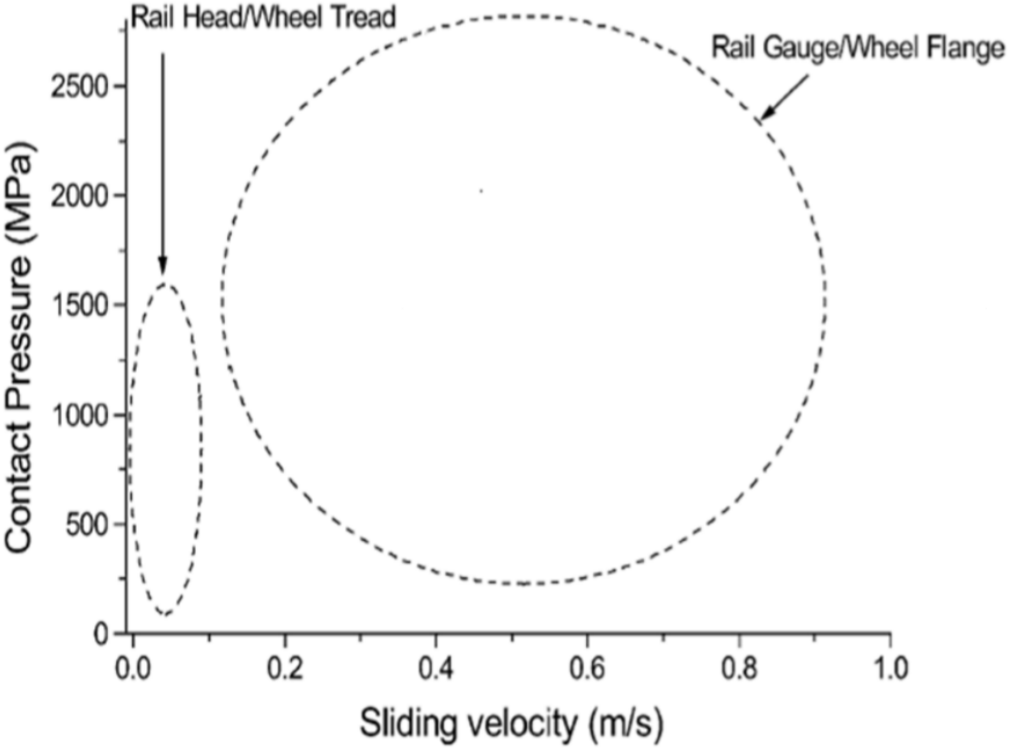


Figure 2. 2: Contact conditions in a wheel/rail contact {5}

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 creepage [9], [10], which is the main source of creep force.

$$\xi = \frac{u_s}{u_r} = \frac{(u_v - u_w)}{u_r}, \boldsymbol{u_r} = (\frac{u_v + u_w}{2})$$

$u_v$ – is the vertical running speed or translational velocity of a wheel over a rail.

$U_w$ – the circumferential velocity of wheel

$U_r$ – is the rolling speed.

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 test 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 [9], [10].

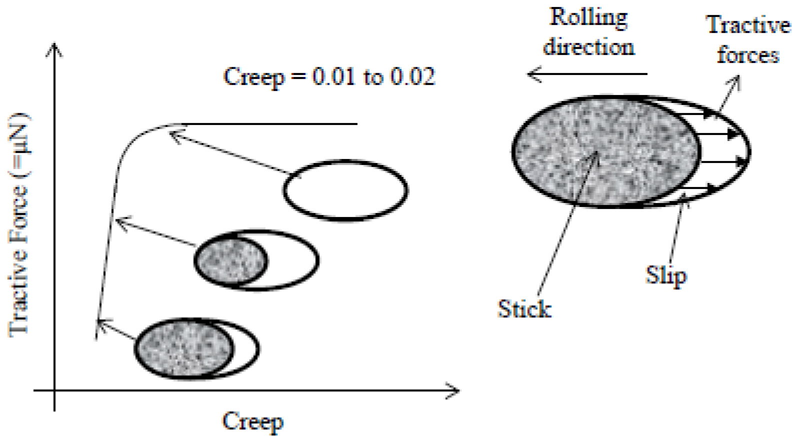


Figure 2. 3: Relationship between tangential force and creep at the wheel-rail contact [5]

### 2.2.1. Friction

In the late 16th century, Leonardo Da Vinci started systematically studying [9], [10]. Friction is defined as the resisting force tangential to the common boundary between two bodies when, under the action of an external force, one body moves or tends to move relative to the surface of the other [E 2.1]. Friction is normally presented by the friction coefficient ($f$), which is defined as the ratio between the friction force ($F_f$) and the normal force ($F_N$) in the contact between the two bodies, as shown in equation E. 2.1.

$$\boldsymbol{f = \frac{F_f}{F_N}} \qquad E\ 2.1$$

Figure 2.4 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 at the centre of mass, as displayed in Figure 2.4, where $k$ is an arbitrary positive constant and the $t$ is time, there will 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 in E 2.2, where $g$ is the acceleration due to gravity. From that instant onwards the body slides with 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 $t_2$ is given by E 2.3, where $a_2$ is the body acceleration at the instant $t_2$. [9, 10]

$$\boldsymbol{f_s = f(t = t_1) = \frac{k.t_1}{m.g}} \qquad (\boldsymbol{E\ 2.2})$$

$$\boldsymbol{f_k = f(t = t_2) = \frac{k.t_2 - m.a_2}{m.g}}, \qquad (\boldsymbol{E\ 2.3})$$

In most triblogical pairs, the static friction is higher than the kinetic friction, being the difference dependent on the materials and contact conditions [E 2.1]. In the case of the steel employed for railway wheels and rails, laboratory investigations have shown that the static friction coefficient can be up to almost twice of the kinetic friction coefficient [E 1.2]. [9], [10]

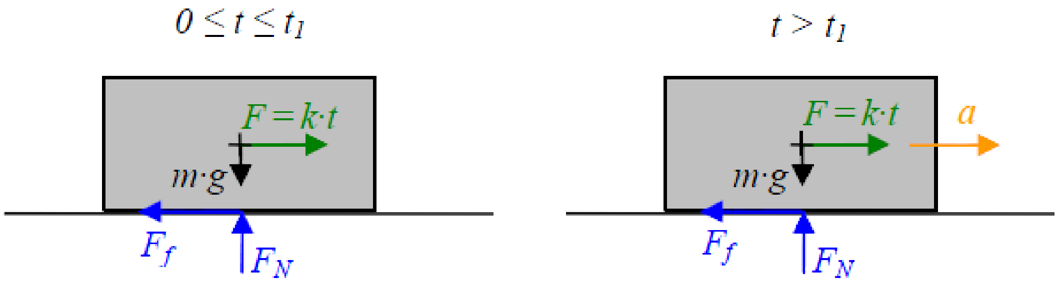
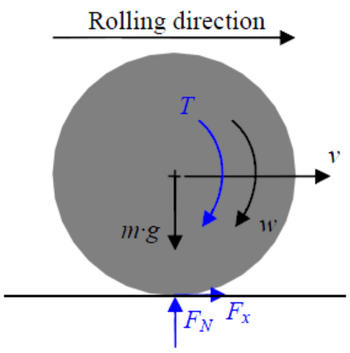


Figure 2. 4: Rectangular solid body on a horizontal plane (forces applied on the body)

### 2.2.2. Adhesion

Maintaining good adhesion between the wheel and rail is imperative for the safe, efficient and reliable operation of a railway network. In train braking, maintaining good adhesion is clearly a safety issue; in traction it is a performance issue, as wheel slippage due to low adhesion can lead to delays. Good control of the adhesion levels can also bring about efficiently savings in terms of reduced fuel consumption.

In a railway context, 'adhesion' is the friction available to transmit tangential force between railway wheel and rail [6], [7], [9], [10]. Therefore, the vertical axis in figure 2.3 could also be labeled 'adhesion'. The term 'adhesion' is used by both braking and driving wheels.



($m$) = railway wheel mass, considered as a solid cylinder

(T) = tractive torque applied at the center of mass of the cylinder at its axis of rotation

($w$) = angular velocity

($v$) = linear velocity

Figure 2. 5: Schematic lateral view of the cylinder on the horizontal plane (forces applied on the cylinder) [10]

The application of the tractive torque causes longitudinal tangential force at the contact interface with the plane, which is known as the traction force ($F_x$) (see Figure 2.5). The ratio between the traction force and the normal contact load is normally named the adhesion or adhesion coefficient ($\mu$), as given in Equation E 2.4.

$$\boldsymbol{\mu_{adhesion} = \frac{F_x}{F_N} \leq \mu_{friction}} \qquad (E\ 2.4)$$

Due to the tractive effort, 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 Equation E 2.5, where $r$ is the radius of the cylinder.

$$\boldsymbol{s = \frac{v^{rel}}{v^{mean}} = \frac{w.r - v}{0.5(w.r + v)}} \qquad E\ 2.5$$

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 of the cylinder to be lower than its linear velocity and Equation E 2.5 changes to Equation E 2.6. In addition, the wheel slip in full sliding conditions during braking is normally referred to as wheel slide.

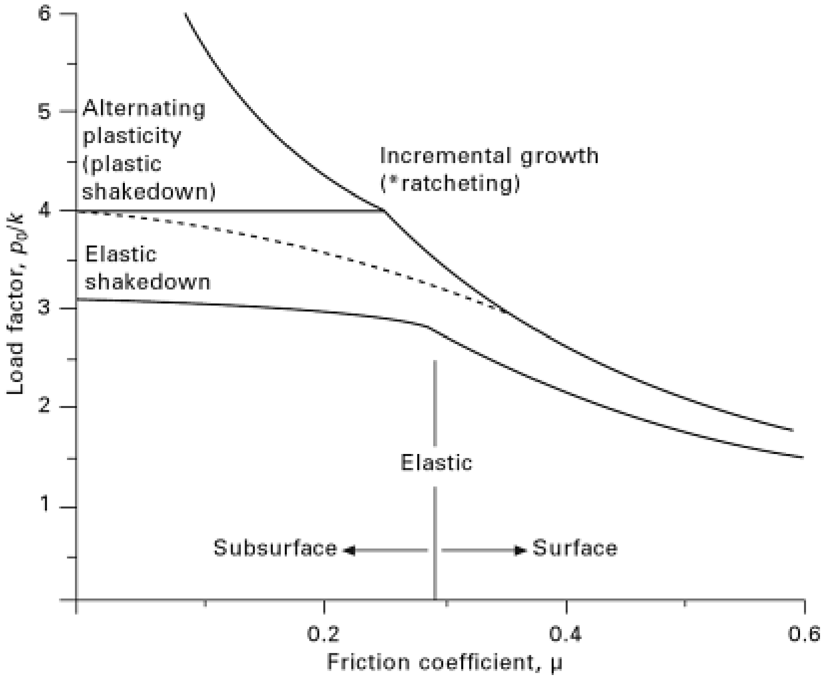
$$\boldsymbol{s = \frac{v^{rel}}{v^{mean}} = \frac{v - w.r}{0.5.(q.r + v)}} \qquad E\ 2.6$$

### 2.2.3. Ambiguity with traction coefficient

In some literature, the term traction coefficient is employed instead of adhesion cefficient, presumably due to the fact that the investigation are mostly performed in traction conditions, i.e. wheel(s) accelerating over rail(s). In principle, both adhesion and traction coefficient may equally be used without loosing correctness, but it may sound odd to describe the braking performance of a railway vehicle based on the traction coefficient. For this reason, some authors have used the term adhesion coefficient in their braking investigations. In order to avoid confusion, while keeping a uniform definition, the term adhesion coefficient is employed in this document referring to both traction and braking operations. [10]

### 2.2.4. Wear

Wear is the loss or displacement of material from a contacting surface. A material can wear by a number of different mechanisms or modes. How a material wears depends on the nature of the material and the other elements of the tribo-system, which include environmental conditions and whether any contaminants are present, for example, wear debris and in the case of the wheel-rail contact, friction modifiers, friction enhancers like sand, leaves, etc.



This wear map shows the relationship between wear behavior and operating parameters.

Material displacement may occur by transfer of material from one surface to another by adhesion or by local plastic deformation. [6, 7]

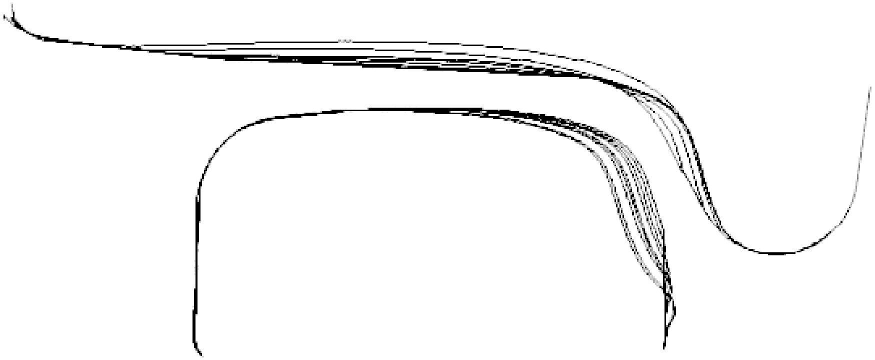


Figure 2. 6: Form changes of wheel and rail from the Stockholm test case

In wheel-rail contact, both rolling and sliding occur in the contacting zone. Especially in curves, there can be a large sliding component on the contact patch at the track side of the rail head (gauge corner). Due to this sliding, wear occurs in the contact under the poorly lubricated condition that is typical of wheel-rail contact, as shown in Figure 2.6. An observation that can be made on sliding wear is that an increase of the severity of loading (normal load, sliding velocity, temperature) leads, at some stage, to a sudden change in the wear rate (volume loss per sliding distance). [6], [7]

## 2.3. Low Adhesion Problem

Since the beginning of railway transportation, wheel-rail adhesion has been limiting the acceleration and deceleration capabilities of rolling stock. Locomotive designers have had to consider the optimal weight distribution for the maximum exploitation of adhesion, leading to changes in wheel arrangement in the course of time as indicated in figure below.

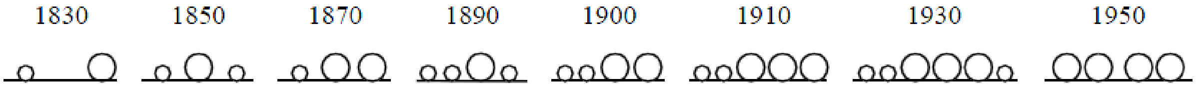


Figure 2. 7: Wheel arrangement of typical express locomotives at different times [10]

In recent decades, special attention has been paid to the limitations in adhesion due to the quest for a more rapid, reliable and denser railway transportation that can satisfy the increasing demands on public transportation. Although advances in technology have facilitated the increase of the tractive and braking capacities of the rolling stock, railway transportation is still characterized by steel wheels and steel rails operating in an open system. Thus, the wheel-rail contact remains easily contaminated by water, leaves or grease, causing many railways worldwide to suffer from low adhesion problems, especially in autumn.[10]

Low adhesion exists when an insufficient adhesion or friction is available in the wheel-rail contact to satisfy a certain requirement. The adhesion requirements in railway transportation are ultimately imposed by the driver, who may operate the train under the influence of pressure exerted by the timetable or the operational conditions on the track. The adhesion available in the wheel-rail contact is limited by the friction, which is dependent on the contact conditions. Under low adhesion conditions, the acceleration and deceleration capabilities of the rolling stock are diminished, compromising traction and braking performance. [10]

## 2.4. Adhesion requirements in railway transportation

In railway transportation, there are normally three different types of adhesion requirements, namely given by tractive/braking capacity of the rolling stock, timetable regulations, and safety during operation. [10]

## 2.5. Adhesion available in the wheel-rail contact

The adhesion available between railway wheels and rails is limited by the friction of steel-on-steel contact. The mechanics of metallic friction has been investigated by several authors. Bowden and Tabor [10] attributed the friction between a hard metal slider on a soft metal surface to a combination of shearing and plowing, i.e. the sum of the force required to shear the metallic junctions formed at the points of contact and the force needed to displace the softer metal in front of the slider. Suh and Sin [10] proposed a theory of metallic friction based on three different mechanisms: deformation of the surface asperities, plowing by wear particles and hard asperities, and adhesion of the sliding surfaces. In a compilation of findings reported by different authors, four mechanisms of metallic friction are given: adhesion of the sliding surfaces, plastic deformation and plowing of one surface by hard asperities of the other surface, elastic deformation of the material below the plastically deformed surface and plowing by wear particles.[9]

Railway transportation occurs in an open system, which cannot impede the entrance of different contaminants in the wheel-rail contact. In the presence of contamination, the friction level can greatly be reduced from that one of clean dry conditions. The amount of adhesion reduction is strongly dependent on the type of contamination, being also influenced by the ambient conditions. [10]

## 2.6. 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 low adhesion 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.

### 2.6.1. 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 and more rarely the wheels.

### 2.6.2. During braking

Low adhesion conditions during braking can affect track capacity and punctuality (equal to the case of low adhesion during traction) threatens the safety of the railway transportation and cause significant damage to wheels. If a train is requested to stop at a signal, the adhesion at the wheel-rail contacts is critical to the rate at which the train can decelerate.

