

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**AFRICAN RAILWAY CENTER OF EXCELLENCE**



**ASSESSMENT AND EVALUATION OF BALLAST  
FOULING AND ITS EFFECT ON DRAINAGE  
PERFORMANCE OF BALLAST; A CASE STUDY ON  
ADDIS-DJIBOUTI LINE**

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**A Thesis in Railway Engineering Civil infrastructure stream**

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A Thesis

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The undersigned have examined the thesis entitled ‘**Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of Ballast; A Case Study on Addis-Djibouti Line**’ presented by **Haimanot Gashaw**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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## **UNDERTAKING**

I certify that research work with title “Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of Ballast; A Case Study on Addis-Djibouti Line” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Haimanot Gashaw

## ABSTRACT

Railway ballast serves as a major structural and drainage component of railroad track, but during service the ballast layer is subjected to both deformation and degradation due to traffic load. The gradual degradation and deterioration of ballast layer increases the number of finer particles within the track which has an effect on track drainage capacity. The aim of this study is to evaluate the degree of ballast fouling using Void Contamination Index (VCI) on some selected sites of Diredawa, Adigala and Dewanle track sections of Addis-Djibouti railway line. Laboratory tests including specific gravity, gradation, crushing value and Los Angeles Abrasion have been conducted on selected sites. Analytical approach has been used to predict the hydraulic conductivity of fouled ballast. For investigating the influence of degree of fouling on overall hydraulic conductivity of fouled ballast, two dimensional flow has been simulated using a finite element software, SEEP/W.

According to VCI values, an average of 30%, 54% and 43% of voids of ballast layer has been filled with fine materials in Diredawa, Adigala and Dewanle track sections respectively. The track drainage capacity in Diredawa is under acceptable drainage category while in Adigala and Dewanie poor drainage category. The results of this study revealed that track maintenance should involve shoulder cleaning of fouled ballast before VCI reaches 35%.

**Key words: VCI, Ballast fouling, Hydraulic conductivity, SEEP/W**

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## NUMENCLATURES

VCI	Void Contamination Index
$e_b$	Void ratio of clean ballast
$e_f$	Void ratio of fouling material
$G_{sb}$	Specific gravity of fouling material
$G_{sf}$	Specific gravity of fouling material
$M_b$	Mass of clean ballast
$M_f$	Mass of fouling material
LAA	Los Angeles Abrasion
LL	Liquid Limit
PL	Plastic Limit
PI	Plastic Index
FI	Fouling Index
AREA	American Railway Engineering Association
ASTM	American Society for Testing and Materials



## **CHAPTER 1 INTRODUCTION**

### **1.1 General**

Currently there are two types of rail tracks commonly used; conventional ballasted track and slab track. Most rail track are the traditional ballasted track which are widely used throughout the world. In this conventional type of track, rails are supported on sleepers which are embedded on a compacted ballast layer up to 350 mm thick [1]. Ballast is the selected crushed granular material placed at the top layer of the substructure in which the sleepers are embedded. It usually contains uniformly graded, hard, strong and high strength unweather material creating a sufficiently large pore structure to facilitate rapid and free drainage [2].

Railway ballast serves as a major structural and drainage component of railroad track, but is known to degrade over time. This progressive degradation increases the amount of finer particles within the ballast over time, called ballast fouling, which decreases its drainage capacity and strength. Railroads commonly remove the fouling material using ballast shoulder cleaners and under cutters, however, these are expensive operations that require large machines and trained personnel. If the track is allowed to degrade for too long, significant track geometry, drainage, stability and settlement problems can arise, creating potentially very costly derailments [3]. Settlement of the rail embankment can lead to issues such as the deterioration of track geometry, speed restrictions on passing trains, uncomfortable riding conditions due to differential settlement, and even possible derailments. Due to ballast fouling problems, maintenance issues always raised commonly in ballasted track. Maintenance of ballasted railway track is a tedious, challenging and costly routine task in which major portion of it spent on geotechnical problems. However, ballast is the best material from both a cost perspective and the relative ease to maintain the material and the resulting track geometry [4].

Ethiopia is now expanding railway transportation system as one mode of transport system which has a great role in reducing other transportation system's crowdedness problem especially inside the capital city Addis Ababa like AALRT and others lines which are now under construction. Among the new lines the line having about 760 km length which has

opened a year before is Addis-Djibouti line. This line is a new standard gauge international railway that serves as the backbone of the new Ethiopian national railway. It provides landlocked Ethiopia with access to the sea, linking Ethiopia's capital of Addis Ababa with Djibouti. The total railway capacity is about 25 million tons of freight annually. Due to aging effect and repetitive heavy load per annum, gradual deterioration and deformation of the ballast layer will be expected on the line.

Railway track ballast fouling is an ongoing issue without a clear understanding of either cause for generation or the source of the fouling materials. This study investigated the source of ballast fouling in selected sites of Addis-Djibouti line and quantified the degree of fouling using a parameter called Void Contamination Index (VCI) by field investigation method. Using finite element software called SEEP/W, seepage analysis for fouled ballast with different values of hydraulic conductivity has been simulated to determine track drainage capacity.

## **1.2 Statement of the Problem**

Ballast, which is the main sub structural part of the ballasted track, designed to support the superstructure, to distribute the imposed load, to provide lateral resistance and to allow free drainage. Though, it is a backbone of ballasted track, deterioration and fouling of ballast is now burning issue which is caused by heavy repeated traffic loading during its life time. As ballast aged and degraded, it is progressively fouled with fine particles which then accumulate and filling void spaces thus impending drainage. The process of fouling when becomes extreme can generate excess pore water pressure under high cyclic loading and then it malfunctions even after using different maintenance techniques. In such situation the contaminated ballast must be cleaned or replaced with fresh ballast which is a costly and time-consuming exercise. Therefore, since the effect of fouling on hydraulic conductivity depends on the nature of fouling materials, proper understanding of the nature of fouling materials is essential irrespective of the quantity of fouling. Understanding the mechanism of fouling for ballasted railway track is an important component for designing cheaper and more durable global track systems.

### **1.3 Objective of the Study**

#### **1.3.1 General Objective**

The main aim of this study is to evaluate the degree of ballast fouling using the parameter called Void Contamination Index (VCI) and to show its effect on drainage capacity at selected sites of Addis-Djibouti line.

#### **1.3.2 Specific Objectives**

- To determine the degree of fouling by using the parameter called Void Contamination Index (VCI)
- To estimate the hydraulic conductivity (k) values for fouled ballast using analytical approach
- To carry out seepage analysis using finite element software SEEP/W in order to capture the drainage capacity
- To do track drainage classification according to models considered

### **1.4 Research Questions**

This study will answer the following questions;

- What are the parameters considered to determine the degree of fouling using VCI?
- How can one estimate hydraulic conductivity for ballast layers having different VCI values?
- How can one account actual track geometry model when carry out seepage analysis using SEEP/W?
- Which criteria is used in order to do track drainage classification?

### **1.5 Significance of the Study**

Many developing countries including Ethiopia is now expanding railroad industry to reduce different transportation problems. The issue raised in this study is not only Ethiopian's but also a concern throughout the world. The importance of this study is multi-

dimensional in different perspectives for Ethiopian railway industry especially for Addis-Djibouti line. The essence of understanding current condition of fouling in the line is important to come up with the appropriate period of maintenance. Therefore, the outcome of this study helps to know the current condition of some sections in the line regarding degree of fouling and its implication on track drainage capacity. Stakeholder then give a great emphasis on sections which are in danger regarding ballast fouling at that line. It gives an initial overview for the coming researchers who are interested on quantification of ballast fouling. For the new railway line plans, as an initial input this research gives about degree of ballast fouling determination and its respective measurements in order to account in their plan.

## **1.6 Methodology**

In this study, to evaluate the degree of ballast fouling Void Contamination Index (VCI) has been used in order to account types of ballast and fouling material. To achieve this laboratory tests including gradation, specific gravity, Los Angeles Abrasion and Crushing Value have been conducted. Field investigation is also done to determine the mass of ballast and fouling material of ballast layer.

To determine the equivalent hydraulic conductivity of ballast that is contaminated with non-uniformly distributed fouled material, a layer by layer simplification method considered. An analytical model based on corresponding VCI values, assuming only the vertical flow, has been used. This approach is in a good agreement with experimental values of hydraulic conductivity.

The track drainage capacity is determined using the ratio of drainage capacity of ballast to the critical flow per unit length of the track. To determine the drainage capacity a finite element software, SEEP/W has been used while maximum rainfall for critical flow.

## **1.7 Scope and Limitation of the Study**

### **1.7.1 Scope**

The scope of this investigation is dependent on quantifying ballast fouling using Void Contamination Index (VCI). Hydraulic conductivity (k) values have also determined

according to VCI values. Moreover, track drainage classification has been done using the software output and critical flow per unit length of the track on that area.

### **1.7.2 Limitation of the Study**

This study is mainly limited to one parameter for ballast fouling quantification. It does not consider other indices to determine the degree of fouling. For this purpose, ballast samples were collected and then laboratory tests have been conducted. The tests are limited on ballast gradation, Los Angeles abrasion, Crushing Value and Atterberg tests for the fouling material. Tests considering rock types were not conducted in this study.

## **1.8 Thesis Structure**

In this study five Chapters are presented. Chapter one presented general introduction part about railway ballast and ballast fouling considering Ethiopian context. What problem raised this issue as title of research has been presented by statement of the problem. Objective of the study, scope and limitation of the study and significance of the study has also presented in this chapter.

Chapter two devoted to literature review about previous studies of ballast. A review about historical back ground of railway track, ballast functions, tests of ballast and forces exerted on ballast are presented. The idea of ballast fouling with a description of possible modes and effects reviewed.

The third Chapter discusses about the site's track location and land use patterns of the line. The methods used to evaluate degree of fouling are briefly described and the materials and procedures used to attain this is presented. Material model, assumptions and simulations are also presented in this chapter.

Chapter four briefly outlines the results of both laboratory tests and field investigations of the study. The discussion assesses fouling prevalence in relation to; sample depth and sample location. The results and their implications with respect to behavior of fouling material within the ballast layer are also presented.

Chapter five presents the study conclusions and summarizes the findings from this research program. Recommendations are also drawn regarding more optimal drainage methods for the line.

## **CHAPTER 2      LITERATURE REVIEW**

### **2.1 Historical Background**

The rail as supporting and guiding element was first utilized in the sixteenth century. The invention of the steam engine led to the first steam locomotive, constructed in 1804 by the Englishman Trevithick. While the railways found themselves in a monopoly position up to the twentieth-century. With the advent of the combustion engine and the jet engine they had to face strong competition in the form of buses, cars and airplanes. Railways can be advantageous as they are characterized by the following [5];

- Reliability and safety
- High degree of automation and management
- Moderate environmental impact

Moreover, railways have a comfort level comparable with automobiles and have the possibility of attaining high speeds which can compete with planes on the middle range distance [5].