Furthermore, damage to wheels due to braking under low adhesion conditions can often occur, particularly in rolling stock not equipped with an adequate wheel slide protection (WSP) system. The blockage or partial blockage of a wheelset during a braking maneuver leads to a high level of slide, causing part of wheel tread to wear off forming a wheel flat. The high temperature in the contact patch, exceeding 800-850 ℃ due to the dissipaed energy, transforms the pearlitic wheel steel austenite. The subsequent rapid cooling of the thermally 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 due to the plastic deformation of the wheel material upon subsequent impacts with the rail [10]. Crack formation may take place in the martensite due to the repeated mechanical lading, leading to the spalling of the martensite steel [10], as shown in Figure 2.8b.

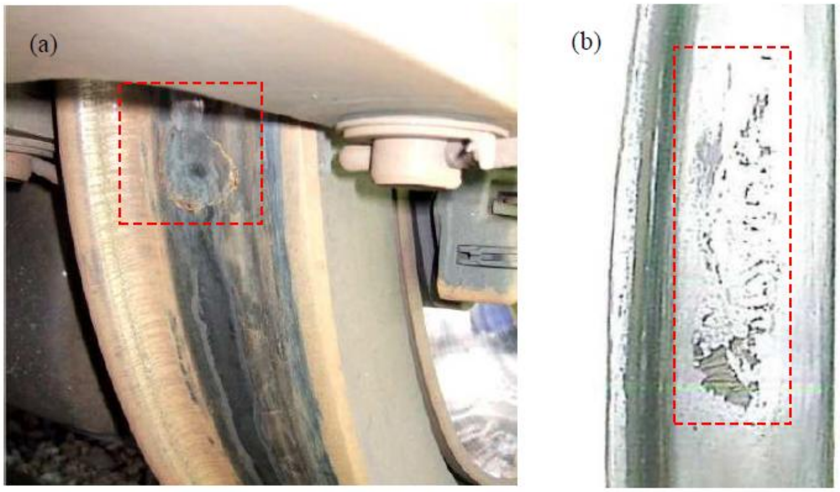


Figure 2. 8: Photograph of: a) A wheel flat due to excessive slide B) a severe wheel flat with spalling [10]

## 2.7. Phenomena in the Wheel-Rail Interface

A great deal of research on adhesion loss was carried out in the UK during 1970s using both laboratory and field. These studies identified factors that contribute to adhesion loss, such as slippery coatings formed by leaves, humidity and oil and wear particles. Recent adhesion problem analyses, together with metrological data from the UK, reveal that approximately one third of the overruns due to adhesion problems occurred when no rail contamination had been reported. However, rail contamination was reported in 43% of the overruns. [6, 7]

A recent literature reviews from the Rail Safety and Standards Board in the UK reveals that, although much field work has been done on low railway wheel-rail adhesion, there is a lack of controlled laboratory experiment. Recently, however, Olofsson and Sundvall (2004), Olofsson (2007), Gallardo-Hernandez and Lewis (2008) and Cann (2006) presented results from controlled experiments. In Olofsson and Sundvall (2004) a pin-on-disc machine with controlled temperature and humidity was used to study how the environment affects the friction between railway wheel and rail steel under leaf lubricated conditions [6, 7]. The results show that the coefficient of friction decreases when the relative humidity increases and decreases even more when the leaves act as a lubricant. When leaves act as a lubricant, the coefficient of friction reaches the same levels as when using ordinary lubricating oils. Olofsson analyzed the surface layers formed between the blackish leaf layer and the steel surface and found a chemically reacted, easily sheared surface layer containing elements. [6], [7]

## 2.8. Effects of sand-based friction modifiers in wheel/ rail contact

Although railway sanding has been proven to improve the adhesion under most of the typical contamination conditions, laboratory and field investigations have shown that sand may act as a solid lubricant in dry wheel–rail contacts. Lubricity is in the scope of this article identified with the reduction of the adhesion coefficient caused by sanding. Depending on the resulting adhesion coefficient, the traction and braking operations of rail vehicles could be affected.

***Several investigations on sanding have been carried out by different researchers. Some of them are presented as follows:***

Andrews [10, 11, 12] investigated the adhesion values given by some mineral powders (silica sand) with a full-scale test bogie. He proposed an empirical relationship in which the adhesion coefficient increased proportionally with the product of particle hardness and size of the mineral powders. However, only one particle size was used for each mineral tested, and his empirical relationship was restricted to particle sizes smaller than 0.4 mm.

Astle-Fletcher [10, 11, 12] stated that the working principle of sanding was mainly achieved by mechanical interlocking of sand particles with the roughness of the wheel and rail surfaces. He also presented an investigation of the most important parameters in the sand applicators, such as proximity to the contact interface and velocity.

Kumar et al. [10, 11, 12] carried out laboratory investigations to analyze the wear and adhesion experienced by sanding on locomotive wheels and they compared it to dry steel-on-steel contacts. The wear rates were shown to increase by an order of 1 to 2 due to application of sand.

The sand increased the adhesion in oily contacts. An increase in the adhesion coefficient with slip on dry contacts during sanding was shown. Nevertheless, slip only up to 1% was used in their work, which is below those found in practice under low adhesion conditions.

Boiteux et al. [10, 11, 12] presented the results of some braking tests performed in field under different contact conditions, in which the adhesion and wheel (gross-) slip were measured with two measuring wheel-sets. They showed that sanding on rails covered by fallen leaves improved the adhesion, while sanding slightly reduced the adhesion on clean rails.

Gallardo-Hernandez et al. [10, 11, 12] showed that sanding can help to overcome low adhesion caused by leaves and water, but it can decrease the adhesion in clean contacts. The findings of all those studies lead to the conclusion that feed rate, particle size, and wheel slip are the most influencing parameters on the solid lubrication effect of railway sanding. However, the influence of all those parameters was not investigated in a single study, and most of the investigations considered a range of parameter variation that does not correspond to the current sanding practice.

Furthermore, the most negative side effect of railway sanding is that it may insulate the electrical conductivity of the wheel–rail contact, depending on the amount of sand entrapped in the contact. The increase in electrical insulation is identified by the increase in the voltage across the wheel–rail contact due to sanding. In practice, if the voltage surpasses a certain threshold value, the functioning of the railway track circuits that are used for the detection of trains can be affected. Thus, the railway traffic signaling would be impaired, causing traffic disruption and perhaps, in the worst case, even collisions of trains. This has led railway organizations to establish standards on railway sanding that guarantee correct functioning of track circuits [10], [11], [12].

More recently, Lewis et al. [10, 11, 12] showed that sanding can help to overcome low adhesion caused by leaves and water but wear was increased by factors between 2 and 10 during sanding. Lewis et al. also investigated the electrical insulation of the wheel–rail contact caused by sanding in both static and dynamic tests. Their results showed that the electrical insulation of the wheel–rail contact varied with the sand feed rate, and complete electrical insulation may occur above a certain sand feed rate.

Although sand has widely been accepted as an effective adhesion improver in most of the contamination conditions, there seems to be a lack of understanding on how sand particle size affects adhesion, electrical insulation and wear in the wheel-rail contact. This hinders not only a possible optimum sanding practice but also the development of suitable sand-based friction modifiers. There exist several standards on sanding, in which specifications on different requirements in the particle size distribution of the sand can be found. The particle size distribution is given in the standards as 0.7-2.8 mm in the UK, 0.63-2 mm in Germany and 0.1-0.6 mm in France. Furthermore, sanding can be activated manually by the driver automatically by the Wheel Slide Protection (WSP) and Traction Control (TC) systems. The activation by the WSP/TC systems is triggered with a certain wheel slip (or slip) threshold. Nevertheless, there is no grasp on how relevant the wheel slip can be on the performance of sanding not only in terms of adhesion but also its impact on wear and electrical insulation. All these facts encouraged the authors to investigate the influence of the particle size, feed rate and wheel slip during sanding on adhesion, electrical insulation and wear of wheels and rails. [10], [11], [12],

***The research results from different papers studied on adhesion showed as follows:***

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

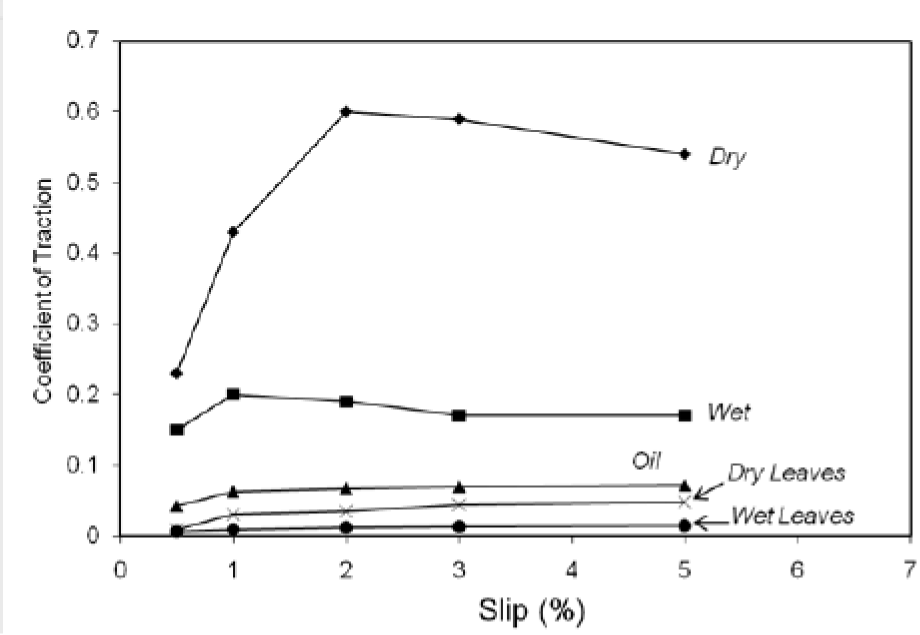


Figure 2. 9: Comparison of coefficient traction with slip at different contaminants [13]

In most railway networks, sand has been studied as a common practice to enhance wheel/rail adhesion and it is another practical measure to overcome low adhesion incidents caused by natural contamination. The study results showed that adhesion coefficient is greatly reduced in the presence of leaf layers. The layers were removed from the disk surfaces progressively with cycles and consequently the adhesion increased. When sand was applied to the wheel-rail interface, the leaf layers were effectively removed in the first few cycles due to the hard abrasive particles action of the sand have penetrated through the contamination layers. Note that the sand particles are more than 10 times harder than the leaf layers. In the tests, the continuous application of sand rapidly led to dry contact conditions as black leaf layers were removed. Larger particle sizes and higher slips lead to higher adhesion coefficient. This in turn leads to deeper plastic deformation in the wheel and rail disks. [10], [11], [12]

Also recent investigations showed how sand particle size distribution affects adhesion, electrical insulations wear of wheel-rail contact. The influence of the particle size on wear rates was found to be dependent on the slip. Higher wear rates of wheel and rail disks were experienced at higher slips for all sands tested. At higher slips the crushed sand particles slide longer distances when traveling through the disk interface, which causes more abrasion and therefore higher wear rates. Besides, material removal due to crack formation is promoted by higher slips because of the higher adhesion coefficient that leads to higher strains. [10], [11], [12]

## 2.9. The results of Effects of friction modifiers unlike sand in wheel/rail contact

In order to fight low adhesion, some practical measures have already been applied in different countries such as vegetation management, rail cleaning methods and friction modifiers (FMs). In most of railway networks, Sand has been studied as a common practice to enhance Wheel/Rail adhesion and another practical measure to overcome low adhesion incidents caused by natural contamination. Besides sanding, many railway organizations have adopted for using other Friction modifiers. Some of which may contain sand or other solid particles to increase the adhesion level under certain contamination conditions. Since the late 90's in UK & Netherlands, two commercial FMs used under poor adhesion conditions. These are FM A and FM B and both are water-based and designed to increase adhesion in different conditions (in dry and wet contact as well as in leaf contaminated contacts). FMA contains several types of solid components, which have different physical and tribological characteristics that provide the final product with varied functionalities such as friction enhancement and film transfer between wheel and rail. Furthermore, there are several polymeric components in FMA, all of which assist promoting adherence to the wheel and rail. FM A tested in successfully in a train depot in Japan to overcome adhesion problems related to rainfall whereas FM B used in autumn on the Dutch and British railway networks to mitigate adhesion problems mostly due to leaves and small amount of water. FMB is a mixture composed of an inorganic gelling agent, stabilizer, water, sand grains and stainless steel particles. [10], [14]

FMB showed the fastest recovery in adhesion for both braking and traction. It was up to 70% faster in braking and up to 93% faster in traction compared to the baseline. On the other hand, the moderate adhesion characteristics of FMA brought about slower recoveries in adhesion for traction requirements when compared to the baseline for all slips considered. For the baseline, it was found that faster adhesion recovery was achieved at higher slips, as it could be expected due to the increased removal effect. An optimum in adhesion recovery is found at 1% slip for FMB due to the balance between leaf layer and FMB removal. For FMA the optimum is also at 1% for braking, while for traction the higher the slip the better the performance due to its moderate adhesion characteristics. In baseline conditions, higher slip leads to better performance in both traction and braking because of the increased removal effect. [10], [14]

Two parameters of an FM play the main role in adhesion recovery: the hardness of the solid particles and the particle size. These two parameters need to be designed in accordance with the hardness and thickness of the leaf layer so as to optimize the removal of leaf layer.

The large hard particles of FMB cause indentations to the wheel and rail disk surfaces; whereas, no indentations are observed as caused by the small particles of FMA. Therefore, a compromise needs to be found for the hardness and size of the solid particles when a FM is developed in order to cut through the leaf layer and not cause severe surface damage on wheel and rail. [10], [14], [22]

# CHAPTER THREE: EXPERIMENTAL METHODS AND CONDITIONS

## 3. Experimental Methods and Conditions

### 3.1. Test Machine Development

A test machine (twin disc test machine) has been designed and developed in Hibret Manufacturing and Machine Building Industry under the license of METEC to simulate interacting surfaces in rolling-sliding contact. The twin test disc machine has been mounted with two discs which represents the rail and wheel contact. Two electric motors have been proposed and used with the machine to independently run the discs. Constant force applying system (threaded component) on the head of twin disc machine has been incorporated to apply the required amount of force on the moving component. Sand feeding system also incorporated to the machine. Generally, the twin disc test machine consist the following parts.

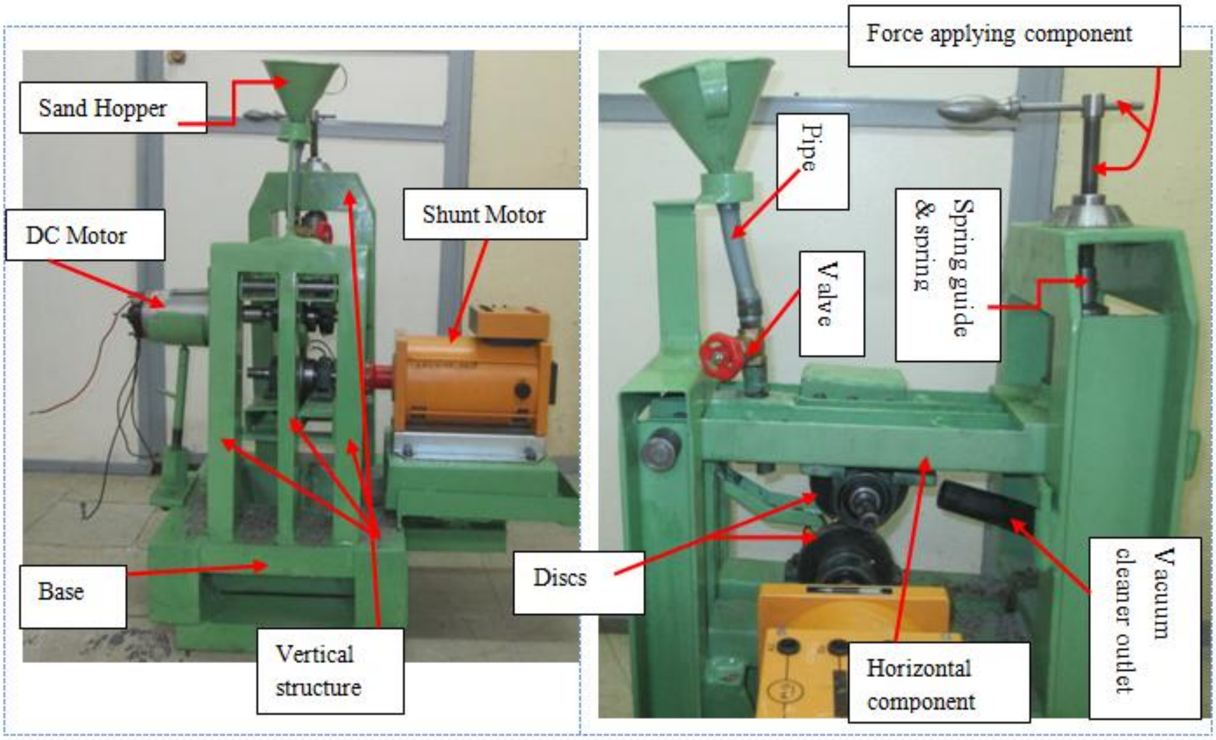


Figure 3. 1: photograph of Twin Disc Test Machine

## 3.2. Test Set up

The test discs have been mounted on independent shafts. Before assembly, the diameter of the discs was measured with a vernier caliper as necessary for the calculations of slip and adhesion coefficient. The slip ratio between the disks has been prescribed by setting different rotational speed of the shafts and maintained constant throughout each test with a controller. The slip ratio is defined in Eq. (1), where $w$ and $r$ are the rotational speed and rolling radius of the disks, respectively. The adhesion coefficient was calculated with the readings of the torque which was interpreted from armature voltage and armature current and the load of spring, as given in Eq. (2) by $T$ and $F_N$, respectively.

$$slip = \frac{w_{wheel} * r_{rail} - w_{rail} * r_{rail}}{w_{wheel} * r_{rail} + w_{rail} * r_{rail}} * 200\% \qquad E\ 3.1$$

$$\mu_{adhesion} = \frac{T}{F_N * r_{rail}} \qquad E\ 3.2$$

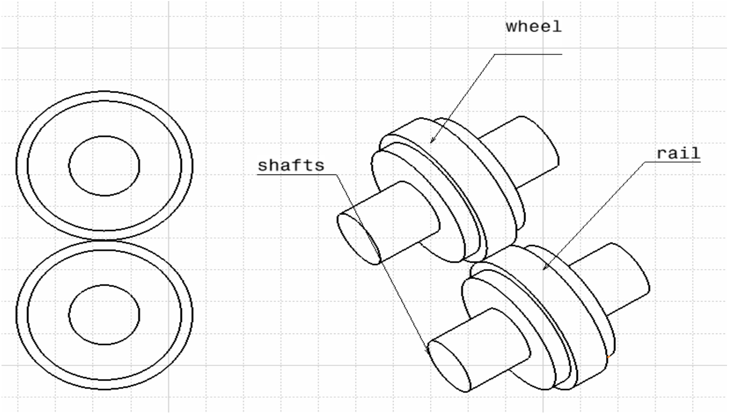
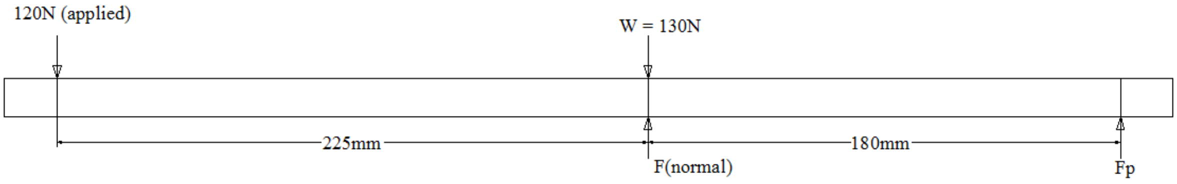


Figure 3. 2: Arrangement of test discs

### 3.2.1. Determination of Applied Force and contact pressure of the Interaction

#### i. Contact force determination

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



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

$$F_N = 400N$$

### ii. Contact pressure distribution determination

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

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

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

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

### iii. Test torque determination

A permanent magnet DC motor with 130 V, power 2.65HP, maximum rotational speed at no load 6700 rpm and a shunt type DC motor with 300W and 220V were assembled to the twin disc machine for test. The test rotational speed was being limited to maximum of 244 rpm because of shunt motor capacity and all parameters of the test were taken from the shunt motor. The shunt motor power is limited to 300W and torque is thus calculated as follows.

$$T_m = \frac{60 \times P}{2 \times \pi \times N}$$

Where, $T_m -$ Torque of motors, P - power of the motors and N - maximum rotational speed of one of the motors during testing

## 3.3. Test Apparatus

The twin disc test machine which was used to carry out the testing is shown schematically in Fig. 3.3 below. This machine has been developed by the researchers corporately under FDRE METEC, Hibret Manufacturing and Machine Building Industry shop found around Mexico, A.A, Ethiopia for two purposes primarily. Firstly, it is for the purpose of investigation of ‘the extent of adhesion loss due to contaminants in wheel and rail contact’ by my colleagues. Secondly, it was developed to investigate ‘the effects of friction modifiers (sand-based FMs) in between wheel and rail contact’ by me. The machine is used to simulate the wheel-rail contact in rolling-sliding conditions. The discs are manually loaded together with the help of threaded component up to the required force and continuously driven at controlled rotational speeds by independent electric motors. The required slip is achieved by adjusting the rotational speeds. A torque was calculated from armature voltage and armature current read by using voltmeter and ammeter which was assembled to both motors (DC permanent magnet motor and shunt motor) to provide required measurements, and a spring element with its guide is mounted on horizontal frame on which wheel disc fixed in line with the threaded component and below it gives an indirect measurement of the normal load. Variable resistors were used for the motors to vary input voltage to control speed.

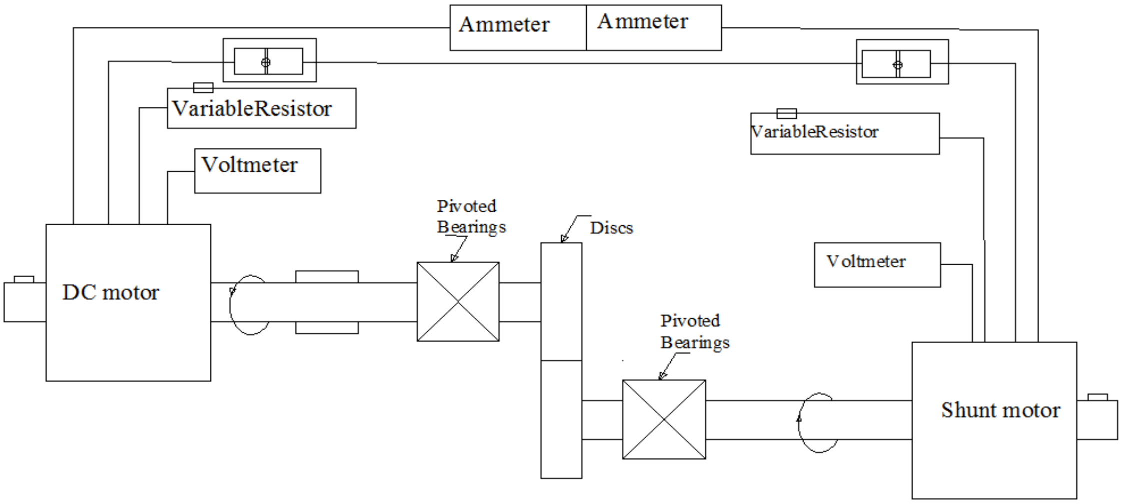


Figure 3. 3: Schematic representation of the twin-disc test machine.

### 3.3.1. Spring element properties used for load balance

The spring is made up of CSN 12090 materials. Balance test machine was used to test force and deflection relationships as shown below. From the obtained test result, spring constant (k) was calculated. Using K value and deflection the amount of load to be applied to the interaction was determined. The spring constant also calculated using the following formula and the results were compared.

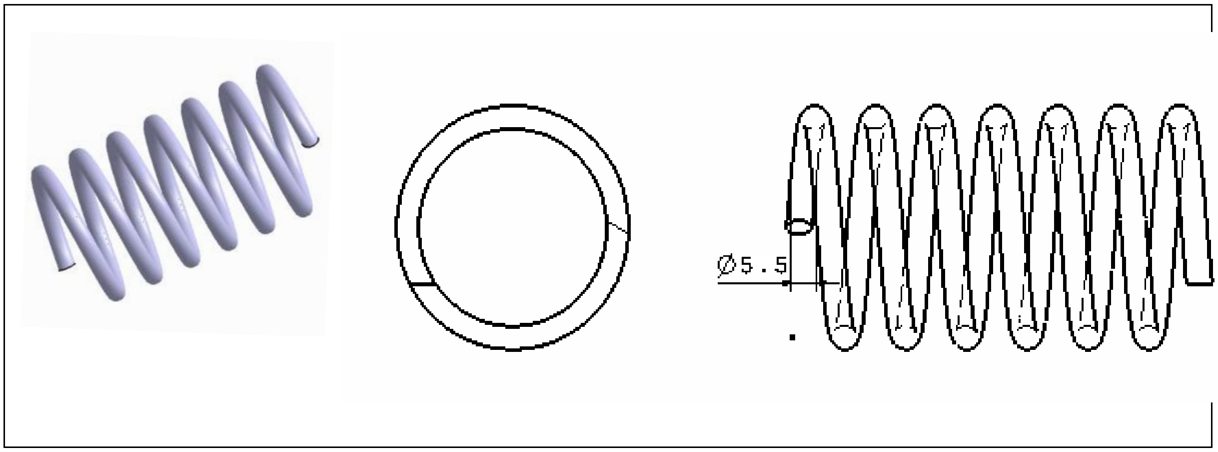
$$\boldsymbol{K = \frac{Gd^4}{8nD^3}},$$

Where, K = spring constant, G = modulus of rigidity of spring materials, d = wire diameter, n = number of active coils, D = mean coil diameter

Load, **F = K.x**, where K is spring constant and x is spring deflection

K = F/x = 40/2 = 20N/mm

Therefore, from the test result a spring with 20N/mm spring constant was used for the determination of load applied to the discs. Also the force and deflection relationship tested in laboratory is shown below.



| Balance machine test result for spring material | | | | | | | |
|---|---|---|---|---|---|---|---|
| F (N) | 0 | 40 | 80 | 120 | 160 | 200 | 240 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| X (mm) | 85.6 | 83.6 | 81.6 | 79.6 | 77.9 | 75.6 | 73.6 |

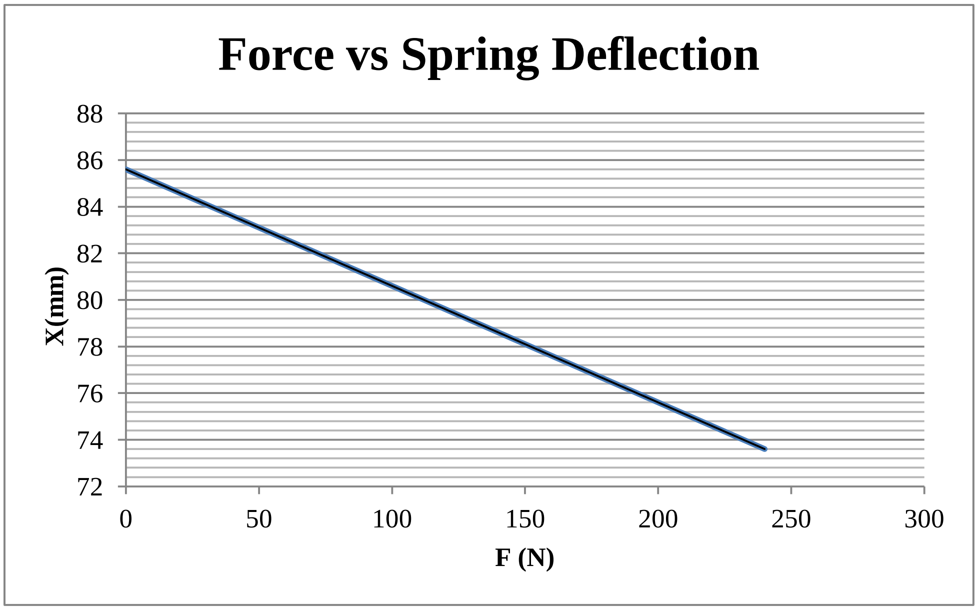


Figure 3. 4: Force Vs spring deflection graph after spring property test

### 3.4. Tested Materials (Tested sand)

Filter sand was used in this work. This filter sand was collected from different areas. One sand sample was collected from two places of Abura areas which is located at 2km from each other found in Meki Wereda. Another sand sample was taken from Langano Lake site found at around 30km from Batu (Zuway) town. These locations are found in East Shoa, Oromia Region, Ethiopia. The laboratory test of the sand was carried out in materials laboratory of OWWDSE. Among the test materials collected, the laboratory result revealed that the sand collected from Lake Langano Site was found to be sand with good property (material fineness, organic impurity, bulk specific gravity, bulk specific gravity (SSD), specific gravity apparent and water absorption (%)). The photograph of sands is given in Fig. 4 shown below. The type of activities of sample test carried out in OWWDSE materials laboratory is as follows.

- Specific gravity of sand
- Sample preparation
- Registration and reporting

- Sieve analysis and gradation
- Organic impurity content

### The Particle size distribution of sand required for test:

→ **The particle size distribution identified (measured) in lab using a laser particle analyzer**

**Filter (river) sand**

After sieving, the particle size distribution was categorized as follows:

→ R-sand (identified as railway sand) - ranges from **0.25 to 1.4mm, with a wide peak at 0.6 to 1mm.**

→ S-sand (identified as small sand) – ranges from **0.06 to 0.3mm, with peak at 0.15mm.**

→ M-sand (identified as medium sand) – ranges from **0.3 to 0.6mm, with peak at 0.35mm.**

→ L-sand (identified as large sand) – ranges from **0.85 to 1.6mm, with peak at 1.2mm.**

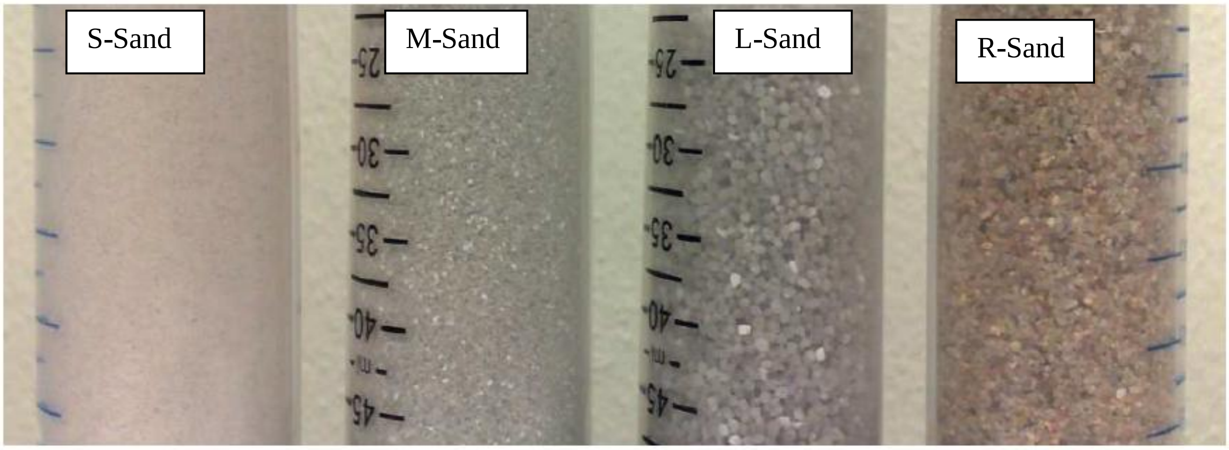


Figure 3. 5: Photograph the tested and prepared sample sands S -sand, M -sand, L -sand, R -sand

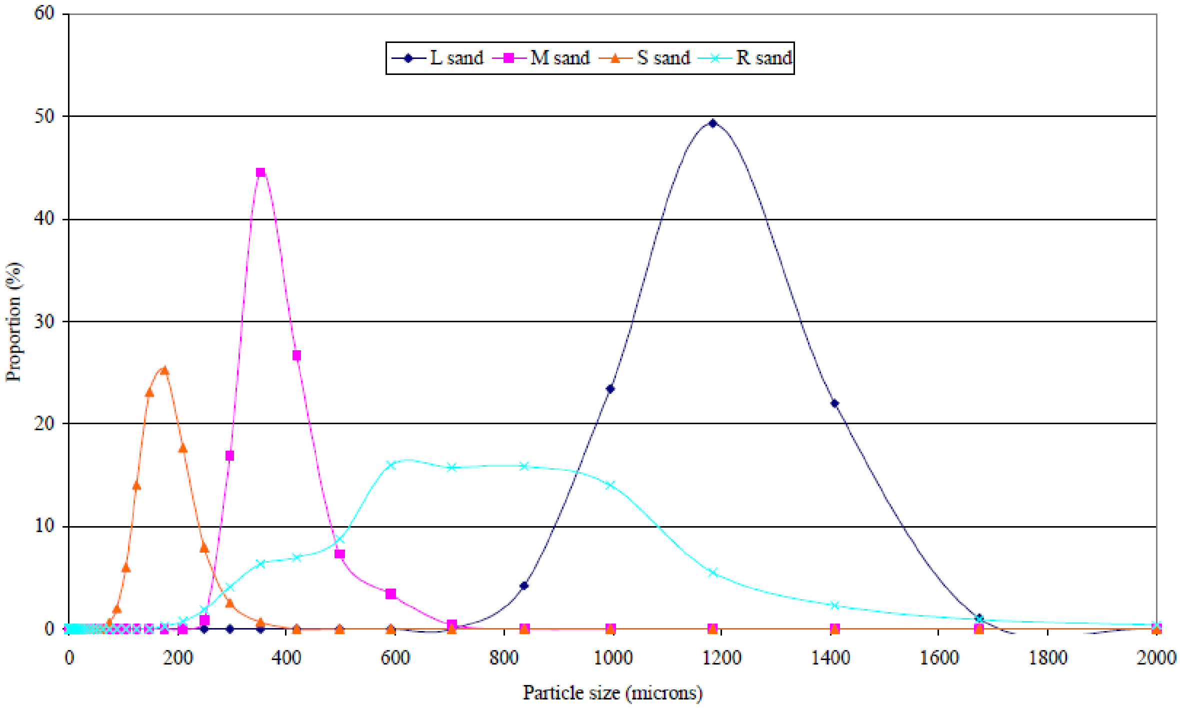


Figure 3. 6: particle size distribution of the tested sands obtained with the laser particle analyser

The sand was fed to the disc interface by means of gravity, as shown in Fig. 3.6. The sand passed through a PVC pipe and was oriented to the disc interface with a chute after exiting the valve. A vacuum cleaner placed behind the discs sucked the sand into the wheel and rail contact, which simulated the compresssed air system used in reality. In rder to regulate the sand feed rate, plastic syringes were used as valves. The orifice had to be modified to achieve the desired feed rate. The different particle size distribution of the four sand types required different orifice sizes because of their different bulk density. In this work, the sand feed rate used was around 7.35g/s, which equates to 7.5g/m taking the distance and rolling speed of the rail as reference. Sand feeding system is shown below in fig. 3.6.