#### **2.1.1 Ethiopian Railway History**

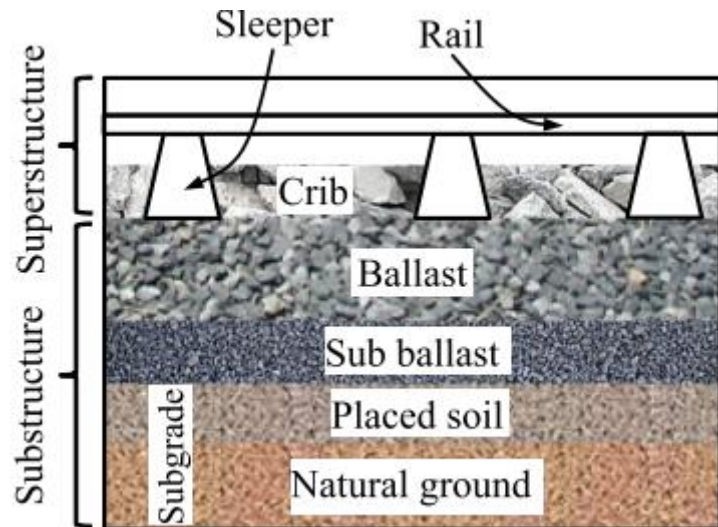
The first train service in Ethiopia began on July 22, 1901, and operated between Djibouti and Dewanle, which was worked by diesel with a total length of 781 Km and was owned by jointly with the government of Djibouti [6].

The old track is not functioning now and have already deteriorated. Therefore, modern and reliable railway system is needed to sustain the economic growth momentum of the country by supporting the demand of freight and passenger mobility [7].

The Ethiopian National Railway that runs to east from Ethiopia to Djibouti forms a vital connection and transport corridor for each of the nation's economy. Currently there are also some additional railway projects which are now under construction in different cities of the country such as; Weldiya-Elidar, Awash-Weldya and Weldya-Mekelle projects [7]. The Ethio-Djibouti railway line is the interest for this study because of the high load per annum. It is the only mixed traffic line operating for both passenger and freight and no researches have been done before concerning ballast fouling on this line. Therefore, ballast fouling problem is raised as an issue for this study.

## **2.2 Ballast Layer**

Ballast is a critical element in the railway track support structure. Desirable ballast material is strong, hard, and durable crushed rock (aggregate) that does not readily deteriorate from applied loading, vibration, or environmental conditions or variations. This stone materials will form a layer below and around the sides of the tie that provides direct vertical support and lateral stability [8]. Figure 2-1 shows typical ballasted railway track section;



**Figure 2-1 Schematic diagram of ballasted railway track [9]**

Ballast may be subdivided into the following four zones [2] stated,

- **Crib:** material between the sleepers
- **Shoulder:** material beyond the sleepers ends down to the bottom of the ballast layer
- **Top ballast:** Upper portion of supporting ballast layer which is disturbed by tamping.
- **Bottom ballast:** lower portion of supporting ballast layer which is not disturbed by tamping and which generally is the more fouled portion.

### **2.2.1 Forces on Ballast**

In order to properly assess the performance and quality of ballast, the loading environment in which ballast operates is an important component to consider. Track forces can only be estimated because the load is complex, depending on train characteristics, operating

conditions (speed, weight), and environmental/track conditions. If any of the previous factors are altered or modified, the estimation of the changed track forces is necessary even if precise measurement of the loading forces is impractical. The three forces that affect the rail track system act in the vertical, lateral, and longitudinal planes. The primary loading forces are generally caused by passing trains, change of temperature, and squeezing forces from maintenance tamping [2].

### **2.2.2 Tests for Ballast Material**

Traditionally, angular crushed hard stones and rocks that are uniformly graded, free of dust and dirt, and not prone to cementing action have been considered good ballast materials. Availability and economic considerations have been the prime factors considered in the selection of ballast material [2].

The engineering properties of the ballast (e.g. modulus, in-situ density, water content, friction angle, grain size distribution, void ratio, drainage, etc.) are important factors in its performance. Engineering properties of ballast especially grain size distribution, void ratio, drainage, friction angle etc. are factors influencing its performance. Generally, ballast material should be sufficiently tough to resist breakage under impact, hard to resist abrasion due to inter particle contact, dense enough to resist lateral forces and finally holding the ties in place. It must be also freeze-thaw resistant which results further degradation due to weathering and chemical effect [10].

A common method for any geotechnical field investigation is the implementation of test pits and trenching for the characterization of earth structures. This has been especially true in the study of railway substructure to investigate ballast, sub-ballast, and subgrade components. Excavating larger trenches during ballast investigations has the benefit of providing access to the ballast cross section, otherwise inaccessible during normal track operations. The trenches provide ease in taking samples and the characterization and recording of the embankment substructure [4].

The cumulative effect of the ballast material characteristics can be evaluated by its mechanical, physical and weathering test [11]. Table 2-1 shows list of some tests for ballast material;

**Table 2-1 Tests for Ballast Particle Characteristics [2]**

Durability	Los Angeles Abrasion Mill Abrasion Deval Abrasion (Wet and dry) Clay lumps and friable particles Crushing Value Impact
Shape and surface characteristics	Flatness Elongation Angularity or roundness Fractured particles Surface texture
Gradation	Size Size distribution Fine particles content
Unit weight	Specific gravity Absorption Rodded unit weight
Environmental	Freeze-thaw breakdown Surface soundness
<b>Cementing Characteristics</b>	
Identification and composition	Petrographic analysis Chemical analysis X-ray diffraction

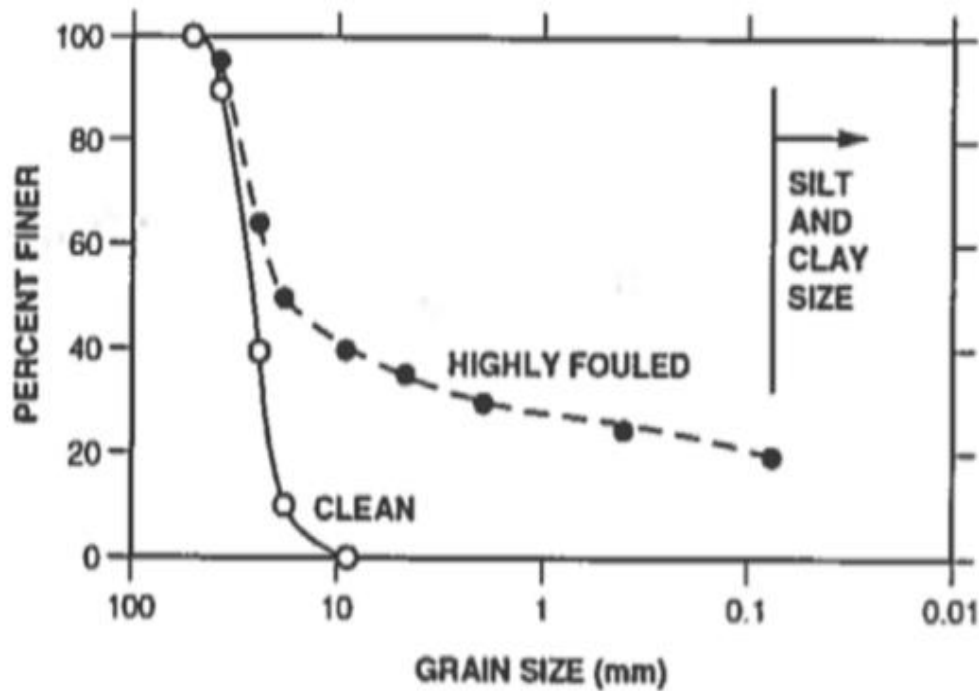
The characteristics of the ballast particles can be measured by the following testing methods;

- Gradation
- Los Angeles Abrasion, LAA (%)
- Crushing Value
- Specific gravity and Absorption

**2.2.2.1 Ballast Gradation**

Ballast gradation is the primary factor affecting the stability, safety and drainage of tracks. Typically, the size of ballast grains varies in the range of 10-60 mm due to the transportation, handling, placement and compaction of ballast. Figure 2-2 shows the gradation curve of both clean and fouled ballast. In accordance with this wide range of size variability and the rail usage of the railroad line, the ballast gradation must provide the two objectives of [1];

- High shear strength to provide increased stability and
- Minimum track deformation.



**Figure 2-2 Ballast gradation curve [2]**

New ballast material supposed to fall under uniformly graded whenever, the fouled ballast material should the requirement for gap graded. Even though there is major problem in degradation and permanent deformation, uniformly graded aggregates are used in ballast structure construction for the sake of drainage requirement [11].

#### **2.2.2.2 Los Angeles Abrasion**

The American Railway Engineering Association (AREA) manual states, LAA is right now the first and the best way of measuring the potential to breakdown of ballast materials under loading. But this test can only measure the degree of abrasion [11].

It has been previously used in North America as an abrasion test for ballast, which is a means to measure toughness or tendency for coarse aggregate breakage. It is a dry test to measure a material's toughness or tendency for coarse breakage. There may cause construction and overall performance problem of the structure if the particle does not have

enough toughness and abrasion resistance [11]. It can be quantified after 500 revolutions by Equation 2.1 as:

$$\text{LAA 500} = \left( \frac{\text{Mo} - \text{M500}}{\text{Mo}} \right) * 100 \quad 2.1$$

Where, LAA 500, Mo, M500 are loss after abrasion test, original sample and sample after abrasion test respectively.

### **2.2.2.3 Crushing Value**

The crushing test gives a relative measure of the resistance of an aggregate to crushing under a gradually applied load. Aggregate Crushing Value (ACV) test is the same in principle as the large odometer test, where a ballast sample is compressed one-dimensionally to a certain macroscopic stress in an odometer or a cylindrical steel mold. This is to determine the relative resistance to crushing of a tasted ballast sample. It can be calculated using Equation 2.2 as [12];

$$\text{CV} = \frac{\text{Weight of fines produced}}{\text{total sample}} * 100\% \quad 2.2$$

### **2.2.2.4 Specific Gravity**

An important factor influencing ballast unit weight is particle specific gravity. which relates to its strength as well as its tendency to break under freezing conditions. Specific gravity is determined by a water displacement method. To Calculate the bulk specific gravity, 23/23°C as per ASTM standard Equation 2.3 is used,

$$\text{Gsb} = \frac{\text{A}}{\text{B+S-C}} \quad 2.3$$

Where, Gsb, bulk specific gravity

A, weight of oven-dry specimen in air, g,

B, weight of pycnometer filled with water, g,

S, weight of the saturated surface-dry specimen, and

C, weight of pycnometer with specimen and water to calibration mark, g. a

According to ASTM, bulk specific gravity on the basis of weight of Saturated surface dry aggregate calculated at a temperature of 23°C by the following Equation 2.4;

$$Gsb = \frac{S}{B+S-C} \quad 2.4$$

The nature of the particle to be porous is an indication of the quality of the aggregate, by porous means, it will contain more water on the space and it will have greater chance to be broken down while freezing. Specific gravity test is best to indicate quality of ballast [11].

### **2.3 Ballast Fouling**

In service the ballast gradation changes as a result of mechanical particle degradation during construction and maintenance work, and under traffic loading, chemical and mechanical weathering degradation from environmental changes, and migration of fine particles from the surface and the underlying layers. Thus the ballast becomes fouled and loses its open-graded characteristics so that the ability of ballast to perform its important functions decreases and ultimately may be lost [2].

Fouling is the term used to indicate contamination of ballast by the presence of fines which is the primary reason why track geometry deteriorates. As the ballast fouled, its performance decreases, resulting in higher settlement and poor drainage [2].

For the fouled ballast samples, the particles smaller than 9.5mm (3/8 in) were assumed to represent the fouling components. The course fouling component consists of particles between 9.5mm (3/8 in) and 0.075mm (No. 200 sieve diameter). These are mainly sand sizes, the fine fouling component, termed fines, consists of those particles finer than 0.075mm, which represent the silt and clay. The effect of ballast fouling is to prevent the ballast from performing its function. The specific effect depends on the amount and the character of the fouling material. Fouling material particles will decrease drainage gradually but remain adequate until the majority of the voids are filled [2].

The phenomenon of ballast rock fouling can be caused by a number of possible factors. The ballast layer is considered fouled when the ballast pore matrix fills with sand sized (4.47 mm) or finer particle [4].

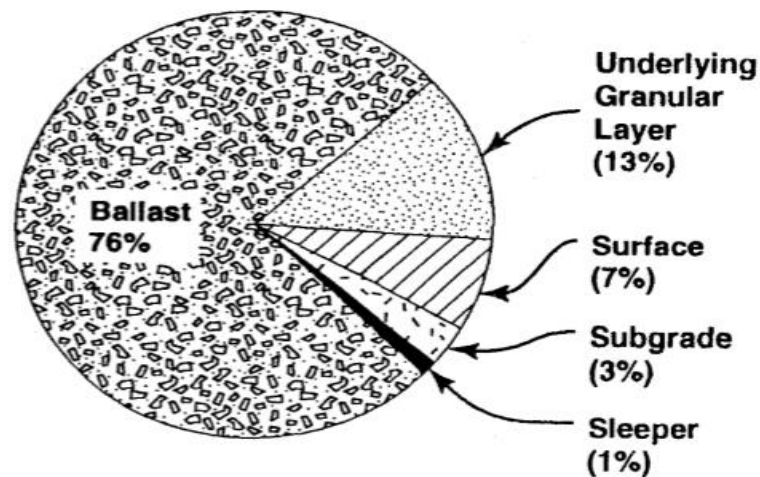
As explained by [2], fouling materials have different sources which can be divided into five categories;

## Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line

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- Ballast break down
- Infiltration from ballast
- Sleeper (Tie) wear
- Infiltration from underlying granular layers
- Subgrade infiltration

An average percent by weight of the fouling components for each of the five fouling categories as shown by Figure 2-3;



**Figure 2-3 Percentage of fouling components [2]**

By far the most important source of fouling is ballast breakdown. Next, but a much smaller contributor, is infiltration of particles from granular layers beneath the ballast. Surface infiltration sources were third. Subgrade infiltration was an uncommon source.

As [1], there are several sources of ballast fouling like fine dust due to particle attrition, ballast degradation (breakage), pumping of formation soil (subgrade) into the ballast, infiltration from underlying granular layers (subbase), sleeper tie wear and infiltration from ballast surface. Source of ballast fouling including the reasons are shown by Table 2-2;

**Table 2-2 Source of Ballast Fouling [1]**

Description	Reason of fouling
Ballast Breakdown	Rail traffic Cyclic loading Vibration Hydraulic action of subgrade slurry Compaction machines Handling Tamping Operations Freezing of water in voids Chemical weathering Thermal stresses
Subgrade infiltration	Poor sub base (filter) layer Insufficient drainage Saturation (saturation of water) Pumping action by cyclic load
Infiltration from underlying granular layers	Old track bed breakdown Migration of sub ballast particles due to poor filtering (inadequate gradation)
Sleeper (tie) wear	Attrition between sleeper and ballast Due to lateral ballast deformation
Infiltration from ballast surface	Delivered with ballast Dropped from passenger and freight trains Wind-blown dirt Water borne fines Splashing from adjacent wet spots Meteoric dirt

### 2.3.1 Fouling Indices

There are several methods of assessing the degree of ballast fouling. These can be broadly classified into two categories [13];

- Mass based measures
- Inherent property based

Fouling index (PI) and percentage of fouling are included under the first category while Percentage Void Contamination (PVC), Void Contamination Index (VCI) and relative ballast fouling ratio are under the second category. Inherent property based measuring of ballast fouling rate are dependent on properties such as bulk volume and specific gravities of fouling materials [13].

**2.3.1.1 Fouling Index**

Fouling Index (FI) is a term to quantitatively measure the fouling particles in the ballast. This evaluation was based on the clay pumping and infiltration of the materials as well as the other sources of fouling such as breakdown particles and the other objects delivered from the ballast, dropped from trains, wind or water blown. Fouling Index is the summation of percentage by weight of ballast sample passing the 4.75mm and the 0.075mm sieves [2].

$$FI = P_{4.75} + P_{0.075} \quad 2.5$$

The different condition of fouling according to Fouling Index is summarized by Table 2-3 as;

**Table 2-3 Categories of Fouling Condition Using FI [2]**

Category	FI
Clean	FI<1
Moderately clean	1<FI<10
Moderately fouled	10<FI<20
Fouled	20<FI<40
Highly fouled	FI<40

If there are more fines available to fill the voids, a greater FI will result with unsatisfactory drainage and resilience capacities of the ballast [14].

However, FI cannot differentiate between types of fouling material having different characteristics like differences in specific gravity. This is a gap when degree of fouling is evaluated by FI.

**2.3.1.2 Percentage of fouling**

An index related to FI is percentage of fouling is the ratio of dry weight of material passing 9.5 mm sieve (3/8” sieve) to the dry weight of the total sample [2] .

FI and percentage of fouling are only based on weight which doesn't give any information about the type of fouling material and type of ballast material thus they may lead to a misinterpretation of the actual degree of fouling if the fouled material contains more than one type of material having different specific gravity.

### **2.3.1.3 Percentage Void Contamination (PVC)**

Because of this importance that FI and percentage of fouling cannot show the relative density of the fouling material and ballast, and do not represent the volume and quantity of fouling materials in the ballast [15] developed Percentage Void Contamination (PVC). The authors Feldman and Nissen defined the percentage Void Contamination (PVC) as the ratio of the bulk volume of fouling material to the initial volume of ballast voids (i.e when it was clean).

$$\text{PVC} = \frac{V_{vf}}{V_{vb}} * 100 \quad 2.6$$

where  $V_{vf}$ , bulk volume of fouling material

$V_{vb}$ , volume of voids within a total ballast

In this quantification type the parameter  $V_{vf}$  needs to be calculated after the fouling material has been compacted [15]. PVC method is a direct measure of percentage of voids occupied by fouling particles but as the total volume of fouling particles is used, the gradation of fouling particles cannot be taken into account. In this regard, PVC may overestimate the extent of fouling [14].

The limitation in this type of mechanism is that during determination of bulk volume of fouling material the compaction process doesn't always represent the actual volume of fouling accurately in a track environment and is time consuming.

### **2.3.1.4 Relative Ballast Fouling Ratio (Rb-f)**

If there are more fines available to fill the voids, a greater FI will result with unsatisfactory drainage and resilience capacities of the ballast. The measurement of volume is time consuming as the total volume of fouling particles is used when using PVC. In this regard, PVC may overestimate the extent of fouling. [14].

By comparing the % fouling and PVC methods, a new parameter called the relative ballast fouling ratio, (Rb-f) have proposed. It is a ratio between the solid volumes of fouling particles (passing a 9.5 mm sieve) and ballast particles (particles being retained on a 9.5 mm sieve) [14].

$$Rb - f = Mf * \left(\frac{Gsb}{Gsf}\right) \frac{1}{Mb} * 100 \quad 2.7$$

Where Mf and Gsf are the mass and the specific gravity of ballast fouling (fines), Mb and Gsb are the mass and specific gravity of ballast respectively.

A quick assessment of ballast conditions can be achieved using the fouling index or % fouling, neither of which can properly represent the influence of different types of fouling materials or specific gravities. But relative ballast fouling ratio can reflect the influence of both the specific gravity and gradation of fouling particles. In this method, only the mass of ballast and the specific gravity of the fouling material need to be measured. Therefore, this method is both quick and realistic, making it more attractive to practicing track engineers [14].

A summarized fouling categories according to Fouling Index, Percentage of fouling and relative ballast fouling ratio have also developed as shown by Table 2-4;

**Table 2-4 Categories of Fouling Based on FI, % Fouling and Rb-f [14]**

Category	Fouling Index (%)	Percentage of fouling (%)	Relative ballast fouling ratio (%)
Clean	<1	<2	<2
Moderately Clean	1 to <10	2 to<9.5	2 to<10
Moderately Fouled	10 to <20	9.5 to<17.5	10 to<20
Fouled	20 to <40	17.5 to<34	20 to<50
Highly fouled	≥40	≥34	≥50

### **2.3.1.5 Void Contamination Index**

A new parameter called Void Contamination Index introduced as a modification of PVC proposed to capture the role of different fouling materials [16]. Since the effect of fouling on geotechnical characteristics such as permeability and shear strength depend on the type of fouling materials, a proper understanding of the nature of fouling materials is pertinent irrespective of the quantity of fouling [2]. The following Equation 2.8 is developed to calculate Void Contamination Index (VCI) ;

$$VCI = \frac{1 + ef}{eb} * \frac{Gsb}{Gsf} * \frac{Mf}{Mb} * 100 \quad 2.8$$

Where ef, void ratio of fouling material

eb, void ratio of clean ballast

Gsf, specific gravity of fouling material

Gsb, specific gravity of clean ballast

The specifications of clean ballast vary widely for different railway organizations throughout the world. Therefore, the changes in void ratio, specific gravity and gradation of clean ballast are expected. There is also a significant variation in the void ratio, specific gravity and gradation characteristics of fouling material such as sand, silt, clay and coal fines, and VCI can take into account all such variations [17].

This approach has a benefit when there are different fouling materials with different specific gravities. The track drainage capacity is also governed by both the location and the extent of fouling.