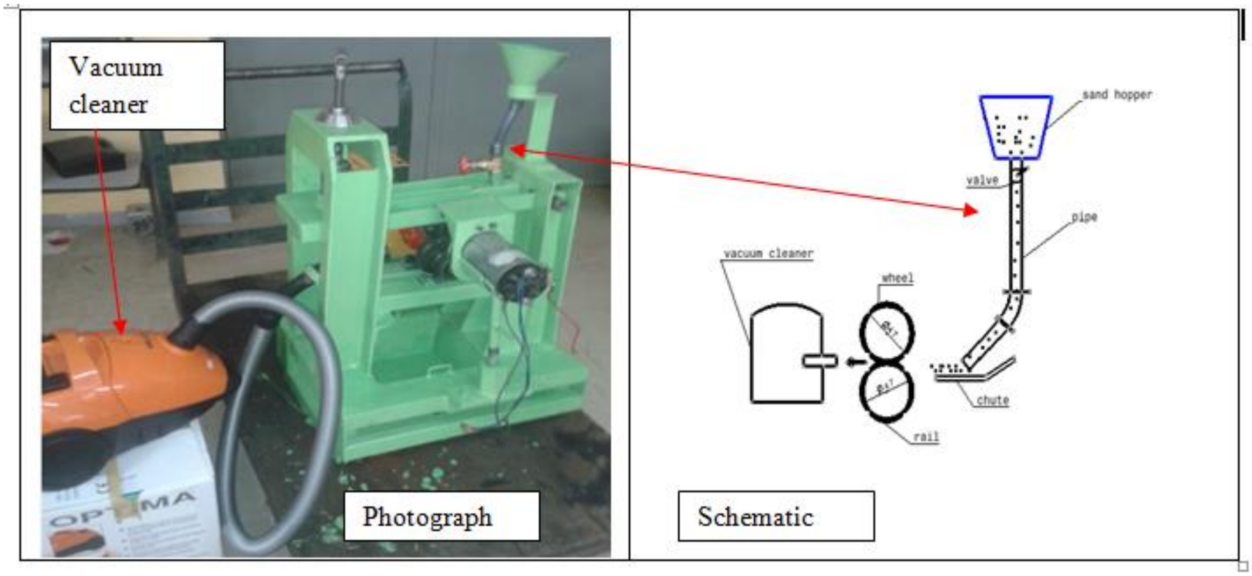


Figure 3. 7: application of sand in the tests: photograph and schematic representation respectively

## 3.5. Test Specimens and Their Materials (wheel and rail)

Around the world, there are various manufacturers of wheel and rail materials. Wheel and rail materials are quite similar in composition, differing slightly in the amounts of carbon, silica, and manganese in the steels used. It is widely known in tribology that pairs of similar metals can exhibit high adhesion and should generally be avoided in applications where they come into contact with each other, so changing one of these materials might reduce wheel and rail wear. [5]

The test discs cut and processed to the required size in HMMBI, METEC. These test specimens were taken from materilals which have similar properties with rail and wheel. Rail was cut from CSN 12071 materials and processed to the required size in workshop whereas the wheel material was cut and processed in workshop from CSN 12071 materials. They had a diameter of 100mm with a contact width of 10mm (see Figure 3.8). The materials composition was calibrated using spectro meter whereas their hardness was measured using hardness test machine. Using hard test machine the rail and wheel hardness range 30-35 HRC and 28-30 HRC, respectively. These materials were heat treated and brought to the stated hardness range. CSN 12071 has $\sigma_y$ = 450MPa and $\sigma_t$ = 750 – 900MPa whereas CSN 12051 has $\sigma_y$ = 460Mpa and $\sigma_t$ = 700 - 800MPa. Table 3.1 reveals the different materials composition of widely used rail (900A rail) and wheel (R7 wheel) and the one used for this thesis work. It is very close to that of rail steel and wheel steel. But as I observed from different literatures, there are international and national standards of rail steel and wheel standards. The international standards (UIC, EN, ISO, IEC) are known by their publicity and availability.

Table 1: The chemical compositions of the wheel and rail materials used

| Chemical composition [wt%] | C | Si | Mn | P | Ni | Cr |
|---|---|---|---|---|---|---|
| UIC60 900A rail | 0.6-0.8 | 0.15-0.5 | 0.8-1.3 | | | |
| R7 wheel | 0.52 | 0.4 | 0.8 | 0.035 | 0.3 | 0.3 |
| CSN12051 (Wheel) | 0.47-0.55 | 0.15-0.4 | 0.5-0.8 | 0.04 | 0.3 | 0.30 |
| CSN12071 (Rail) | 0.6-0.7 | Max 0.35 | 0.6-0.8 | | | |

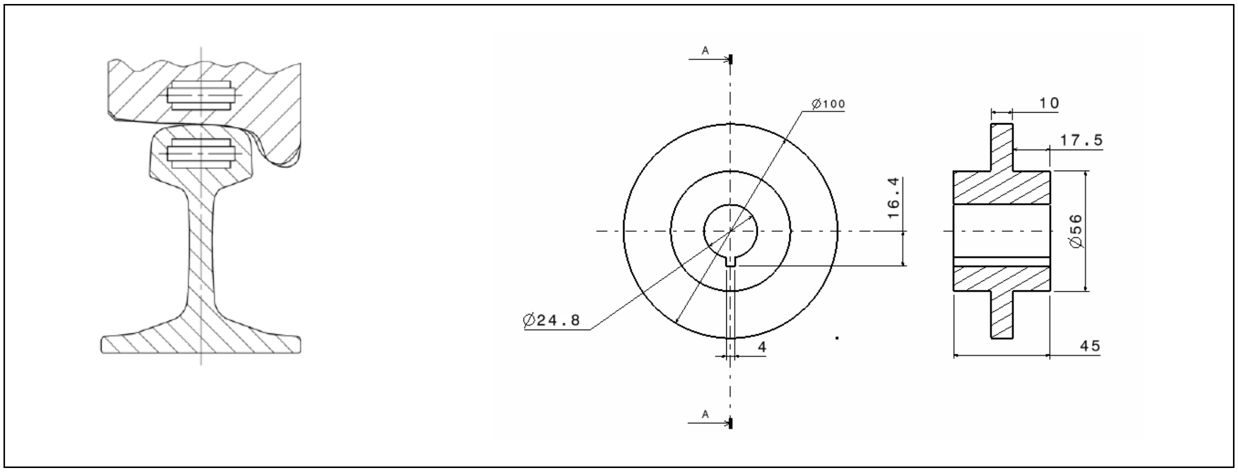


Figure 3. 8: Orientations and Dimensions of the Wheel and Rail Disks Specimens

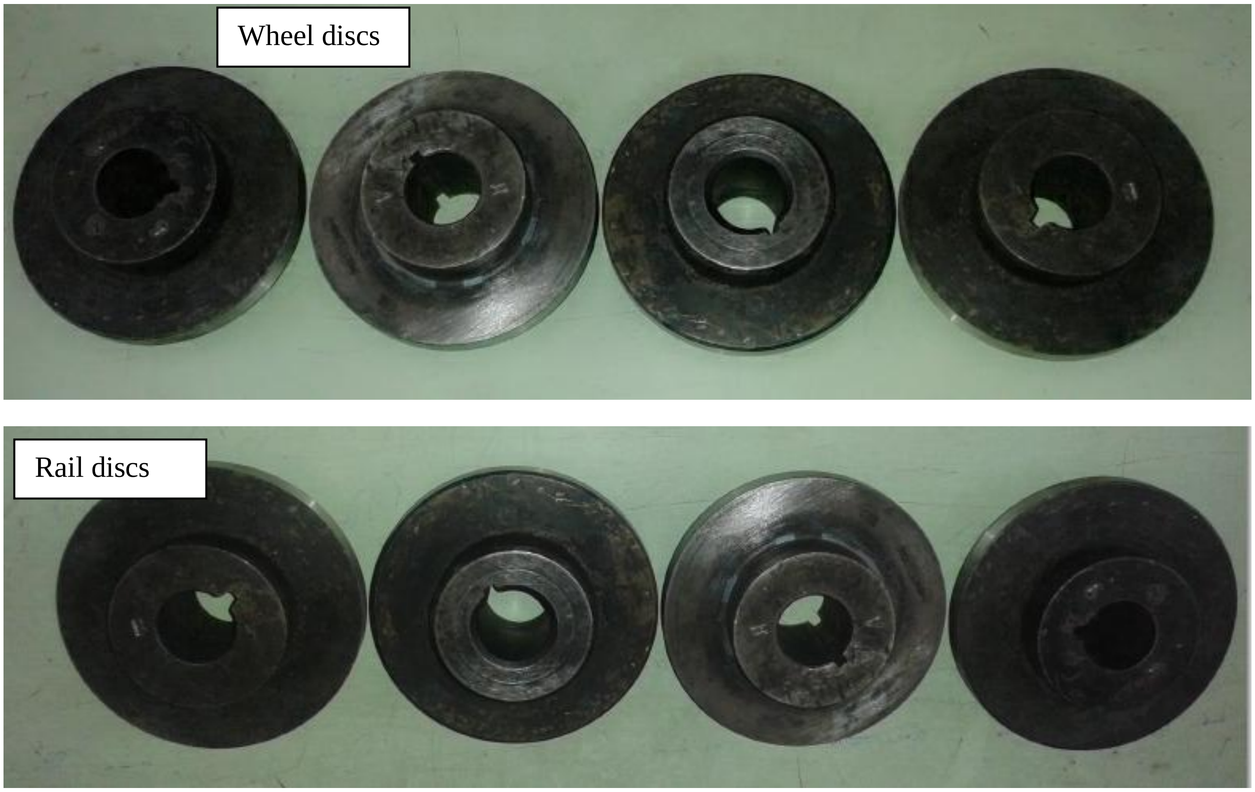


Figure 3. 9: Photograph of wheel and rail discs

### 3.5.1. Test Specimen Surface Roughness Conditions

All engineered surfaces are rough to some degree, even when the most advanced surface finishing techniques are used. In most machine elements, surface topography affects friction, wear, and longevity. Moreover, surface topography affects the size of the real contact area. As shown in Fig. 1.10, surface roughness reduces the nominal contact area to a number of small asperity contact areas ('contacting asperities') that must support the entire normal load. [5], [9], [15]

To investigate the adhesion and friction between wheels and rails, the surface roughness or surface topographies of wheels and rails need to be considered. Wheels and rails are finished by grinding and turning, respectively. Though the newly finished surfaces of wheels and rails must meet national standards, the initial surface topographies are usually run-in very quickly. Lundmark et al. [16] investigated the influence of traffic on both surface roughness and rail profile after grinding or re-turning of wheels by measuring their surface roughness on heavy-haul lines. They found that the $S_a$ (i.e., arithmetical mean height of the surface) value of the newly ground rail surface changed from ~10μm to ~1μm after the first 1.5 days of traffic. However, 2D roughness, $R_a$, is usually used for rails. The $R_a$ value of newly ground rail surfaces must not exceed 10μm, according to the Swedish National Traffic Administration. The 2D and 3D roughness parameters are discussed by Thomas [17]. Wheel and rail profiles are often measured in situ using the MINIPROF system [18], while surface topography can be measured using, for example, a stylus instrument or atomic force microscope. However, these techniques require the use of cut-out wheel/rail sections, making them unsuitable for field measurements. In addition, the replica technique is often used to "copy" real surfaces in the field to create negative images; surface replicas can then be measured using a stylus instrument [19] or an optical surface profiler [16].

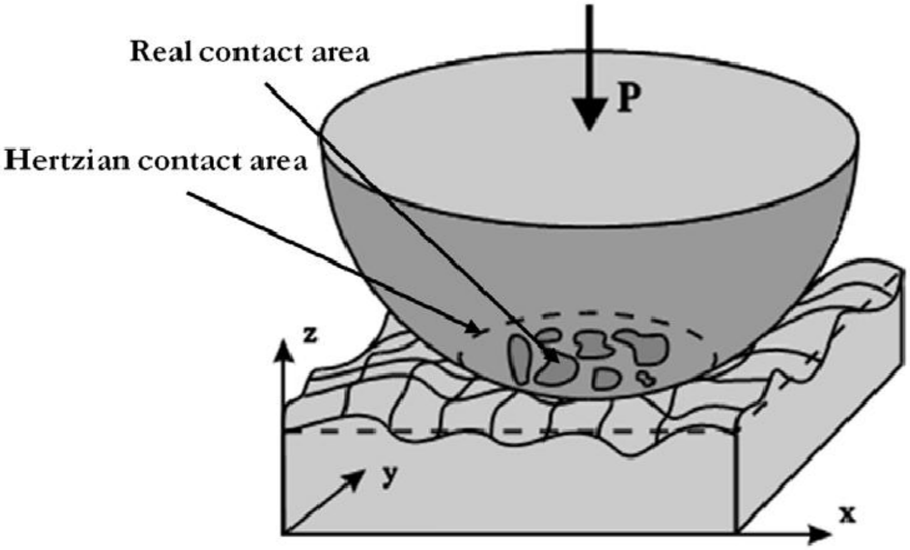


**Figure 3. 10: Schematic of a contact between a rough surface and a smooth sphere [15]. The nominal contact area is indicated by the hatched line; contact points form the real contact area within this.**

Surface roughness of both wheel and rail changes with time (i.e., with number of passing wheels) and with wear in general

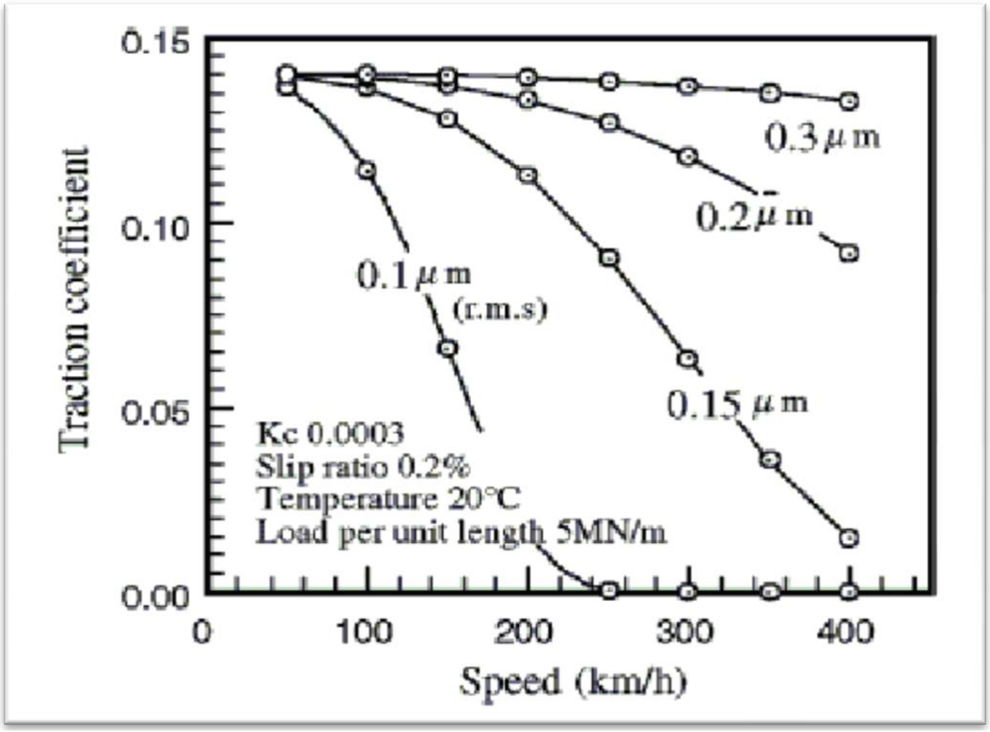


**Figure 3. 11: Effects of roughness on traction coefficient and rolling speed [20]**

The unused or low-roughness pair had $R_a$ values of 4.11 and 2.65μm for the wheel and rail, respectively; this roughness is typical of unused surfaces [16]. The sand-damaged or high-roughness pair had $R_a$ values of 12.45 and 20.38μm for the wheel and rail, respectively; this roughness is fairly high but still can be found in the field [21]. But the contact surfaces of disc specimens were ground to a roughness of 1 micron according to [13].

According to [13], the contact surfaces of wheel and rail discs were ground to a roughness of micron. Severe surface damage was seen in the discs after sand application. Post test Ra value of the wheel was 13.91μm and of rail was 5.51μm.

For this thesis work, four wheel discs and four rail discs was prepared for the whole test as shown on fig. 3.9 above. The surface roughness was measured using surface roughness tester in Metrology Laboratory SMIE, AAiT. The surface roughness was measured at four different sections of the discs to obtain a reasonable consistency; large scatter (i.e., the difference between the mean value and the maximum and minimum value) was obtained in the measurements due to the non-uniform presence of indentations on the surfaces. The below written one is the average value obtained from four measurements taken for each wheel and rail discs. But the surface topography of wheel and rail discs was not exactly the same from one wheel to another or from one to another due to operation conditions as shown below. The wheel and rail discs were labeled as W-A, W-B, W-C, W-D and R-A, R-B, R-C, R-D, respectively.

Table 2: Surface roughness values of wheel and rail discs before test

| **Surface roughness wheel and rail Before test** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Activity | Wheel-A | Wheel-B | Wheel-C | Wheel-D | Rail-A | Rail-B | Rail-C | Rail-D |
| 1. | 1.116 | 1.116 | 0.623 | 0.517 | 0.975 | 0.914 | 0.623 | 0.924 |
| 2. | 1.237 | 2.374 | 0.747 | 0.671 | 0.97 | 1.596 | 0.747 | 1.055 |
| 3. | 1.414 | 1.576 | 0.894 | 0.512 | 0.954 | 1.111 | 0.894 | 1.207 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 4. | 1.278 | 1.323 | 0.677 | 0.533 | 1.04 | 1.707 | 0.677 | 1.818 |
| **Av.** | **1.261** | **1.597** | **0.735** | **0.558** | **0.985** | **1.332** | **0.735** | **1.251** |
| **Max.** | **1.414** | **2.374** | **0.894** | **0.671** | **1.040** | **1.707** | **0.894** | **1.818** |
| **Min.** | **1.116** | **1.116** | **0.623** | **0.512** | **0.954** | **0.914** | **0.623** | **0.924** |

| Rail discs surface roughness, Ra (in micron) | | | | Wheel discs surface roughness, Ra (in micron) | | | |
|---|---|---|---|---|---|---|---|
| R-A | R-B | R-C | R-D | W-A | W-B | W-C | W-D |
| **1.261** | **1.597** | **0.735** | **0.558** | **0.985** | **1.332** | **1.393** | **1.251** |
| Rail discs mass (in grams) | | | | Wheel discs mass (in grams) | | | |
| **1109.2** | **1112.5** | **1108.8** | **1116.0** | **1100.3** | **1106.6** | **1080.4** | **1093.2** |

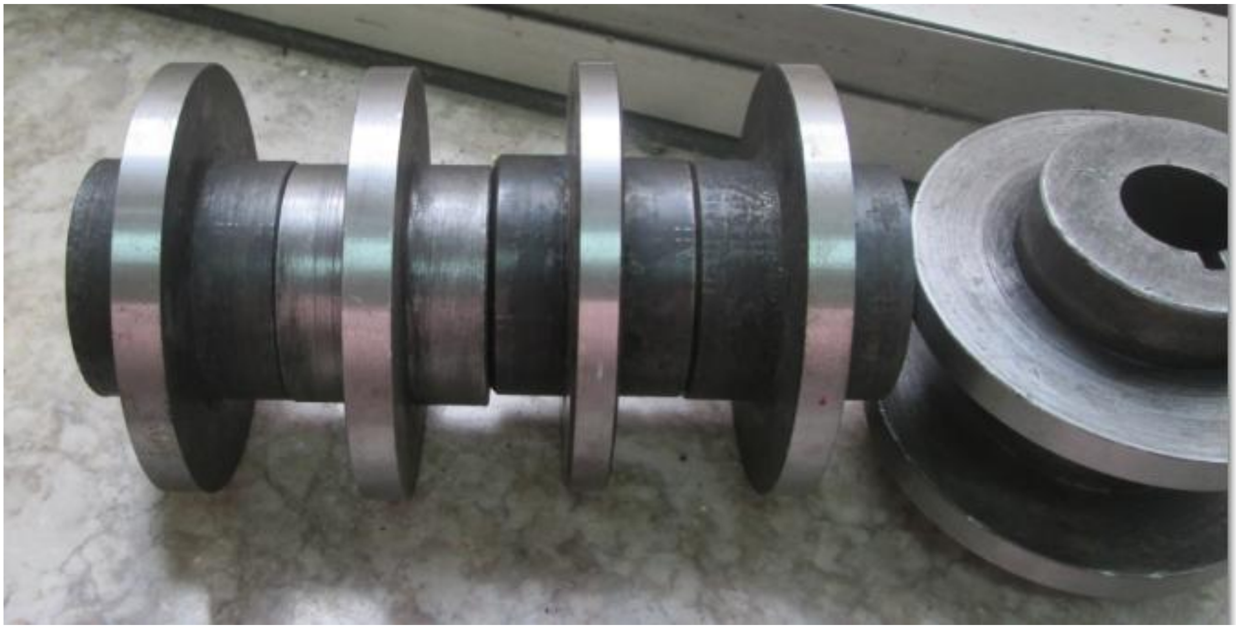


Figure 3. 12: photograph of wheel and rail contact surface before test

## 3.6. Test Procedures

In the tests, all size sands were fed to the discs interface by means of gravity as shown in figure 3.13 below. After exiting the valve, the sand passed through a PVC pipe and was oriented to the disks interface with a chute. A vacuum cleaner placed behind the disks sucked the sand into the wheel-rail contact, which simulated the compressed air system used in reality. One funnel helped the sand feed to the PVC pipe. In order to regulate the sand feed rate, valve was used.

The orifice had to be modified to achieve the desired feed rate. The different particle size distribution of the four sand types required different orifice sizes because of their different bulk density.

In each test, the discs were allowed to run in for 3000cycles. The tests were performed at different slips (0.25, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10) in which the sand was continuously fed to from the start of the test. These slips are representative values found during traction and braking operations in practice. An angular speed of the wheel disc preset 400 to 442rpm to create slip value. A baseline or dry test (i.e. without sand applied at the interface) was conducted besides the tests with four sands to assess the effectiveness of sands on adhesion improvement. Before and post running each test the rail and wheel discs were placed in a bath of ethanol with ultrasonic vibration. Mass measuring device with $\pm 0.1$ was used to measure the mass loss after each test. The surface roughness of the discs was measured with surface roughness tester.

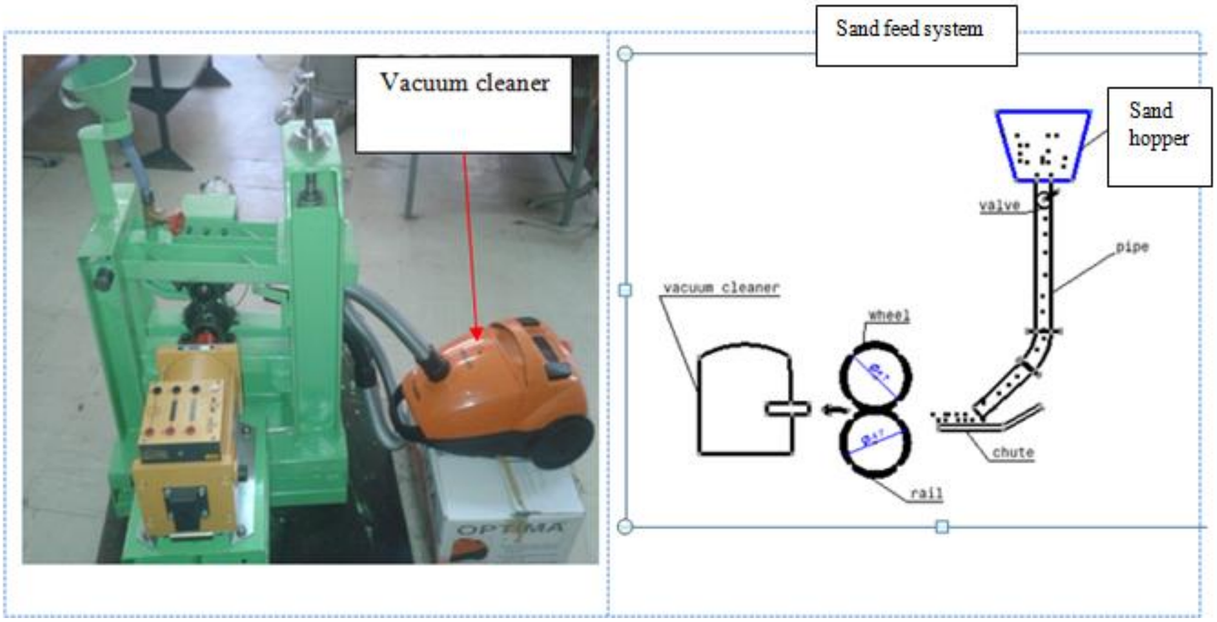


Figure 3. 13: sand application method in the test set-up: photograph (left) and schematic (right)

## 3.7. Test Conditions

The test disks will be mounted on independent shafts. By means of spring and threaded element a controlled load of a 400N was applied on the disks producing a maximum Hertzian pressure of 51kPa in the contact zone which is representative of the contact between wheel tread for passenger train. Since cylindrical disks are used in the experiments, a line contact of 10mm is present. In the tests, the wheel disk was adjusted to rotate faster than the rail disk to realize the slip; the rotational speed of the rail was maintained at 400rpm, equivalent to 0.98m/s of rolling speed.

# CHAPTER FOUR: RESULTS AND DISCUSSION

## 4. Results and Discussion

### 4.1. Results

During the test, each test was run for several cycles. The results of the test on adhesion, surface microscopy, surface topography and mass loss will be discussed in this chapter.

#### 4.1.1. Adhesion

The adhesion results after application of sand samples and dry test at different slips have been shown through figure 4.1 to 4.6. Moreover, a baseline for dry clean contact was given to compare the adhesion coefficient to those under clean steel-on-steel conditions. Comparing the dry baseline with the baseline it can be seen that the adhesion coefficient was increased in the presence of sand in between wheel and rail contact. This is good agreement with previous research carried out with roller rig but different test conditions. [10]

After initial cycles, the adhesion coefficient exhibited a steady pattern for the test with S-sand and M-sand, which was not observed in the tests with R-sand and L-sand, as it was revealed through figure 4.1 to 4.6. R-sand incorporated broad particle size distributions than any other sand particle size distributions, the load borne by the particles was not held constant as the particles travel through the disks contact interface. The largest particles bear the contact load first, and break up accordingly until sufficient numbers of particles withstand the contact load. During the test, when the last large size sand particles sucked to the disks interface, very loud sound was heard and quickly reduces the rotational speed of the disc with small increase in adhesion coefficient values. Fluctuations were observed in the adhesion coefficient results when the largest size hits the interface and torque increased with adhesion coefficient increment. The Coarse sand crushed and the resistance torque decrease in small value with increase in rotational speed. During this time, adhesion coefficient value also decreased in small value. The range of the particle size distributions of S, M and L sands was much narrower; so that all the particles that entered the contact can be roughly bear the same contact load. However, due to its large particle size L-sand experienced more break-up than smaller sand particle size and finer sand particle size has been observed after test below the contact interface in the garbage. Therefore, more oscillations in the adhesion coefficient occurred. Oscillations in adhesion coefficient caused by particle break-up in three-body abrasion test were also observed by other researchers.

The adhesion coefficient was not directly read from the test and calculated using equation E 3.2. The torque used to calculate the adhesion coefficient was calculated from the following equation.

$$\mathrm{T} = \frac{\epsilon_a \times I_a}{\omega_m} \qquad E\ 4.1$$

Where,

T-torque, $\epsilon_a$ - Armature voltage, $I_a$- Armature current, $\omega_m$-angular velocity,

$$\text{Here, } \omega_m = 2 \times \pi \times \frac{N}{60}$$

$$\mathrm{T} = \frac{\epsilon_\mathrm{a} \times \mathrm{I_a} \times 60}{2 \times \pi \times \mathrm{N}} = 9.554 \times \frac{\epsilon_\mathrm{a} \times \mathrm{I_a}}{\mathrm{N}} \qquad \text{E 4.2}$$

Where, N −rotational speed of shunt motor shaft coupled with wheel disc

These variables, armature voltage and armature current were directly read from voltmeter and ammeter during test per each activity, respectively. Rotational speed of shunt motor used to calculate angular velocity and of DC permanent magnet motor was also directly read from Speedometer or non contact tachometer which is sensor type.

The adhesion coefficient values obtained post test by S-sand and M-sand was very near to dry test value. The difference in adhesion coefficient among these test conditions were vey narrower. On other hand, the CoA values by L-sand oscillated or fluctuated throughout the test duration. The fluctuation in CoA was also seen with R-sand but it was not higher as it was seen with L-sand.

The adhesion coefficient was increased due to the application of sand and above the base line for all tested sand particle sizes and this result is good agreement with the previous research conducted. The properties of the (slip Vs adhesion coefficient) graphs supported the previous test result. [10] The percent increase of adhesion coefficient due to particle size at all tested slips shown in table 4.2 taking base line as reference.

Table 2: Adhesion increment due to sand particle sizes

| Slip | 0 | 0.25 | 0.5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S-sand (%) | 38 | 36 | 46 | 48 | 24 | 8 | 10 | 11 | 7 | 7 | 13 | 14 | 16 |
| M-sand (%) | 58 | 53 | 63 | 51 | 26 | 9 | 11 | 11 | 11 | 10 | 14 | 19 | 21 |
| R-sand (%) | 67 | 64 | 69 | 62 | 34 | 23 | 21 | 27 | 19 | 21 | 21 | 26 | 33 |
| L-sand (%) | 68 | 68 | 75 | 67 | 41 | 26 | 34 | 30 | 35 | 32 | 37 | 40 | 38 |

Table 3: Calculated values for all test activities of all sand sizes and dry test

| Test Act. | | Values of $T_{calculated}$ , $T_{constant}$, $\mu_{adhesion}$ per test for each slip | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Test 8 | Test 9 | Test 10 | Test11 | Test12 | Test13 |
| slip | | 0 | 0.25 | 0.5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Dry test | TCal. | 0.6 | 0.83 | 0.93 | 1.51 | 2.9 | 3.5 | 3.34 | 3.43 | 3.39 | 3.43 | 3.32 | 3.26 | 3.2 |
| | Tcons | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| | μa | 0.1 | 0.14 | 0.15 | 0.25 | 0.48 | 0.58 | 0.56 | 0.56 | 0.57 | 0.57 | 0.55 | 0.54 | 0.53 |
| S-Sand | TCal. | 0.96 | 1.35 | 1.65 | 2.87 | 3.77 | 3.77 | 3.74 | 3.77 | 3.66 | 3.67 | 3.81 | 3.81 | 3.79 |
| | Tcons | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| | μa | 0.16 | 0.22 | 0.28 | 0.48 | 0.63 | 0.63 | 0.62 | 0.63 | 0.61 | 0.61 | 0.63 | 0.63 | 0.63 |
| M-Sand | TCal. | 1.43 | 1.82 | 2.38 | 3.08 | 3.87 | 3.82 | 3.77 | 3.79 | 3.84 | 3.76 | 3.85 | 4.01 | 4.04 |
| | Tcons | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| | μa | 0.24 | 0.3 | 0.4 | 0.51 | 0.65 | 0.64 | 0.63 | 0.63 | 0.64 | 0.63 | 0.64 | 0.67 | 0.67 |
| R-Sand | TCal. | 1.83 | 2.31 | 2.94 | 3.87 | 4.39 | 4.49 | 4.26 | 4.59 | 4.18 | 4.29 | 4.18 | 4.41 | 4.73 |
| | Tcons | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| | μa | 0.3 | 0.39 | 0.49 | 0.65 | 0.73 | 0.75 | 0.71 | 0.77 | 0.7 | 0.72 | 0.7 | 0.73 | 0.79 |
| L-Sand | TCal. | 1.88 | 2.65 | 3.65 | 4.47 | 4.89 | 4.68 | 5.07 | 4.78 | 5.26 | 5.03 | 5.22 | 5.39 | 5.08 |
| | Tcons | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| | μa | 0.31 | 0.44 | 0.61 | 0.75 | 0.81 | 0.78 | 0.85 | 0.8 | 0.88 | 0.84 | 0.87 | 0.9 | 0.85 |