The expected ballast behavior according to Void Contamination Index value is also developed as shown by the following Table 2-5 [16];

**Table 2-5 Expected Ballast Behavior with respect to VCI**

Zone	VCI range	Expected Ballast Performance
1	$VCI \leq 25\%$	Lubrication of ballast –increased axial strain with increasing VCI
2	$25\% \leq VCI \leq 50\%$	Stabilization of ballast- little increase in axial strain with increasing VCI
3	$VCI > 50\%$	Impeded drainage- increased axial strain with increasing VCI and generation of pore water pressure

## **2.4 Hydraulic Conductivity Determination**

Hydraulic conductivity can be approximated or determined by different methods [18];

- Field Method
- Experimental Method
- Empirical

### **2.4.1 Field Method**

One reliable and easy way to determine the hydraulic conductivity in the field is to use the Auger-hole Method. The Auger-hole Method obtains the average hydraulic conductivity. The rate at which the water rises in the hole is measured and then converted by a suitable formula of hydraulic conductivity. But the auger-hole method is rarely used for determining hydraulic conductivity compared to empirical and laboratory methods [18].

### **2.4.2 Experimental Method**

[19] have investigated the permeability characteristics of different material and ratio of fouling using a series of constant head permeability test. Their experimental researches showed that the relationship of permeability capacity and fouling ratio of railway ballast is correlated. The fouling ratio increase leads to the permeability capacity decrease and influences both the aggregates permeability and strength.

Henry Darcy was the first to empirically define the saturated flow of water through porous media and was conducted using constant head permeability tests on river sand. Manometers were used to measure the pressure head near the top and bottom of the pipe within the sand. Two variables are used to describe the flow Darcy measured which are the discharge velocity ( $v$ ) and hydraulic gradient ( $i$ ),

$$V = ki \quad 2.9$$

$$V = \frac{Q}{A} \quad 2.10$$

where  $Q$ , flow rate of water and

$A$ , is the full cross-sectional area of the flow

Whereas, the actual seepage velocity is the ratio of discharge velocity and porosity of the sand.

$$i = \frac{\Delta h}{L} \quad 2.11$$

where  $\Delta h$ , the change in total head found from the measurement

taken in the manometers

$L$ , the length between the manometers

where,  $v$  is average velocity of fluid,  $i$  is hydraulic gradient, and  $k$  is the coefficient of permeability (hydraulic conductivity). The best way to evaluate the value of  $k$  for a particular porous medium is by conducting field or laboratory experiments such as constant head or falling head permeability test.

The Constant Head Permeability Test is preferred for soils with  $k > 10^{-3}$  cm/sec (granular soils), and the Falling Head Test is preferred for soils with  $k < 10^{-5}$  cm/sec (fine grained soils). The constant head permeability test for hydraulic conductivity is based on equation 2.12 whereas Falling head permeability test for hydraulic conductivity is based on equation 2.13 [18].

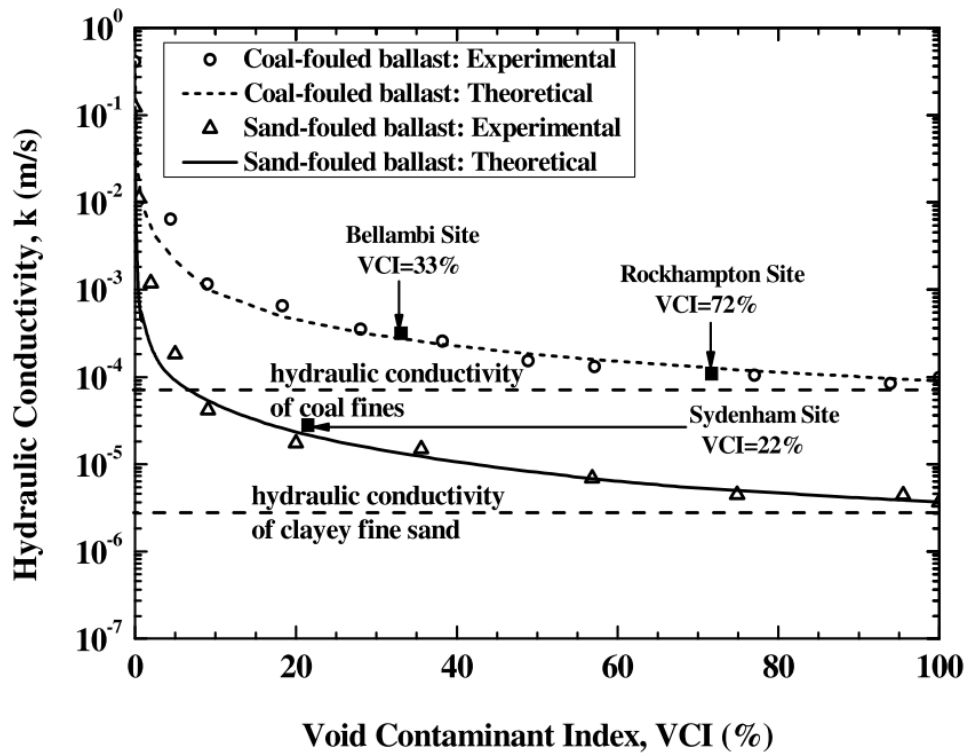
$$k = \frac{QL}{Aht} \quad 2.12$$

Where  $k$  is the hydraulic conductivity,  $Q$  is the flow rate,  $L$  is the length of the specimen,  $A$  is the cross-sectional area,  $h$  is the difference in head, and  $t$  is time.

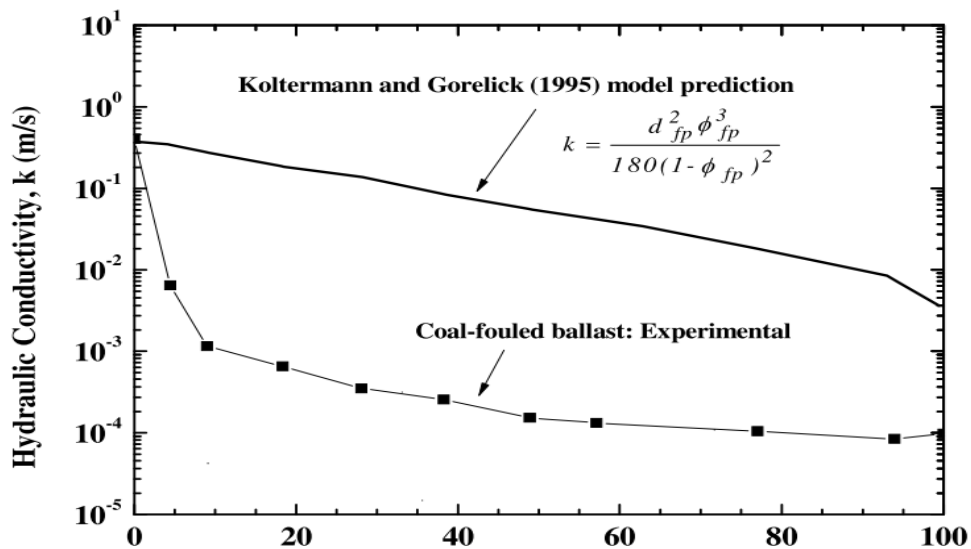
$$k = \frac{2.3aL}{At} \log\left(\frac{h_1}{h_2}\right) \quad 2.13$$

Where  $k$  is the hydraulic conductivity,  $a$  is the cross-sectional area of the supply reservoir,  $L$  is the length of the soil specimen,  $A$  is the cross-sectional area of the soil specimen,  $t$  is time, and  $h_1$  is the hydraulic head at time zero, and  $h_2$  is the hydraulic head at time,  $t$ .

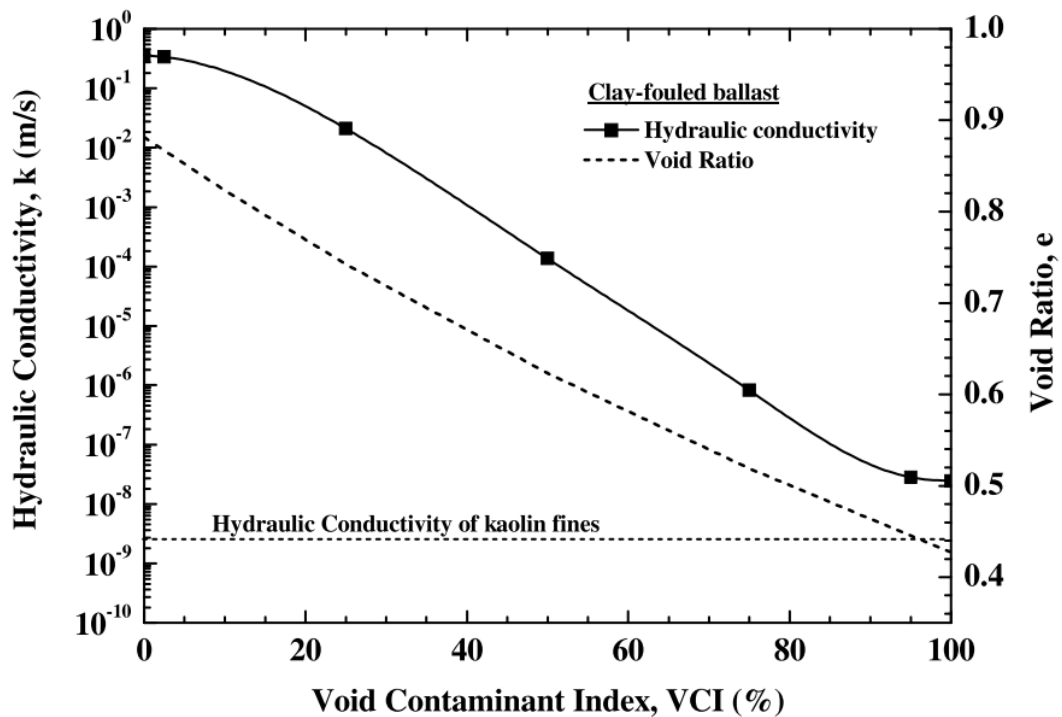
The laboratory tests to measure their FI, PVC and VCI values and large-scale hydraulic conductivity tests were carried out on ballast samples to see the effect of fouling. Further extensive laboratory tests were carried out by varying VCI from 0 to 100 to get hydraulic conductivity values corresponding to different VCI obtained from experimental results and Figure 2-4 shows the results of this experimental tests [16];



(a)



(b)



(c)

Figure 2-4 Variation hydraulic conductivity with Void Contaminant Index (a-c)

### 2.4.3 Empirical Method

Many researchers have presented several empirical formulae based on the characteristics grain size of the medium to model hydraulic conductivity [1].

Hazen's Approximation is an empirical relation between hydraulic conductivity with grain size. As [1] stated that the following Hazen's Equation 2.15 can be used to estimate the permeability of granular aggregates:

$$K = C(D_{10})^2 \quad 2.14$$

where, k is the coefficient of permeability and C is an empirical constant which varies in the range of 40-150.