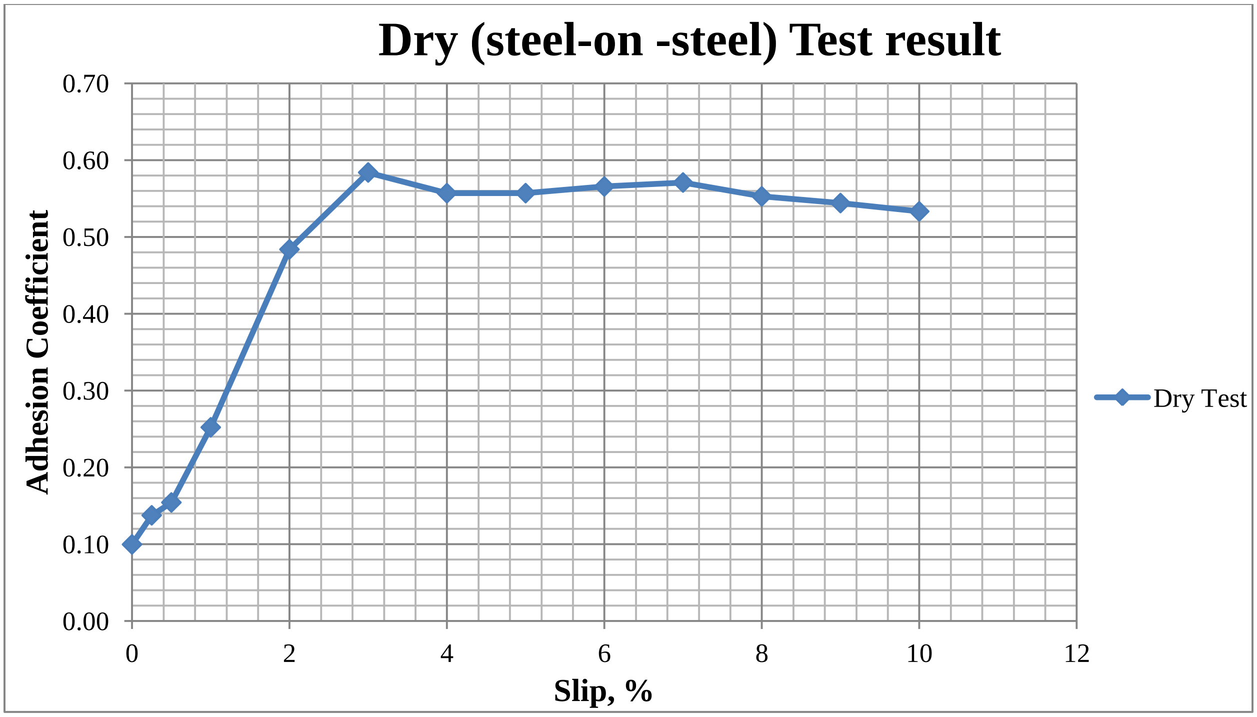


Figure 4. 1: Graph of slip Vs adhesion coefficient of dry test (steel disc-on-steel disc)

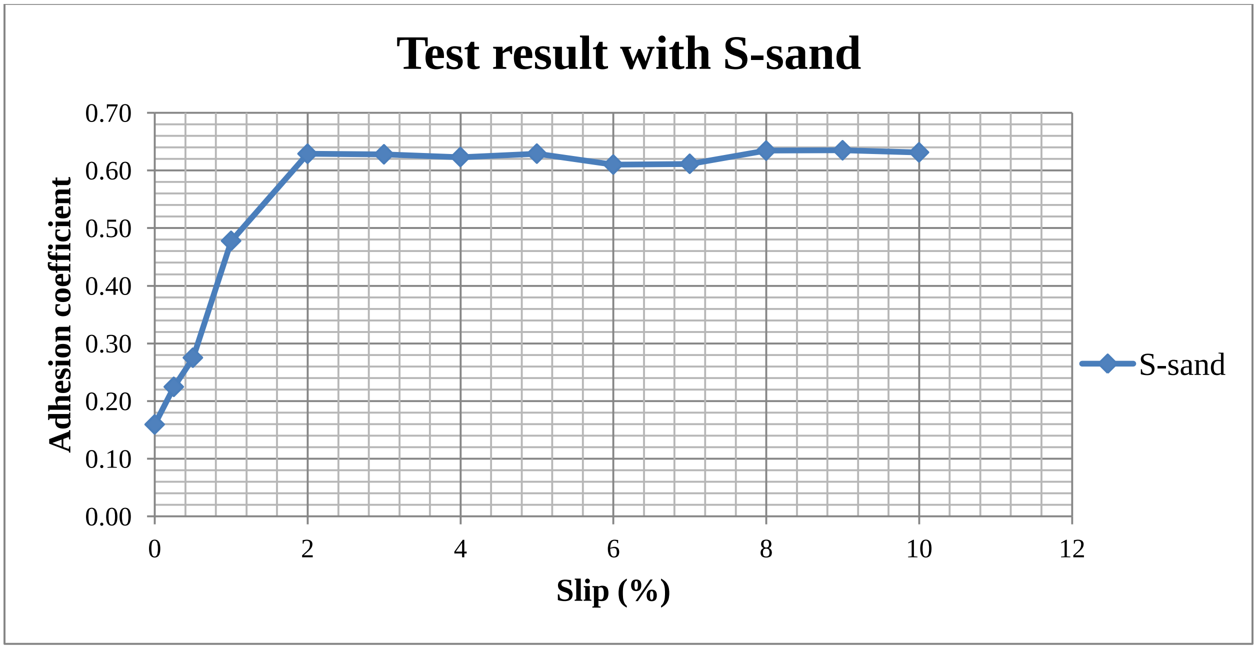


Figure 4. 2: Graph of slip Vs adhesion coefficient of tested result with S-sand

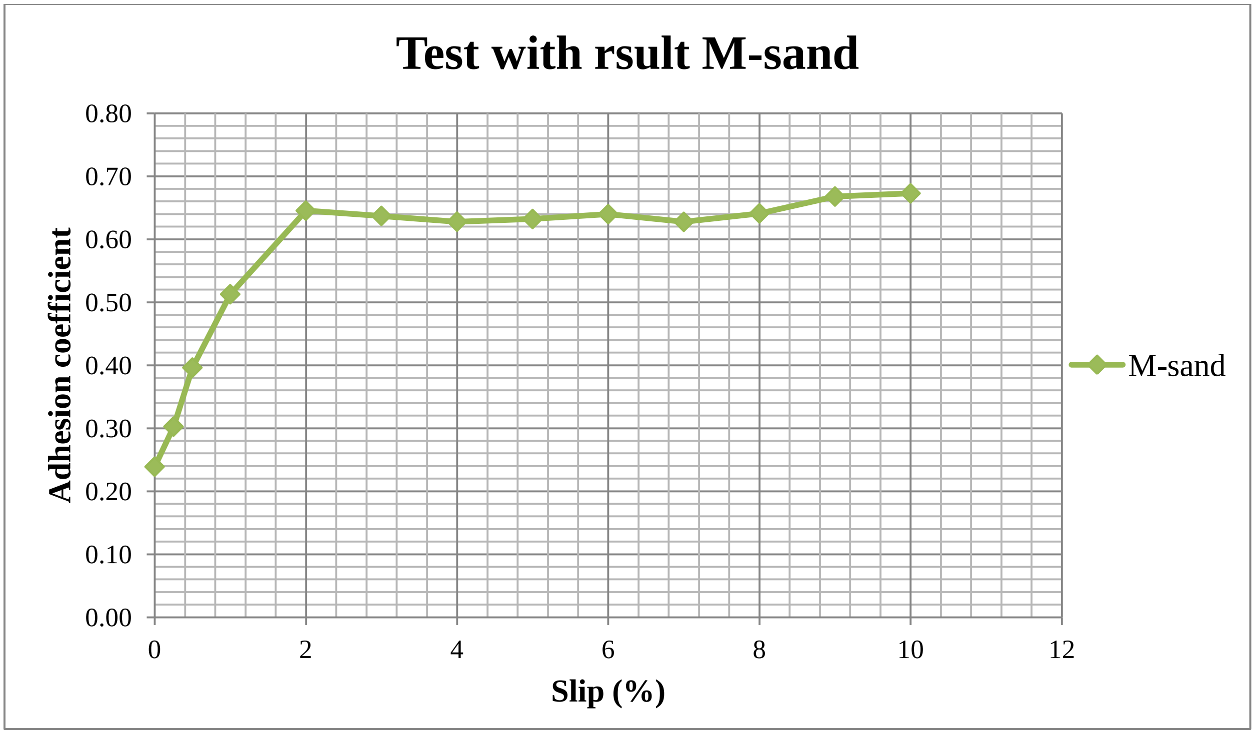


Figure 4. 3: Graph of slip Vs adhesion coefficient of tested result with M-sand

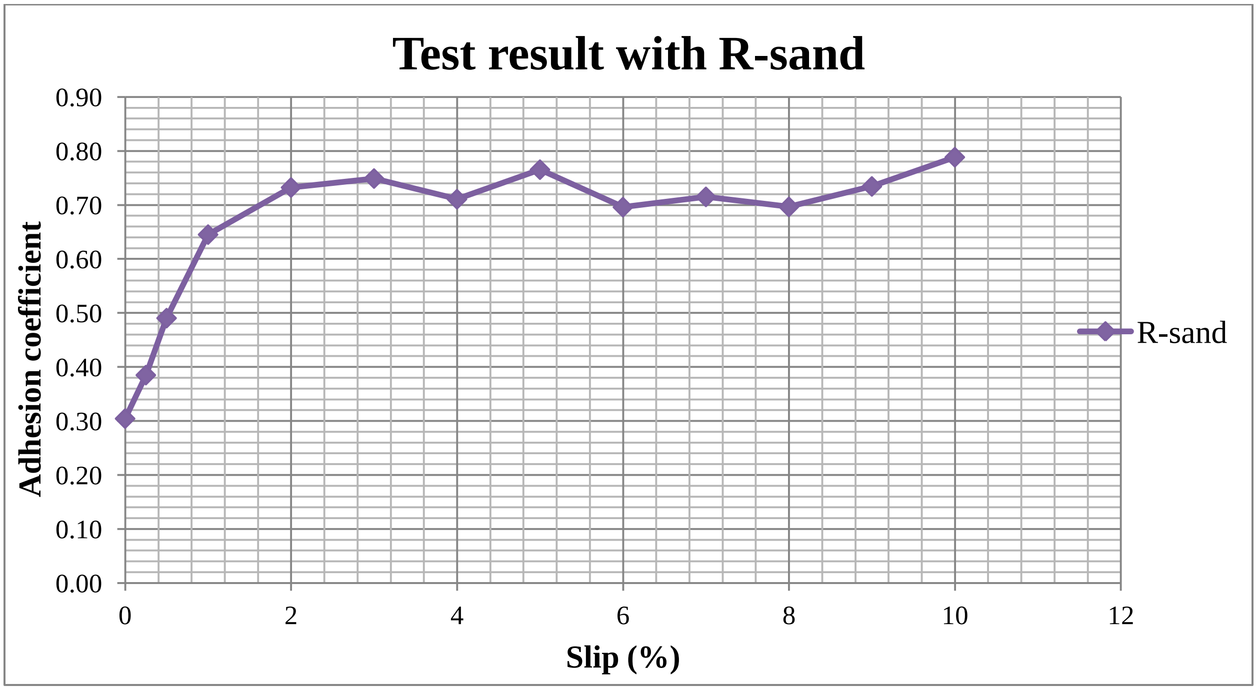


Figure 4. 4: Graph of slip Vs adhesion coefficient of Tested result with R-sand

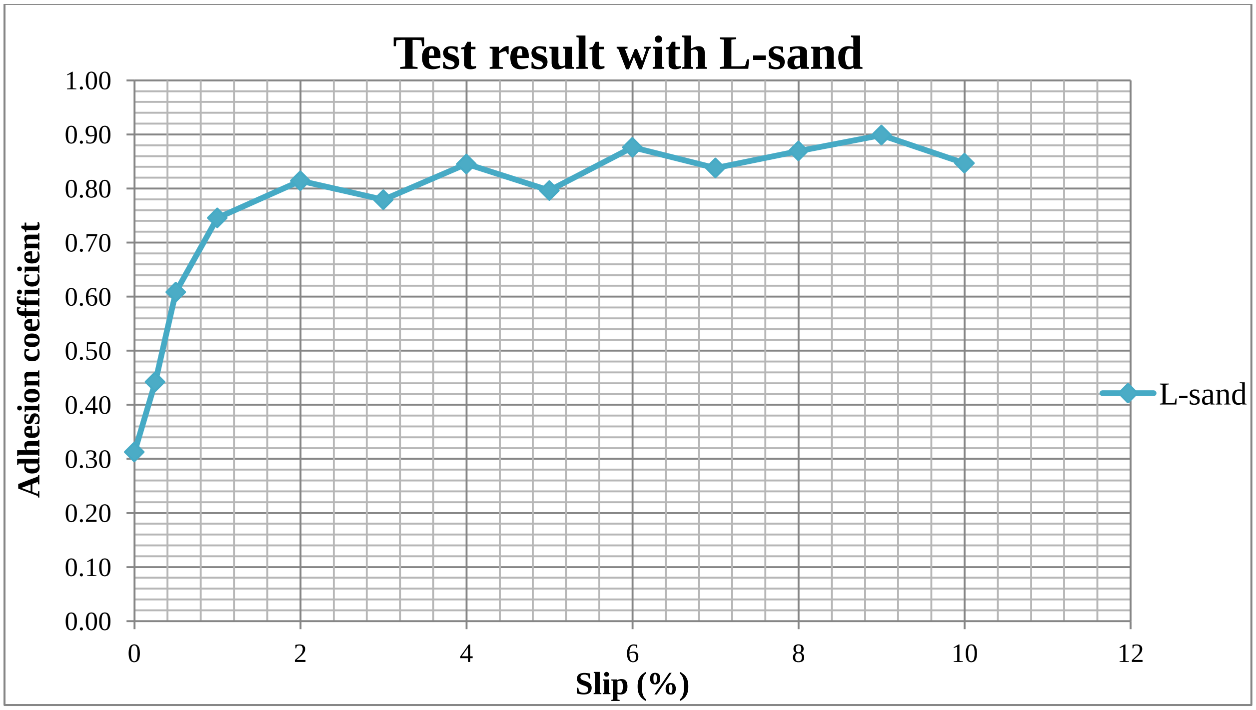


Figure 4. 5: Graph of slip Vs adhesion coefficient of tested result with L-sand

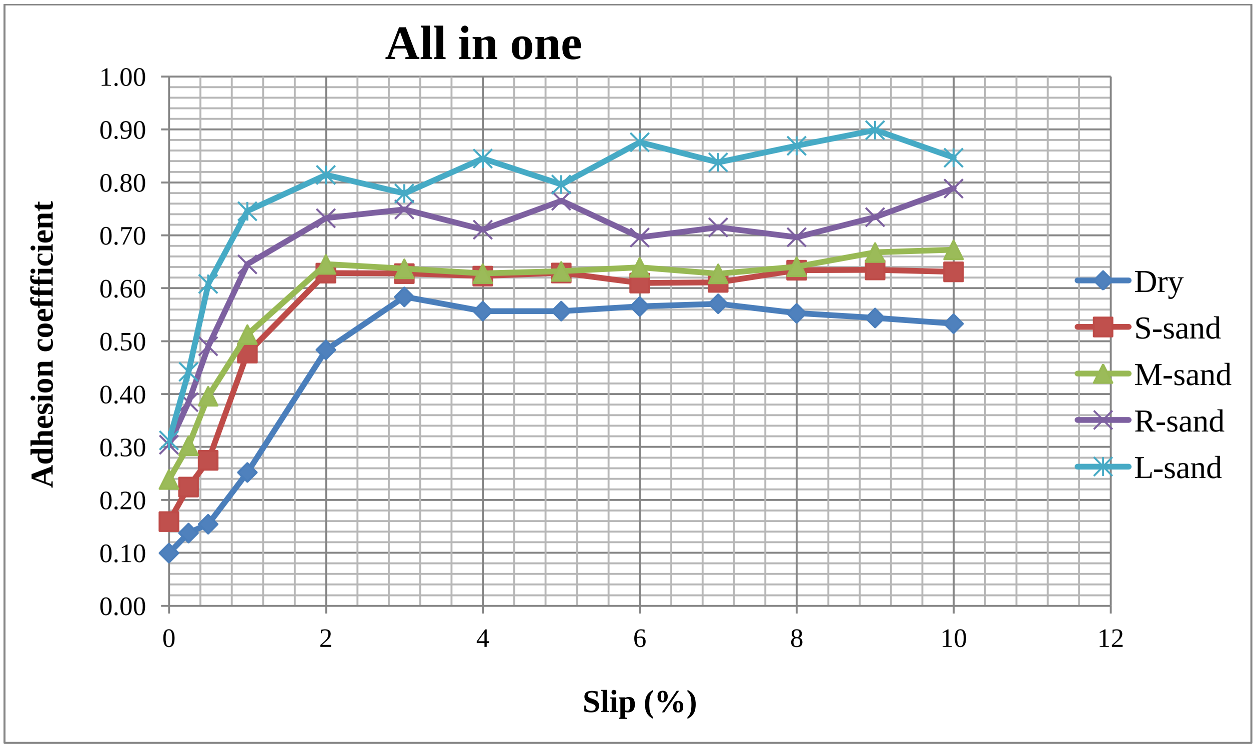
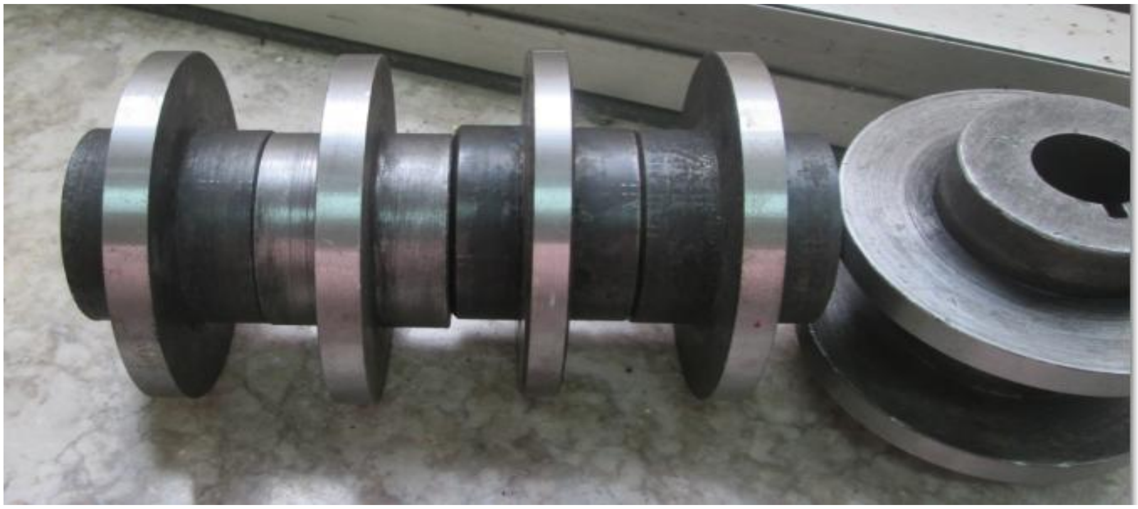


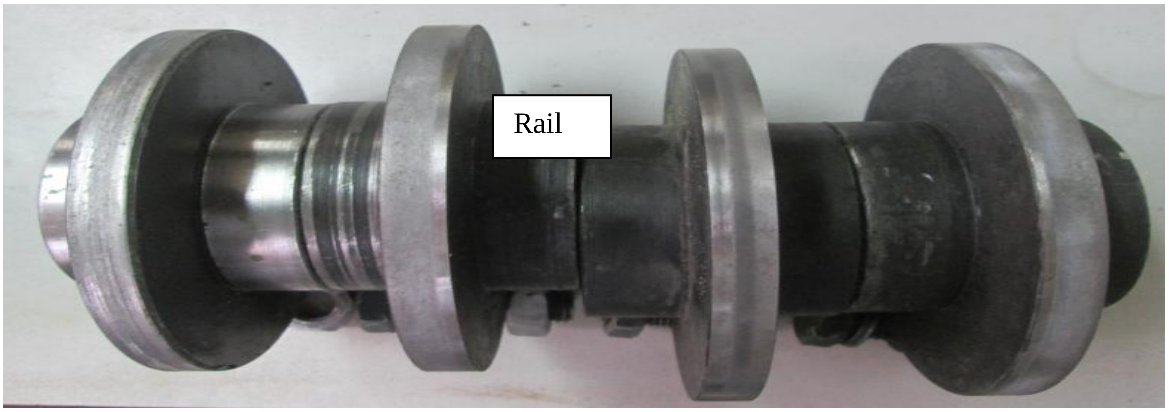
Figure 4. 6: Graph of slip Vs adhesion coefficient of all sands in one

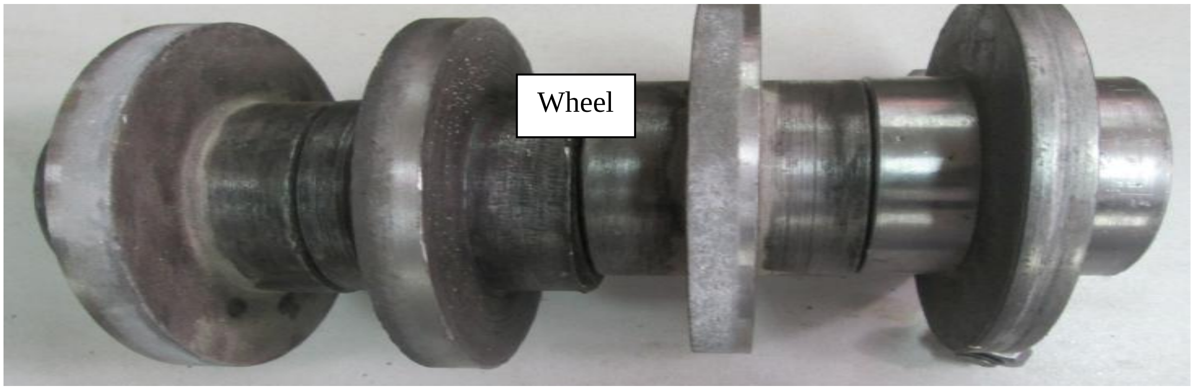
### 4.1.2. Surface Microscopy

After sand test completion, the surfaces of the discs were examined under an optical microscope. Before this activity, the sand particles indent and abraded in both disks was removed with ultrasonic vibration in a bath of ethanol. Then the examination was taking place and the surface morphology presented considerable differences before and after test. In addition, the surface morphology presented considerable differences corresponding to the slip applied and the sand used. During the sanding, it is obvious that crushed sand particles embed in the softer steel surfaces.



a) **Before test**





b) After test

Figure 4. 7: photograph of wheel and rail after and before test (a. before test and b. after test)

### 4.1.3. Surface roughness

The average roughness value of the disc surfaces before test was measured and described in chapter 3. All the disc surfaces revealed the increase in average roughness with respect to their initial surface roughness values for each discs post test. It can be seen that all the disc surfaces were roughened up during sanding. In general, the test results showed that the wheel presented a rougher surface than the rail for all tested sand particle sizes, which could be characterized to the differences in hardness as sand particles would be more likely to indent the softer wheel surfaces. Furthermore, there seemed to be a tendency of having rougher surfaces at higher slips for most of the sands. This can be characterized to the increased abrasive effect of sand particle with slip. The surface roughness was measured at four different sections of the discs by using surface roughness tester in Metrology Laboratory SMIE, AAiT to obtain a reasonable consistency; large scatter (i.e., the difference between the mean value and the maximum and minimum value) was obtained in the measurements due to the non-uniform presence of indentations on the surfaces.

In figure 4.8, 4.9, and 4.10, it can be understood that S-sand led to the least rough surfaces for wheel disc but for rail disc it was seen with M-sand. The least rough surface of wheel disc with S-sand could be characterized by small particle size. As it could be seen from the test result, the roughness value of the wheel discs increased with increase in sand particle sizes (Ra, µm values of wheel discs with S-sand, M-sand, R-sand and L-sand were 2.399, 4.607, 6.054 and 7.345, respectively). But for rail discs, high surface roughness value was seen with R-sand and least surface roughness value was seen with M-sand.

Table 4.4: Surface roughness values of discs post test for all sands

| **surface roughness of wheel and rail post test** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Test | Wheel-A | Wheel-B | Wheel-C | Wheel-D | | Rail-A | Rail-B | Rail-C | Rail-D |
| 1 | 5.545 | 6.425 | 8.527 | 7.969 | | 1.104 | 1.848 | 5.881 | 4.729 |
| 2 | 3.012 | 5.184 | 5.82 | 8.234 | | 1.15 | 1.68 | 5.52 | 4.92 |
| 3 | 3.6 | 7.537 | 6.304 | 6.529 | | 2.63 | 1.68 | 5.92 | 6.385 |
| 4 | 2.484 | 5.67 | 6.506 | 8.881 | | 2.345 | 1.5 | 5.328 | 12.19 |
| **Av.** | **3.660** | **6.204** | **6.789** | **7.903** | | **1.807** | **1.677** | **5.662** | **7.056** |
| **Max.** | **5.545** | **7.537** | **8.527** | **8.881** | | **2.630** | **1.848** | **5.920** | **12.190** |
| **Min.** | **2.484** | **5.184** | **5.820** | **6.529** | | **1.104** | **1.500** | **5.328** | **4.729** |
| **Surface roughness difference before and after test of average value of discs** | | | | | | | | | |
| **Diff.** | **2.399** | **4.607** | **6.054** | **7.345** | | **0.823** | **0.345** | **4.927** | **4.58** |

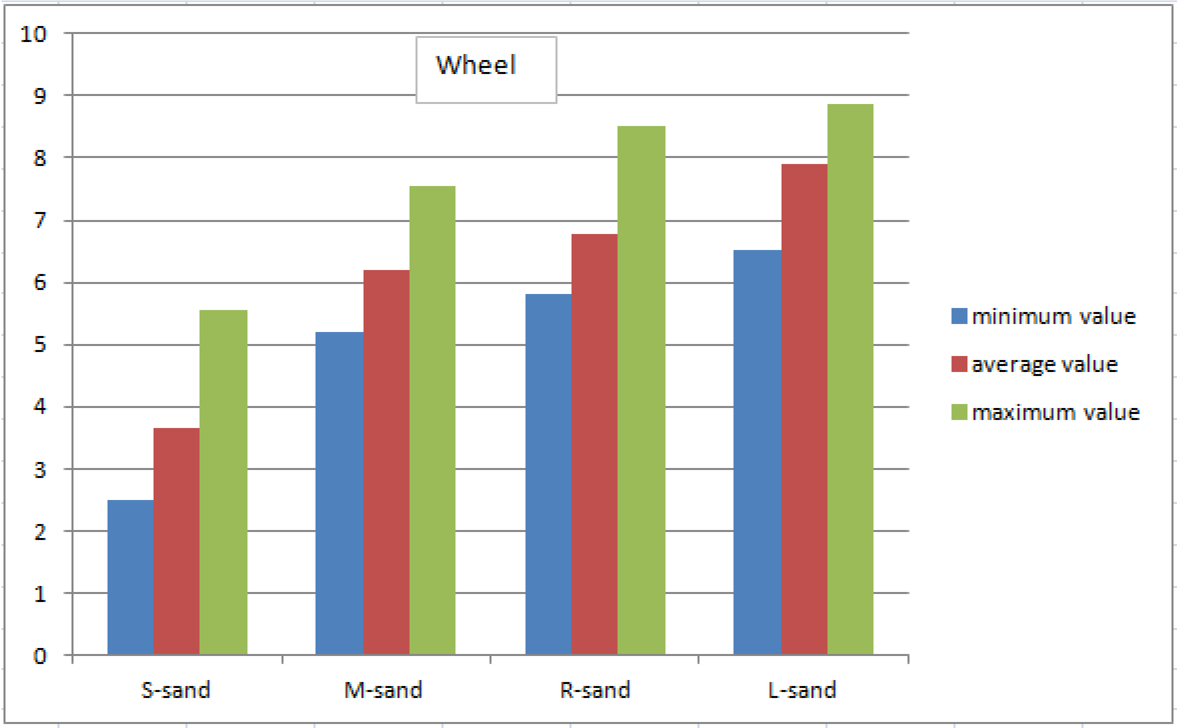


Figure 4. 8: Increase in surface roughness of wheel disc after full test with all sands

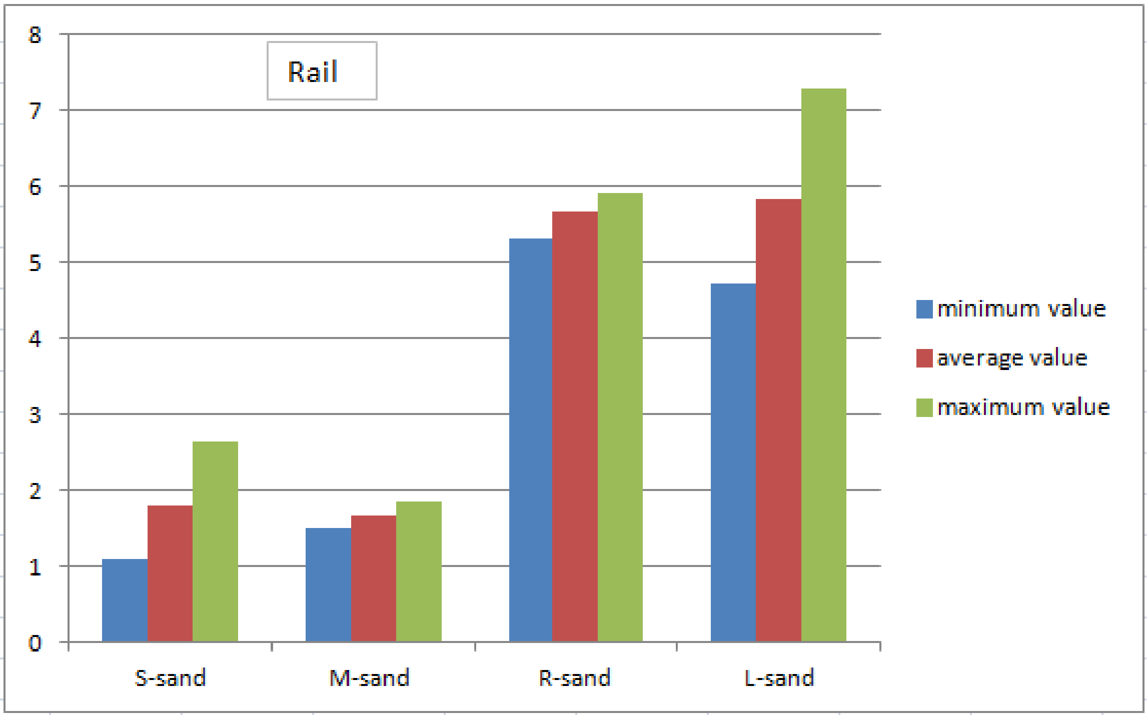


Figure 4. 9: Increase in surface roughness of rail disc after full test with all sands

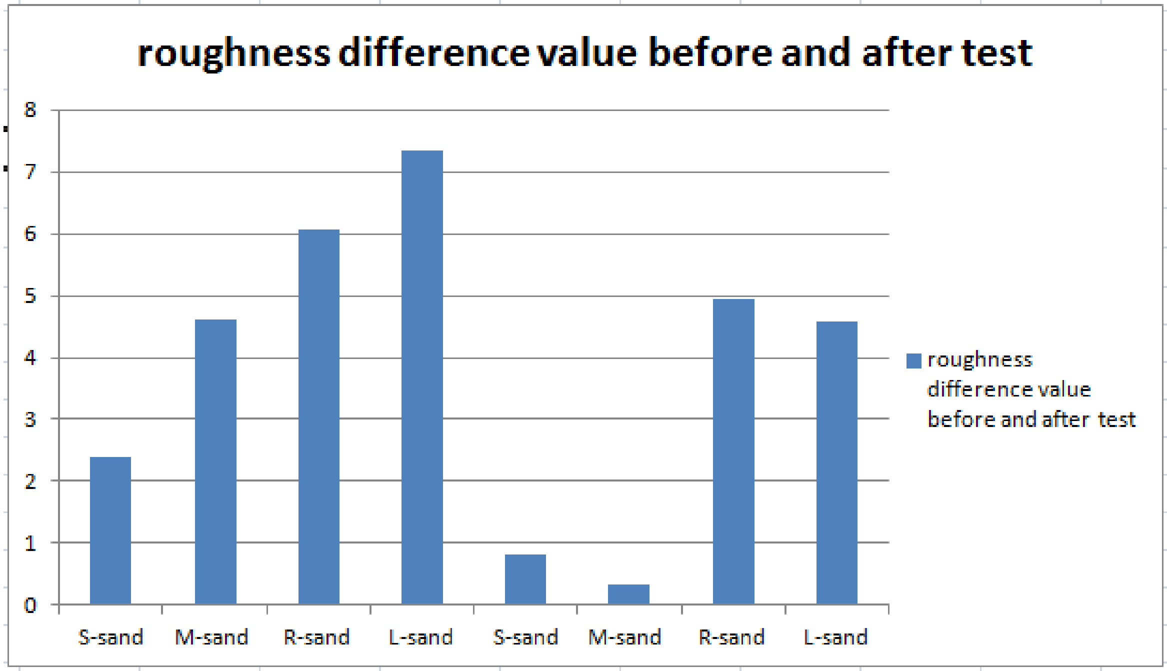


Figure 4. 10: Surface roughness difference before and after test for wheel and rail discs

### 4.1.4. Mass loss and wear mechanisms

The mass loss of the wheel and rail discs was measured to get an indication of the wear rates. But sand particles may indent and abraded deeper in the softer wheel disc. The results of the test have been depicted in figure 4.11. Comparing the test results, it was seen that the softer wheel disks wore more than the harder rail disks under all test conditions. This is good agreement with previous research carried out with roller rig [10]. The difference of the wear rates under all test conditions was not very large because the difference in hardness of the two disks (wheel discs and rail discs) is not large. Generally, the excessive wear was not resulted with all sand particle sizes tested and these sand particle sizes can be used as a FM depending on operation conditions of railway line. Because the adhesion coefficient property resulted due to the application of sand particle sizes with all slips was almost similar to the previous researches conducted. [10]

Moreover, higher wear rates of wheel and rail discs were experienced at higher slips for all sand particle sizes tested and mass loss increased with sand particle sizes. Higher mass loss was seen with L-sand for wheel discs but with R-sand for rail discs. The least mass loss was observed with S-sand for wheel discs but with S-sand no mass loss was observed for rail discs. This effect could be happed due to mass measurement in grams not in microns but mass loss practically happed for all tested sands. Also the mass balance device has only one digit precision (±0.1). Since wheel and rail discs are very hard steel materials, the wear rates and mass loss are very slow and could not be explained exaggeratedly in figures within the limited test conditions.

| **Rail discs mass (in grams)** | | | | **Wheel discs mass (in grams)** | | | |
|---|---|---|---|---|---|---|---|
| R-A | R-B | R-C | R-D | W-A | W-B | W-C | W-D |
| Before test for rail | | | | Before test for wheel | | | |
| 1100.3 | 1112.5 | 1108.8 | 1116.0 | 1109.2 | 1106.6 | 1080.4 | 1093.2 |
| After test for rail | | | | After test for wheel | | | |
| 1100.3 | 1109.7 | 1105.4 | 1112.0 | 1109.1 | 1102.7 | 1074.7 | 1088.3 |
| Difference in mass of rail after test | | | | Difference in mass of wheel after test | | | |
| 0 | 2.8 | 3.4 | 4.0 | 0.1 | 3.9 | 5.7 | 4.9 |

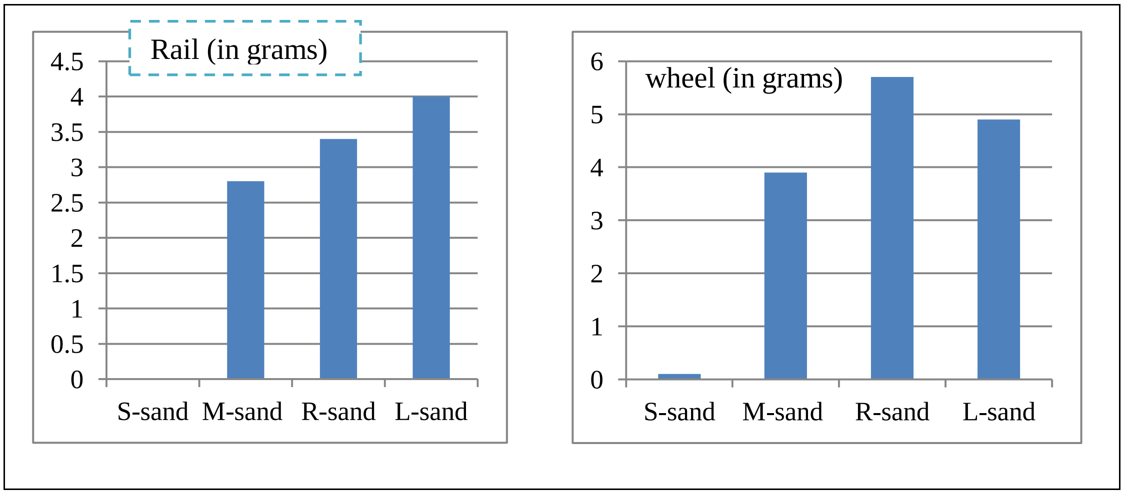


Figure 4. 11: Mass loss of rail and wheel disks with all sands after test

From the above results, the wear rate with S-sand, M-sand, R-sand and L-sand of wheel discs within the test conditions were 0.009%, 0.35%, 0.53% and 0.45%, respectively. For rail discs, the wear rate was 0%, 0.25%, 0.31% and 0.36% with -sand, M-sand, R-sand and L-sand, respectively.