While these models work well for some types of granular materials such as sands and silts, for coarse-grained aggregate such as ballast having a larger and inter-connected pore structure, the change of hydraulic conductivity with respect to the porosity is usually insensitive, unless a large amount of fines are accumulated within the voids [16]. To

## **Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line**

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represent the hydraulic conductivity ( $k$ ) of a mixture of granular and fine-grained soil, Kolterman and Gorelik proposed Equation 2.17;

$$K = \frac{d^2 f b \phi^3 f p}{180 * (1 - \phi f p)^2} \quad 2.15$$

Where  $\phi f p$  is the composite porosity of the mixture and  $d f p$  is the representative grain diameter.

For the ballast having different degrees of fouling typical values of  $k$  have presented by Table 2-6 ;

**Table 2-6 Permeability Values for Fouled Ballast [2]**

Fouling Category	Fouling Index	Representative K values (mm/sec)
Clean	<1	25-50
Moderately clean	1-9	2.5-25
Moderately fouled	10-19	1.5-2.5
Fouled	20-39	0.005-1.5
Highly fouled	>39	<0.005

### **2.4.4 Equivalent Hydraulic Conductivity of Ballast**

To determine the equivalent hydraulic conductivity of ballast that is contaminated with non-uniformly distributed fouled material, a layer by layer simplification may need to be considered. An analytical model is considered here with, assuming only the vertical flow [16]. The equivalent hydraulic conductivity for ballast mixed with the contaminating fines can be obtained as;

$$K = \frac{K_b * K_f}{K_f + \frac{VCI}{100} * (K_b - K_f)} \quad 2.16$$

Where  $K_b$  and  $K_f$  are the hydraulic conductivities of clean and fouled ballast layers.

## Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line

The calculated hydraulic conductivity of fouled ballast based on this Equation 2.16 was in a good agreement with the experimental data [16].

### 2.5 Effect of Ballast Fouling

The fouling process can create a number of detrimental effects on railway embankments, prompting the need to understand and mitigate the fouling process. The primary effect of ballast fouling is the modification of the settlement rate of the embankment. Testing found that settlement increased considerably as water content and fouling severity increased especially for wet clays. Increases in water content also allowed moist clay and moist silt fouled ballast to experience greater settlement compared to water deficient samples. Thus as ballast fouling severity and its subsequent water retention ability increases, the risk of increased differential settlement and degradation of track settlement can occur, compromising the safety of the rail embankment. The following Figure 2-5 explained the effect after the tests have conducted [4];

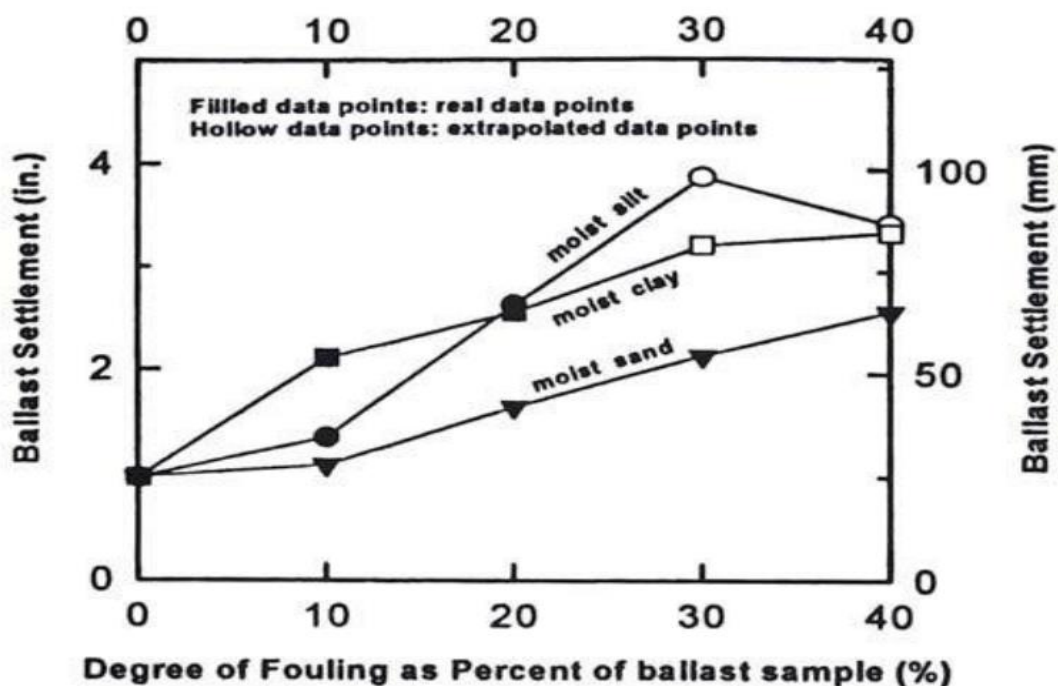


Figure 2-5 Effect of fouling type and material type on ballast settlement

The effect of fouling on permeability depends on the type of fouling materials (e.g. coal vs. clay). Therefore, the proper understanding of the nature of fouling materials is pertinent

irrespective of the quantity of fouling. For example, sand and coal fouling may not decrease the overall permeability of the track significantly, while clay fouling can decrease the track drainage more dramatically [2].

The hydraulic conductivity decreases when the degree of contamination increases. However, coal contaminated ballast shows a lesser reduction in hydraulic conductivity compared to the clay-fouled ballast at a higher degree of contamination (VCI >50%). Moreover, at a lower degree of contamination (VCI <50%), clay-fouled ballast yields a higher hydraulic conductivity than the coal-fouled ballast. This is because, at low levels of contamination, cohesive clay particles simply attach to the surface of the ballast aggregates (less void filling), while cohesion less coal material accumulates and compacts at the bottom of the specimen impeding drainage. For a larger degree of contamination, the overall hydraulic conductivity of ballast is mainly governed by the hydraulic conductivity of the contaminated material itself [16].

Railroad ballast fouling is a source of major distress that causes track instabilities and high maintenance and replacement costs. When ballast is fouled, the voids among the large aggregate become filled with fine particles that can block drainage and decrease the shear strength of the ballast layer. Ballast fouling has an effect on particle movement and associated impact on dynamic train-track interaction [20].

The increase in fine fraction seriously alters the deformation-strength characteristics of the original ballast, depending on the amount of fouling materials mixed with fresh ballast. In addition, since the altered grain-size distribution of fouled ballast results in water retentively characteristics different from fresh ballast, cyclic plastic deformation of railroad ballast becomes more remarkable in case of fouled ballast [21].

The fouling materials can reduce the friction angle at inter-particle contact points which reduces the strength and can cause instability of track structure. Furthermore, past studies on the effects of fouled ballast on drainage showed that drainage is significantly reduce when the fouling index is 30 or greater. Results of studies showed that sand did not impact the hydraulic conductivity of ballast significantly; however, clay and silt caused a significant reduction on hydraulic conductivity of ballast [22].

## **2.6 SEEP/W**

The finite element-based groundwater modeling software, SEEP/W, can simulate both saturated and unsaturated flow. For these two conditions, the program applies the overall principle that the flow of water through soil follows Darcy's law. However, the governing equation for all the calculations is Richards' equation, represents in a more suitable form the unsaturated flow [23].

$$\frac{\partial}{\partial x} \left( K_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \Theta}{\partial t} \quad 2.17$$

Where H, is total head

$K_x$ , is hydraulic conductivity in the x-direction.

$K_y$ , is hydraulic conductivity in the y-direction.

Q, is the applied boundary flux.

$\Theta$ , is volumetric water content.

t, is time.

This fundamental partial differential equation states that the difference between the flow entering and leaving an elemental volume at a point in time is equal to the change in volumetric water content. As it can be seen, Richards' equation can be used for saturated and unsaturated conditions. The right part of the equation would become zero when the first case is applied or in steady-state conditions [23].

There are primarily two ways of obtaining hydraulic conductivity curves– either by direct measurement or by estimation. Direct measurement of hydraulic conductivity curves is tedious and time consuming. Therefore, hydraulic conductivity curves tend to be estimated from water characteristic curves, analytical models, and grain size curves. Brooks and Corey model (1966), Van Genuchten model (1980), Brutsaert model (1966) and so one are some of the popular hydraulic conductivity models are used in SEEP/W [23].

Many computer software's have come in general use, and any hard computations and simulation can be carried out through them by giving them appropriate inputs and

data. This results in less error frequency and more detailed analysis when compared with field observations. The numerical model SEEP/W can be employed to carry out simulation of seepage and phreatic surface. The SEEP/W program is capable enough to simulate quite effectively seepage rates and phreatic surfaces in homogenous and non-homogenous conditions [24].

## **2.7 Drainage Capacity of Track**

The description of the track components would not be complete without mentioning one of the most important items--the drainage system [2]. Drainage plays a significant role in the stability and safety of a track substructure. In saturated tracks, poor drainage can lead to the buildup of excess pore water pressure under train loading. [1]. As explained by [1], water can enter into the load-bearing stratum from 4 different sources;

- Precipitation (rain and snow)
- Surface flow from adjacent hill slopes,
- Upward seepage from subgrade, and
- High groundwater table in low-lying coastal region

As flow through ballast track can occur in both vertical and horizontal directions, a 2-D seepage analysis was conducted using the finite element software, SEEP/W to determine the drainage capacity with respect to various fouling conditions. Hydraulic conductivity values corresponding to different VCI obtained from experimental results were used as input parameters in the analysis. For most large-size granular materials, the hydraulic conductivity of the granular assembly tends to be isotropic. The hydraulic conductivity of coarse granular materials is often dictated by the lower particle fraction size for which 15% by mass is finer. The difference in values of  $k_h$  and  $k_v$  for coarse aggregates is considerably less than those for fine grained materials such as silt and clay [16].

The critical flow rate over the unit length of the track ( $Q_c$ ) is adopted from the maximum rainfall intensity and the maximum drainage capacity ( $Q$ ) is determined from the seepage analysis of ballast layer for various levels and conditions of fouling. In this context, a ratio between the computed track drainage capacity and the critical flow ( $Q/Q_c$ ) is introduced as a dimensionless index to classify the drainage condition. If the ratio  $Q/Q_c$  equals 1,

track becomes saturated under the given rainfall. When the ratio  $Q/Q_c$  is greater than 1, the track drainage is classified into various categories i.e. “Acceptable drainage”, “Good drainage”, as well as “Free drainage” and when it becomes less than 1, the drainage is classified as “Poor drainage”, “Very poor drainage”, and “Impervious” based on the output of the numerical SEEP/W analysis[16].

To predict track drainage, a finite element analysis employing the software SEEP/W was conducted to simulate two-dimensional flow within a typical track substructure. Laboratory evaluated values of hydraulic conductivity were used as input parameters. Exploiting track symmetry, it was sufficient to model one half of the track [25].