## 4.2. Result Discussion

The twin disc test machine has been used to produce the proposed result. The results derived in all test conditions have been compared well with previous results of research works and actual track measurements. Dry test (steel-on-steel) carried out carefully to compare the effects of sand application and other contaminants with it. The CoA for dry test was increased gradually up to 3% slip and smoothly continues but light decrease at higher slips.

In all sanding systems, the adhesion coefficient values were higher than the CoA values of dry test and increase in CoA was enhanced with the increase in slip values.

For this particular tests, higher wear rates was obtained as the slip increased for all sand samples tested. Also higher wear rates was obtained as the sand particle size increased for the sand samples tested.

In this work, the same feed rate has been employed for all tested sand particle sizes in order to reproduce what happens in practice among railways using similar feed rates but different sized sand samples.

Laboratory investigations have shown that the sand particle size distributions can greatly influence the adhesion coefficient obtained during sanding. In future, investigations of the effects of different feed rate on damage to wheels and rails for a given sand practice sizes could be treated in a similar approach to the one presented in this work. Accordingly, the influence of sand feed rate on adhesion can be examined.

### The Limitations Observed during Test

Both wheel and rail discs are in complete rotational motion. All sand particle sizes allowed from pipe could not be sucked by vacuum clear to the contact surface and rest on the rail as it happens in practical.

The load applied to the contact point was limited by motor capacity and the actual effect of load and sand could not be observed.

The twin disc test machine is not equipped with controllers (shaft encoders and motor controllers). For this reason, personal computer could not be connected to the test machine and motor torque cannot be directly read.  Instead, torque was calculated from equation E 4.2.

# CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

## 5. Conclusions and Recommendations

### 5.1. Conclusion

The influence of sanding parameters (i.e., particle size distribution and slip) on the adhesion, wear rate and surface roughness from a laboratory investigation has been presented in chapter 4. The twin disc test machine has been used to simulate the wheel/rail contact in rolling-sliding conditions. Different slips (0.25, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10) have been considered in testing that are representative of actual braking and traction operations of railway network. Four different sizes of sand have been used to investigate the influence of the particle size with constant feed rate throughout the test. Depending on the test results obtained from the test conditions the following conclusions can be drawn.

- The adhesion coefficient was increased during the test for all tested sand particle sizes. But higher adhesion coefficient values were recorded at higher slips with larger sand particle sizes.
- The test results showed that the particle sizes and slips have a strong influence on wear and surface roughness. At higher sand particle sizes (R-sand and L-sand) and slips, large wear rate and higher surface roughness values was seen and observed.

### 5.2. Recommendation

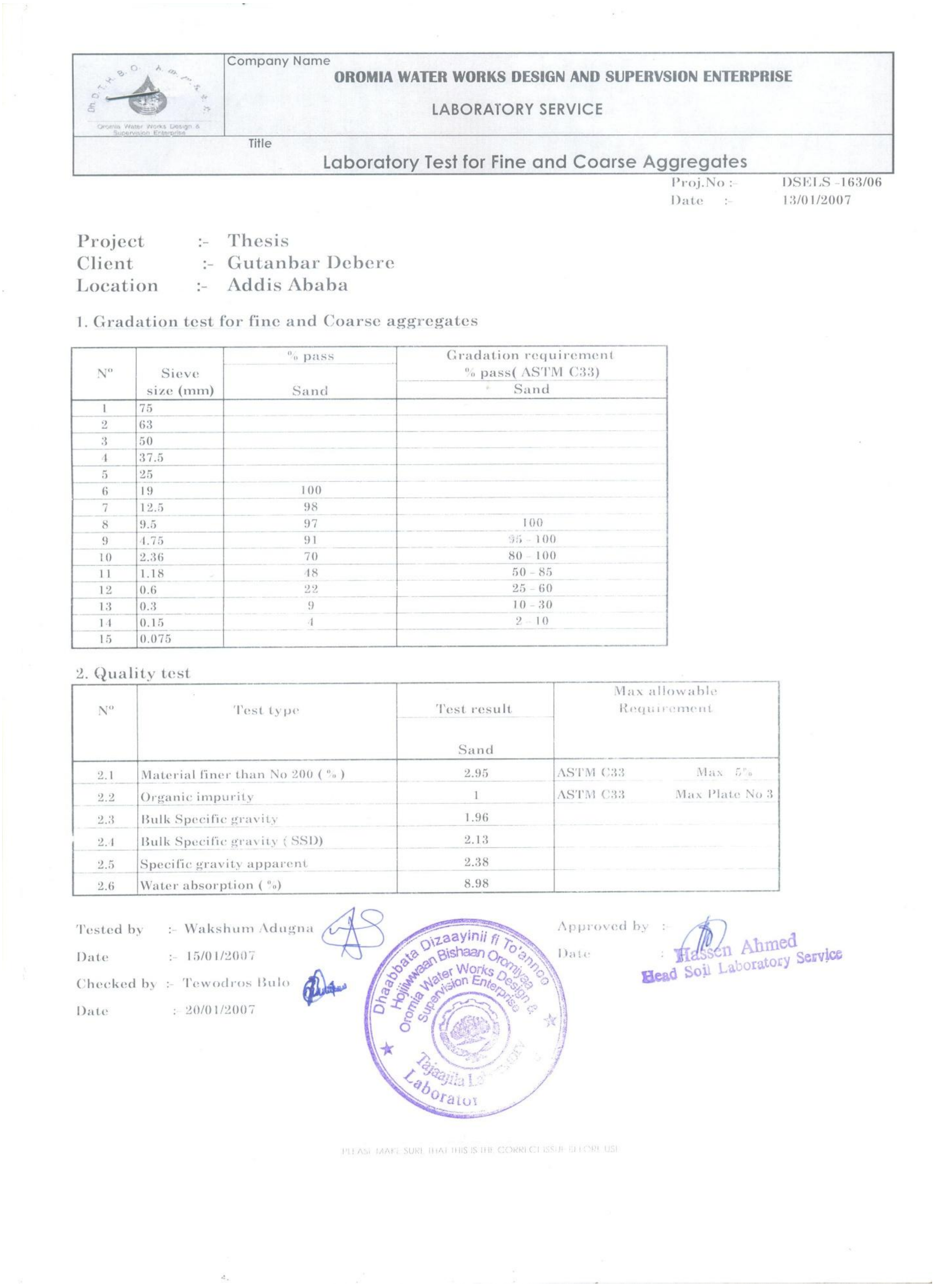
This research area is very crucial for Ethiopian railway network as it is a safety issue. The effects of friction modifiers (sand-based) in the wheel and rail contact haven’t been studied for the context of Ethiopia. Hence, this work is the first using materials found in Ethiopia and the results obtained from the investigation is almost similar with research results conducted in the past time by different researchers particularly in Europe. It is a clue to establish complete and equipped research center by ERC to conduct different researches on this and other areas. If ERC found this center, the choice of using own materials will increase and the import this materials will be likely minimized. For example, according to the operation and service department of ERC sand used for train will be supplied from China. The test results showed that ERC probably can use the sand found in Ethiopia instead of importing from abroad.

## 5.3. Future work

The investigations of effects of friction modifiers in wheel and rail contact can be conducted by considering different test conditions. Therefore, this thesis work has been carried out using the same feed rate for all sand particle size distributions (the same feed rates for all test activities). To suggest the future work on this area, first the twin disc test machine drawbacks stated in chapter 4 should be solved. Subsequently, further investigations of the effects of friction modifiers by taking into account the following test conditions can be conducted for the context of Ethiopia.

- Investigations of effects of sand-based friction modifiers using different sand feed rates for the four sand particle size distributions considered in this work
- Adhesion recovery of sand for leaf contaminated wheel and rail contact for the case of Ethiopia (after study of leaf which contaminates Ethiopian railway lines) using sand particle size considered for this study.
- Investigations of effects of friction modifiers other than sand.
- Investigations of effects of sand-based friction modifiers using different sand feed rates and same feed rates for the four sand particle size distributions considered in this work with silica sand
- The influence of sand particle size distributions on adhesion recovery in leaf contaminated contacts by means of field tests.

# ANNEX: Laboratory Test Results Of Sand Sample



| Company Name |
|---|
| **OROMIA WATER WORKS DESIGN AND SUPERVSION ENTERPRISE** |
| LABORATORY SERVICE |
| Title |
| Laboratory Test for Fine and Coarse Aggregates |

Proj.No :- DSELS -163/06
Date :- 13/01/2007

Project :- Thesis
Client :- Gutanbar Debere
Location :- Addis Ababa

1. Gradation test for fine and Coarse aggregates

| N° | Sieve size (mm) | % pass | Gradation requirement % pass( ASTM C33) |
|---|---|---|---|
| | | Sand | Sand |
| 1 | 75 | | |
| 2 | 63 | | |
| 3 | 50 | | |
| 4 | 37.5 | | |
| 5 | 25 | | |
| 6 | 19 | 100 | |
| 7 | 12.5 | 98 | |
| 8 | 9.5 | 97 | 100 |
| 9 | 4.75 | 91 | 95 - 100 |
| 10 | 2.36 | 70 | 80 - 100 |
| 11 | 1.18 | 48 | 50 - 85 |
| 12 | 0.6 | 22 | 25 - 60 |
| 13 | 0.3 | 9 | 10 - 30 |
| 14 | 0.15 | 4 | 2 - 10 |
| 15 | 0.075 | | |

2. Quality test

| N° | Test type | Test result | Max allowable Requirement | |
|---|---|---|---|---|
| | | Sand | | |
| 2.1 | Material finer than No 200 ( % ) | 2.95 | ASTM C33 | Max 5% |
| 2.2 | Organic impurity | 1 | ASTM C33 | Max Plate No 3 |
| 2.3 | Bulk Specific gravity | 1.96 | | |
| 2.4 | Bulk Specific gravity ( SSD) | 2.13 | | |
| 2.5 | Specific gravity apparent | 2.38 | | |
| 2.6 | Water absorption ( %) | 8.98 | | |

Tested by :- Wakshum Adugna
Date :- 15/01/2007
Checked by :- Tewodros Bulo
Date :- 20/01/2007

Approved by :-
Date :

Hassen Ahmed
Head Soil Laboratory Service

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# REFERENCES

1. José A. Lozano, Jesús Félez, Juan de Dios Sanz and José M. Mera, Railway Traction, Universidad Politécnica de Madrid Spain, 2012
2. Website, History of Rail Transport. Wikipedia, the Free Encyclopedia. http://en.wikipedia.org/wiki/History of rail transport, Accessed Date, 20-03-2014.
3. Prof. Tekn. Dr. Elias Kassa, Rail-Vehicle System Dynamics Lecture Note, Addis Ababa Institute of Technology, November-December 2012
4. Website, Rail Transport in Ethiopia. Wikipedia, the Free Encyclopedia. http://en.wikipedia.org/wiki/Rail transport in Ethiopia, Accessed Date, 23-02-2014
5. Jon Sundh, On wear transitions in the wheel-rail contact, KTH Industrial Engineering and Management, 2009
6. U Olofsson, Wheel-rail Interface Standard Handbook edited by R. Lewis
7. Ulf Olofsson and Roger Lewis, Handbook of Railway Vehicles Dynamics
8. Ulf Olofsson, Yi Zhu, Saeed Abbasi, Roger Lewis, Stephen Lewis, Tribology of the wheel-rail contact – aspects of wear, particle emission and adhesion, Department of Machine Design KTH Stockholm Sweden, (Department of Mechanical Engineering, Sheffield University, UK), 2013
9. Yi Zhu, Adhesion in the wheel–rail contact under contaminated conditions, 2011
10. Oscar Arias-Cuevas, low adhesion in the wheel-rail contact, Delft University of Technology, 2010
11. O. Arias-Cuevas, Z. Li, R. Lewis, Investigating the Lubricity and Electrical Insulation Caused by Sanding in Dry Wheel–Rail Contacts, ORIGINAL PAPER 2009.
12. Oscar Arias-Cuevas, ‘Zili Li’, Roger Lewis, A laboratory investigation on the Influence of particle size and slip during sanding on the adhesion and wear in the wheel-rail contact, international conference, 2009
13. E.A. Gallardo-Hernandez, R. Lewis, Twin disc assessment of wheel/rail adhesion. Wear 265 (2008).

14. O. Arias-Cuevas, Z. Li, R. Lewis and E.A. Gallardo-Hernández, Rolling-Sliding Laboratory Tests of Friction Modifiers in Dry and Wet Wheel-Rail Contacts, Wear, 268 (3-4), 2010
15. Yi Zhu, adhesion in the wheel-rail contact, KTH Industrial Engineering and Management, 2013
16. J. Lundmark, E. Höglund, B. Prakash, Running-in behaviour of rail and wheel contacting surfaces, Proceedings of the International Conference on Tribology, 20-22 Sep. 2006
17. T.R. Thomas, Rough surfaces, 2nd edition, Imperial college press, 1999.
18. C. Esveld, L. Gronskov, MINIPROF wheel and rail profile measurement, in: Proceedings of 2nd Miniconference on Contact Mechanics and Wear of Rail/Wheel Systems, Budapest, Hungary, 1996.
19. U. Olofsson, T. Telliskivi, Wear, plastic deformation and friction of two rail steels—a full-scale test and a laboratory study, Wear. 254 (2003) 80–93.
20. G. Vasic, F.J. Franklin and A. Kapoor, New Rail Materials and Coatings , University of Sheffield, 2003
21. P. Dings, M. Dittrich, Roughness on Dutch railway wheels and rails, Journal of Sound and Vibration. 193 (1996) 103–112.
22. Z. Li. O. Arias-Cuevas, R. Lewis, E. A. Gallardo-Hernandez, Rolling-Sliding Laboratory Test of Friction Modifiers in Leaf Contaminated Wheel-Rail Contacts, Tribo Letter, 2009.
23. Oscar Arias-Cuevas, Low adhesion in the wheel-rail contact, 2010
24. F.P. Bownden and D. Tabor, The Friction and Lubrication of Solids. Clarendon Press, Oxford (1956)
25. N.P. Suh and H.C. Sin, The Genesis of Friction, Wear 69 (1981) .
26. ASM Hanbook, Volume 18, Friction, Lubrication and Wear Technology, ASM International (1992)
27. S. Kumar, K. Krishnamoorthy, D.L. Prasanna Rao, Wheel-Rail Wear and Adhesion with and without Sand for a North American Locomotive, journal of Engineering for Industry 108 (1986).

28. W. Zhang, J. Chen, X. Wu, X. Jin, Wheel/rail adhesion and analysis by using full scale roller rig, Wear 253 (2002).

29. U. Olofsson, K. Sundvall, Influence of Leaf, Humidty and Applied Lubrication on Friction in the Wheel-Ralil Contact: Pin-on-Disc Experiments, Juornal of Rail and Rapid Transit 218 (2004).

30. Rail Safety and Standards Board, Evergreen House, 160 Euston Road, London NW1 2DX, 2008

31. Katrin Mädler, Manfred Bannasch, Materials Used for Wheels on Rolling Stock, Deutsche Bahn AG, Technical Center, Brandenburg-Kirchmöser, Germany