**Table 2-7 Track Drainage Capacity Criteria**

Drainage Classification	Range
Free drainage	$Q/Q_c > 100$
Good drainage	$10 < Q/Q_c < 100$
Acceptable drainage	$1 < Q/Q_c < 10$
Poor drainage	$0.1 < Q/Q_c < 1$
Very poor drainage	$0.001 < Q/Q_c < 0.1$
Impervious	$Q/Q_c < 0.001$

## **2.8 Maintenance Methods of Ballast**

To manage the poor track conditions that fouling causes to rail track infrastructure, rail companies perform routine maintenance on rail track to increase the safety and prolong operational life. Through progressive train traffic loading and ballast fouling, vertical and lateral movement of the track rails occur over time, making periodic maintenance essential to correct track orientation. Maintenance costs for ballast rehabilitation run into the 100\$ of millions per year, making the improvement of ballast performance and engineering an important goal for railway companies [4].

Timely maintenance of railway substructure is essential to provide continuous service at a reasonable cost. Maintenance decisions within the railway industry depend on available

information from inspections, standards, and individual and institutional experience. There are two approaches for track maintenance planning; one is performance-based and the other mechanistic-based. Performance based approach is for creating comprehensive maintenance model using significant historical data whereas mechanistic-based assess the performance of various track components based on their respective mechanical properties [26].

### **2.8.1 Tamping**

Tamping is the primary maintenance method for improving the stiffness of the substructure to increase its ability to resist track movement. The tamping operation is run by a tamping machine and is intended to improve the long wave length faults that arise from long term rail traffic [4]

Tamping is said to be the most effective way of correcting faults in track geometry. The tamped ballast underneath the rail tie will soon compact back to its pre-tamped profile. Tamping causes small amounts of particle breakage, with higher tamping maintenance cycles creating greater amounts of particle breakage which then cause the formation of fouling particles [2].

Therefore, during periodic tamping as both a general maintenance procedure as well as during track under cutting, possible ballast fouling contributions should have taken into account.

### **2.8.2 Shoulder Cleaning**

Shoulder cleaning is a newer ballast maintenance procedure with claims by tamping machine manufacturers that it reduces track fouling. Replacing the shoulder ballast of the railway embankment has become an increasingly common maintenance procedure for the rehabilitation of fouled track. Ballast shoulder cleaning is a type of undercutting that removes the previous shoulder ballast that has deteriorated over its service life and replaces it with freshly quarried ballast that meets the ballast specification. The intent behind the shoulder cleaning is to increase the hydraulic conductivity of the shoulder ballast and to allow fine grained material within the central ballast zone to drain out through the shoulders once saturated [4].

### **2.8.3 Ballast Undercutting**

Ballast undercutting is currently the most comprehensive option for the rehabilitation of fouled ballast layers. However, undercutting is time consuming, disruptive to rail traffic, and expensive well[2]. The procedure entirely replaces the ballast layer and replaces it with both fresh ballast and recycled ballast of suitable size screened directly out of the undercut track material. Currently this is the only way to fully rehabilitate the shoulders and center of track ballast without entirely removing the rail track [4].

## CHAPTER 3 MATERIALS, METHODS AND PROCEDURES

### 3.1 Description of Study Area

#### 3.1.1 General

This study was conducted on Ethio-Djibouti railway line which has two sub-sections; Sebeta-Adama- Mieso section and Mieso- Dewanle section. Engineering geologic survey of the line was conducted as per Chinese codes, specifications and regulations for railway engineering [27].

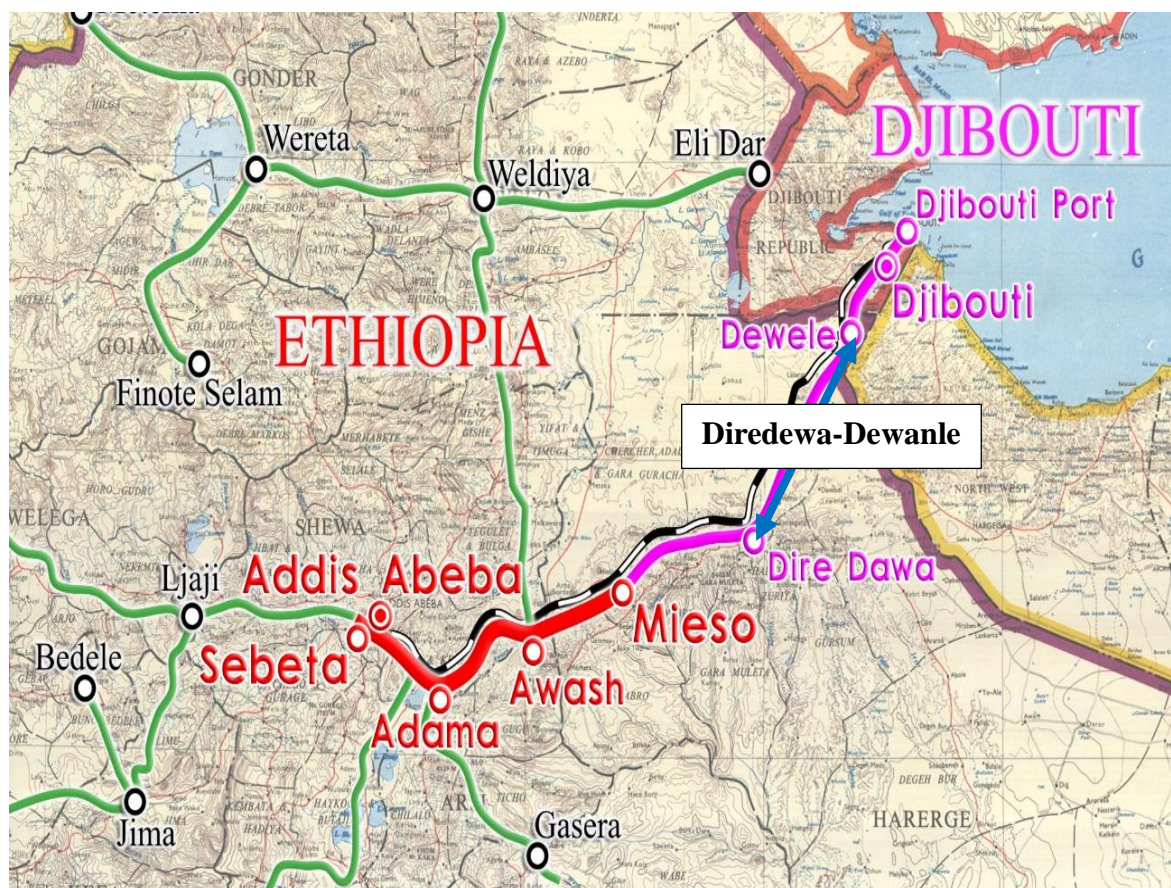


Figure 3-1 Location of study area

Technical reports have showed that, Sebeta-Adama-Meiso section is situated at plateau in central Ethiopia. It starts from Sebeta southwest to Addis Abeba, passes eastward through Akaki Beseka, Dukem, Bishoftu, Mojo, Adama, Welenchiti, Metehara, Awash and Asebot and ends at Mieso. The line is 318.961 km long where as Mieso-Dewanle section line starts from Mieso and reaches Dawanle, a city on Ethiopia-Djibouti border via Afdem, Bike, Erer, Diredawa, Harwa, Mile, Adigala, Lasart and Aysha with a total length of

339.182Km. The interest for this study is the second section of Addis- Djibouti line specifically Diredawa-Dewanle section.

### **3.1.2 Climate**

The average annual temperature is 16°C, 20.6°C and 23.3°C in the capital city, Mieso and Diredawa respectively. Generally, the temperature is highest from March to May and relative low from November to January. The dry season lasts from October to May in most regions. The average annual rainfall in the plateau areas is 1000 ~ 1500mm and 250 ~ 500 mm in depressions and valleys [27].

### **3.1.3 Terrain and Landform**

The Engineering report presented by [27], confirmed the line belongs to shallow hilly and alluvial plain landform; view from the overall terrain, the line runs in the East African Great Rift Valley, close to the foot of a hill of the mountain chain in the right side; the terrain of the left side of the line is relatively flat and wide, with small topographic relief in different section; the overall terrain is high in southwest and low in northeast, with a general relative high difference of more than ten meters. In terms of landform, the areas along the line can be divided into shallow hilly.

### **3.1.4 Geology**

According to the site geological mapping and survey, in Meiso-Diredewa section of the line there are basically no major unfavorable geological problems such as landslide, avalanche, gob and others along the line; the main engineering geological problems along the line are weak bedrock interbred, hazardous falling rocks, active fractures, river scouring and silting. Due to frequent intermittent volcano eruption, the degree of weathering of igneous rocks along the whole line is uneven and weak interbred are easily formed, which will significantly affect the bridge and deep cutting works [27].

The region from Adigala to the border city Dawanle belongs to hilly area, with relatively great topographic relief, where the vegetation is not developed. The lithology is sandstone with rock joints and fissures develop and crushed rock, the occurrences of joints are  $240^\circ \angle 15^\circ$ ,  $305^\circ \angle 8^\circ$ , thick bedding, heavy weathering. The rocks are easy to collapse and fall when cutting the mountain massif in construction [27].

#### **3.1.4.1 Special rocks and Soil**

**Swelling soil (rock):** Swelling soil are widely distributed in the surface of alluvial plain, valley and the hilly areas, mainly are grayish brown or dark gray silty clay with hard plastic shape, 0.5 ~ 8m in thickness, locally develop fissures on surface at dry season, cracks depth up to 20 cm or more; swelling rock distributes in DK291 +600 ~ 292 +000 section, with strong-moderate weathered basalt in the upper part and the completely - strong weathered mudstone (with a moderate to strong expansibility) in the lower part . The swelling soil usually drastically expands, softens and collapses after absorbing water while compresses and fractures when losing water. Attention shall be paid to the bed of swelling (rock) soil cutting and low filling embankment, which should be replaced, improved or enhanced; and measure shall be taken according to its intensity of expansibility and thickness of swelling stratum [27].

**Salinized Soil:** It mainly distributed in low-lying sections of the plain areas, mostly sulphate saline soil, mainly from the tertiary mudstone at partial sections along the line, with high content of sulfate ions migrating with surface water, so that soluble salt gathered in low-lying place. For its moisture, swelling, dissolution subsidence and corrosion properties, related engineering works are required to take appropriate measures. In the construction site of salinized soil section, test samples are taken and test pits are increased for further identification [27]. In this study, assessment works have been done primarily in order to get an initial overview about the extent of ballast fouling problems on that line.

### **3.2 Assessment of Ballast Fouling**

Although the inspection of ballast is difficult, the role in track performance and stability is critical and techniques are advancing for systematic evaluation of ballast condition. Therefore, before evaluating ballast fouling condition, the first task should be undertaken is assessing the selected areas in order to determine critical fouled site and to choose sampling pits. Furthermore, inspection works were done on each areas to observe the type of ballast and subgrade material used, to see the extent of ballast contamination.

In this study, emphasis was given for the second section of Ethio-Djibouti line; Mieso-Dewanle section specifically Diredeba-Dawanle section due to the following reasons;

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- The poor ballast material quality
- Speedy and frequent wind condition
- Poor subgrade material
- Poor drainage condition

This study has been conducted at three selected sites of Diredeba-Dewanle section Diredeba, Adigala, and Dewanle. Some tests have also done on the quarry site which is called Elbahe found on Somlia region for comparison purpose. During visual inspection, the defects on sleepers, ballast, rails and fasteners and on switches and turnouts were observed in addition to fouling conditions. In addition, inspection was helpful to observe foreign materials other than ballast grain size such as blown fines. When someone tried to touch the ballast which was surrounded by those fines it seems it couldn't stand by itself. Since the voids are full of fines, ballasts have been adopted fines support. Generally, there was no clean ballast which is free from contamination. Anyone can easily observe this and reach on the conclusion of the ballasts are in danger with fouling even if the degree is unknown. The degree of fouling needs knowledge of how to determine and by what technique. This study mainly focused at evaluating the degree at which the ballasts are in danger with fouling on those selected sites.



**Figure 3-2 Elbahe quarry site**



**Figure 3-3 Ballast fouling condition on the line**

### **3.2.1 Types of Rock for Ballast**

In the design report of Ethio-Djibouti line, basalt is the only rock type which has been used for ballast. During visual inspection, there was no uniformity in rock types for those selected track sections. The visual inspection to know about types of rock used for ballast material helped to have a prediction before testing.

There were different types of ballast encountered during visual inspection. Most of them look like Igneous rock based on their color and identification mechanisms in many literatures. Most of them are categorized under extrusive Igneous rock but there were also Intrusive ones.

- **Basalt:** is a fine grained, dark-colored Igneous rock
- **Scoria:** dark-colored, Vesicular Igneous rock
- **Diorite:** is a coarse grained Intrusive Igneous rock

The following Figure 3-4 shows different types of ballast encountered on the track during inspection and assessment.



**Figure 3-4 Variety of Ballast Types on the Track During Inspection Laboratory tests**

### **3.3 Materials**

The railroad ballast material was taken from the quarry and was excavated from track sections of selected sites at Addis-Djibouti line. The fouling materials have been collected from the track for laboratory tests. These materials were not characterized before for study purpose. Several tests have been conducted to determine the properties of ballast and fouling materials at Diredeewa railway laboratory in this study.

### **3.4 Procedures**

In this study, all test procedures have been conducted according to the corresponding ASTM standard. Laboratory tests such as; Gradation, Los Angeles Abrasion, crushing value and specific gravity tests have been performed in accordance with this standard. The results were also compared with ASTM requirements.

### **3.5 Laboratory Tests**

#### **3.5.1 Gradation of Ballast**

The ballast coarse aggregates were separated by conducting a sieve analysis test, where the distribution of particle size was determined. Ballast aggregates were sieved with a sieve manually. Separation was achieved from retained particles of different sieve sizes starting at 63 mm opening and ending at 16 mm.

The sieving process in the laboratory have been done into two ways. During the first stage of sieving, the whole ballast sample was run through different sized large sieve designed for aggregate. The second sieve stage involved splitting the fines accumulated during the large sieving and sieving them with a smaller set. The materials passing 9.5 mm sieve are called fouling materials.

Four samples have been taken from Elbahe quarry site and five samples from each of Diredeba, Adigala and Dewanle track sections in order to see how ballast gradation looks like. The following Tables 3-1, 3-2, 3-3 and 3-4 shows the gradation at each selected sites and the corresponding plots found on Appendix A of this paper.

**Table 3-1 Gradation of Fresh Ballast Samples at Elbahe Quarry Site**

<b>Sample</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
<b>Sieve opening (mm)</b>	<b>% passing</b>	<b>% passing</b>	<b>% passing</b>	<b>% passing</b>
<b>16</b>	5.9	6	6.3	6.1
<b>25</b>	6.27	6.8	6.75	6.4
<b>35.5</b>	16.12	16.35	16.54	16.64
<b>45</b>	48.55	48.45	48.62	48.59
<b>56</b>	97.46	97.52	97.58	97.6
<b>63</b>	100	100	100	100

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The percentage passing on each sieve for each collected samples at the quarry site (Elbahe) is almost the same. The difference is insignificant and negligible therefore, gradation curve for one sample can represent the whole samples at that site.

**Table 3-2 Gradation of Ballast on Different Sites of Diredewa Track Section**

Chainage	DK 126+700	DK 126+950	DK 127+200	DK 127+450	DK 127+700
Sieve opening (mm)	% passing	% passing	% passing	% passing	% passing
16	10	11.23	10.5	10.75	11.1
25	31.76	31.85	31.5	31.45	31.28
35.5	61.24	61.2	61.35	61.4	61.45
45	83.47	83.52	83.62	83.7	83.58
56	97.81	97.9	97.75	97.85	97.8
63	100	100	100	100	100

**Table 3-3 Gradation of Ballast on Different Sites of Adigala Track Section**

Chainage	DK 237+150	DK 237+400	DK 237+650	DK 237+900	DK 238+150
Sieve opening (mm)	% passing	% passing	% passing	% passing	% passing
16	10.5	10.56	10.62	10.68	10.57
25	13.5	13.45	13.6	13.63	13.71
35.5	21.7	21.82	21.75	21.5	21.92
45	45.96	46.2	45.85	46.51	46.35
56	97.81	97.75	97.6	97.5	97.85
63	100	100	100	100	100

**Table 3-4 Gradation of Ballast on Different Sites of Dewanle Track Section**

Chainage	DK 347+100	DK 347+350	DK 347+600	DK 347+850	DK 348+100
Sieve opening (mm)	% passing	% passing	% passing	% passing	% passing
16	8.4	8.56	8.45	8.31	8.43
25	14.42	14.48	14.5	14.35	14.4
35.5	31.63	31.25	31.4	31.5	31.72
45	53.65	53.7	53.55	53.67	53.6
56	92.4	92.46	92.15	92.31	92
63	100	100	100	100	100

### 3.5.2 Los Angeles Abrasion Test

For ballast to transmit the upcoming load to the underlying layer and then to sub grade, the particle needs to be tested in order to know whether it is hard enough to resist crushing, degradation and wear. The characteristics of the ballast particles can be measured by many tests but for this study Los Angeles Abrasion and crushing tests. The American Railway Engineering Association (AREA) manual states, LAA is right now the first and the best way of measuring the potential to breakdown of ballast materials under loading. But this test can only measure the degree of abrasion. Ballast samples from the quarry called Elbahe were also taken for the LAA test in order to compare with the ballast from the track.

LAA test was undertaken to assess the wear characteristics of the rock types used in the ballast. Testing was done following ASTM Standard C 535 working with a total sample weight of 10 kg. As per the standard, the total test sample of 10 Kg have used for LAA, The LAA test measures material toughness (tendency for breakage). There are standards which use abrasion balls weighing 2 Kg and 1.5Kg but for this study a ball with weight of 1.5 Kg is used. The machine is automatic once arranging the time, it will stop crushing the stones based on it. The tests have been done at the selected sites including at Elbahe quarry site in order to see the difference between the fresh ballast and ballast on the track of the line. The Los Angeles abrasion test distinguished clearly between the superior quality material and the very poor material.

The Los Angeles Abrasion test results for Elbahe, Diredawa, Adigala and Dewanle track sections can be found on Appendix B of this paper.

### 3.5.3 Crushing Value Test

This is a method for the determination of ballast crushing value which gives a relative measure of the resistance of ballast to crushing under a gradually applied compressive load. To get a reliable result taking at least two samples and calculating the average is preferred. In this study, two samples have been taken from each of selected sites and from quarry site then an average value has been calculated. Table 3-9 shows the crushing value test results at each selected railway section.

**Table 3-5 Average Crushing Aggregate (CA) Value for each Site**

Section	Elbahe quarry		Dire-dewa		Adigala		Dewanle	
Sample	1	2	1	2	1	2	1	2
Mass of ballast before loading (G1) (Kg)	10	10	10	10	10	10	10	10
Mass of ballast after loading (G2) (Kg)	8.15	8.3	7.16	7.34	5.5	5.15	6.45	6.75
$CA(\%) = \frac{G1 - G2}{G1} * 100$	18.5	17	28.4	26.6	45	48.5	35.5	32.5
Average CA (%)	<b>17.75%</b>		<b>27.5%</b>		<b>46.75%</b>		<b>34%</b>	

### 3.6 Degree of Ballast Fouling

In this study to evaluate degree of ballast fouling at each site Void Contamination Index (VCI), which can show the role of different fouling materials, has been used. Because fouling materials can have different void ratio, specific gravity and gradation which result in altering ballast layer characteristics. The fouling Equation 3.1 has been used to calculate degree of fouling at each selected site;

$$VCI = \frac{(1 + e_f)}{e_b} * \frac{G_{sb}}{G_{sf}} * \frac{M_f}{M_b} * 100 \quad 3.1$$

Where  $e_b$ , is void ratio of clean ballast

$e_f$ , is void ratio of fouling material

$G_s$ , is specific gravity of clean ballast

$G_{sf}$ , is specific gravity of fouling material

$M_b$ , is mass of clean ballast

$M_f$ , is mass of fouled ballast

The total length covered at each section was 1250 meters with an interval of 250 meters. The first section was Diredawa, specifically at Melka-Jebdu station. And the others were Adigala and Dewanle track sections.

To attain this, both field investigation and laboratory tests have been used. Field investigation was used to determine the mass of clean ballast, mass of fouling material and thickness of ballast excavated whereas laboratory tests were used to know specific gravity of ballast and specific gravity of fouling material. The procedures used in the field can be found on Appendix C of this paper.

### **3.6.1 Specific Gravity of Ballast**

The specific gravity of a given material is defined as the ratio of the weight of a given volume of material to the weight of an equal volume of distilled water. It is denoted by  $G_s$ . For this study specific gravity for both ballast and fouling material were determined. This was conducted as per standard ASTM and determines bulk specific gravity on the basis of weight of saturated surface-dry aggregate.

Ballast sample as per standard used for this procedure and the result is reported at a temperature of 20°C. This test method was performed in accordance with ASTM C127. According to the standard sample of aggregates is immersed in water for 24 hours to essentially fill the pores. Then the sample is weighed after it is removed from the water and the surfaces of the particles are towel dried. Next, the sample is submerged in water and weighed. Finally, the sample is oven-dried and weighed for final dry mass. Using the mass values and the formulas provided by the test method will result in obtaining the specific gravity and absorption of the aggregate.

The temperature correction factor (K) at varying temperature has found from ASTM standard. The following table 3-10 shows all values of K at varying temperature. And for this study a temperature correction factor of 0.9993 has been used. The following Tables

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3.11,3.12 and 3.13 are specific gravity of one site from each selected sections and the others are found on Appendix D of this document.

**Table 3-6 Values For Temperature Correction (K) at Varying Temperature as per ASTM**

Temperature (T °C)	K
16	1.0007
17	1.0006
18	1.0004
19	1.0002
20	1.0000
21	0.9998
22	0.9996
23	0.9993
24	0.9991
25	0.9988
26	0.9986
27	0.9983
28	0.9980
29	0.9977
30	0.9974

**Table 3-7 Specific gravity of ballast at Dire-dewa section (Melka-Jebdu)**

Test#	1	2	3	Average	
A	Mass of oven dry sample in air (g)	1603.4	1610.3	1612.5	
B	Mass of Pycnometer filled with water water(g)	1696.5	1710.6	1650.3	
C	Mass of pycnometer +SSD Sample +water	2820	2810.4	2814.3	
S	Mass of SSD sample	1729.9	1745.1	1772.9	
Gsb	Bulk specific gravity	2.85074	2.70243	2.90961	

**Table 3-8 Specific gravity of ballast at Adigala section**

Test#	1	2	3	Average	
A	Mass of oven dry sample in air (g)	1550.8	1648.2	1579.1	
B	Mass of Pycnometer filled with water water(g)	1700	1695.6	1670	
C	Mass of pycnometer +SSD Sample+water	2826.4	2835.4	2857.3	
S	Mass of SSD sample	1825.6	1769.4	1754.2	
Gsb	Bulk specific gravity	2.60916	2.80839	3.09221	

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The laboratory results for specific gravity of ballast sample three at Adigala section shows a little bit different from the other two samples. When such big difference happened, we have to ignore the one which contradicts (3.09) from the other results. Therefore, taking the average of the two samples, we have calculated the specific gravity of ballast at Adigala section.

**Table 3-9 Specific gravity of ballast at Dewanle section**

	Test#	1	2	3	Average
A	Mass of oven dry sample in air (g)	1572.4	1627.8	1658.1	
B	Mass of Pycnometer filled with water water(g)	1687.2	1675.25	1684.7	
C	Mass of pycnometer +SSD Sample+water	2814.3	2825.61	2841.36	
S	Mass of SSD sample	1750.2	1762.74	1775.64	
Gsb	Bulk specific gravity	2.80689	2.87649	2.86665	

### 3.6.2 Classification of Fouling Material

In this study the fouling material types and characteristics have been different for those selected sections. Grain size distribution and Atterberg limit tests have been conducted to know the engineering properties of fouling materials. Moreover, Specific gravity tests have also been conducted.

Fouling materials are materials passing 9.5 mm sieve so to differentiate ballast with fouling materials has been done by sieving.





**Figure 3-5 Fouling Materials on the track**

This test was conducted to determine whether the soil consists of predominantly gravel, sand, silt, or clay sizes and, to the extent limit. The determination of the fractions of the particles will help to identify the soil type. Based on grain size based classification method, samples of fouling materials found Diredewa has been categorized under coarse sand whereas clay is in Adigala and Dewanle.

**Table 3-10 Fouling Materials at Diredawa Section**

Type of soil	Gravel	Sand			Silt			Clay
		Coarse	medium	Fine	Coarse	medium	Fine	
particle size (mm)	>2	2-0.6	0.6-0.2	0.06	0.02	0.006	0.002	<0.002
particle retained, %	9.53	63.58	9.43	6.91	4.18	3.57	2.18	0.62

**Table 3-11 Fouling material at Adigala section**

Type of soil	Gravel	Sand			Silt			Clay
		Coarse	medium	Fine	Coarse	medium	Fine	
particle size (mm)	>2	2-0.6	0.6-0.2	0.06	0.02	0.006	0.002	<0.002
particle retained, %	0.75	2.52	3.65	4.36	6.85	10.25	13.17	58.45

**Table 3-12 Fouling material at Dewanle section**

Type of soil	gravel	sand			silt			Clay
		coarse	medium	fine	coarse	medium	fine	
particle size (mm)	>2	2-0.6	0.6-0.2	0.06	0.02	0.006	0.002	<0.002
particle retained, %	1.82	3.6	4.71	5.81	8.32	11.91	12.16	51.67

### 3.6.3 Specific Gravity of Fouling Material

Based on laboratory tests the sections were fouled by clay and crushed ballast (Sand). The test results have shown that selected sites of Dire-dawa track sections have fouled by sand materials whereas at selected sites of both at Adigala and Dewanle clay is the dominant material which makes the ballast to be fouled.

The specific gravity of crushed ballast was determined in accordance with ASTM D854. The average specific gravity was determined to be 2.65 whereas the average specific gravity of clay was determined to be 2.72 and 2.71 at Adigala and Dewanle sections. The results of specific gravity for each sections have found on Appendix D of this paper.

### 3.6.4 Void Ratio

Void ratio for ballast and fouling material was determined by the weight-volume relationship and the corresponding values have been calculated using equation 3.2.

$$e = \frac{G_s \rho_w}{\rho_d} - 1 \quad 3.2$$

Where e, is void ratio, G<sub>s</sub>, is specific gravity, ρ<sub>w</sub> is water density and ρ<sub>d</sub> is dry density.

The dry density data of ballast is taken from previously investigation works for those sections and all the results are on Appendix D of this paper.

## 3.7 Hydraulic Conductivity of Fouled Ballast

To determine the equivalent hydraulic conductivity of ballast, analytical model which assumes non uniformly distributed fouled material has been used for this study since fouling materials accumulates more towards the bottom of the ballast layer due to vertical

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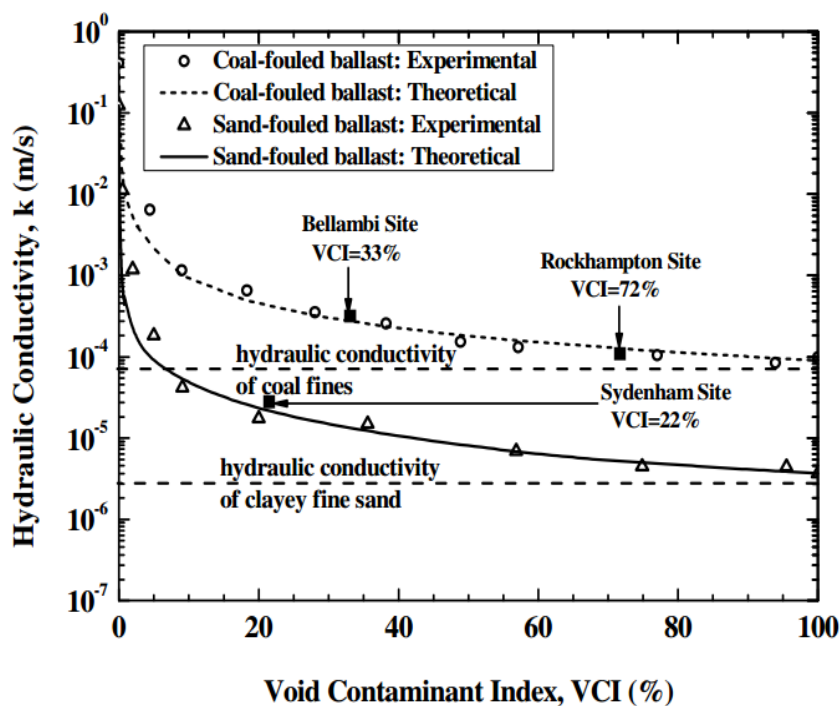
migration under rainwater and vibration under train passage. Therefore, for contaminated ballast with non-uniformly distributed fouled material analytical model used for equivalent hydraulic conductivity determination.

$$K = \frac{k_b * k_f}{k_f + \frac{VCI}{100} * (k_b - k_f)} \tag{3.3}$$

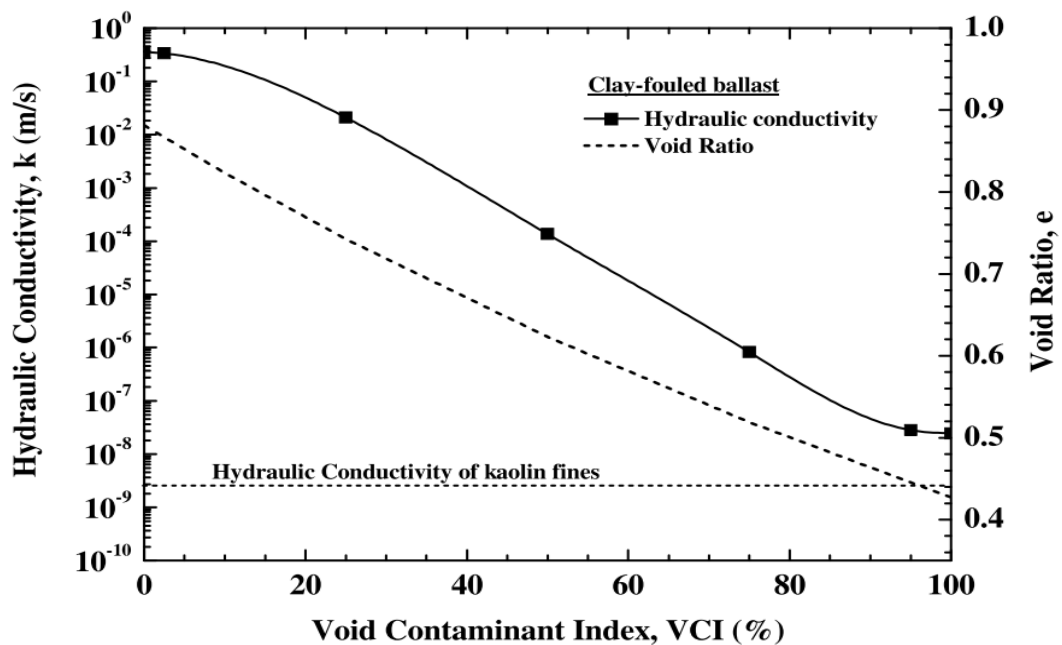
Where  $k_b$ , hydraulic conductivity of clean ballast

$k_f$ , hydraulic conductivity of fouled ballast

For hydraulic conductivity of clean ballast Selig and Water (1994) criteria has been used and to estimate the fouled ballast hydraulic conductivity the experimental results done by Tennakoon (2012) and his colleagues has been inferred. An average value for hydraulic conductivity of clean ballast for all section has taken to be 0.0375 m/sec. But for fouled ballast case, the values are dependent on the fouling material types. Therefore, Diredawa is fouled by sand whereas Adigala and Dewanle are fouled by clay material. The experimental result graphs by Figure 3-13 has been referred for this case. Hydraulic conductivity values for each sections have found on Appendix E of this paper.



(a)



(b)

Figure 3-6 Experimental results used for estimation of hydraulic conductivity of fouled ballast by a) sand b)clay

### 3.8 Seepage Analysis

Steady-state seepage analyses were performed on three selected cross sections of Ethio-Djibouti railway line. The analyses were performed using the computer program SEEP/W (2012), part of the geotechnical analysis software package Geo Studio 2012, developed by GEO-SLOPE International, Ltd. which is a finite-element modeling program that evaluates seepage.

To use SEEP/W, section geometry is entered into the program as distinct ballast layers. Permeability or hydraulic conductivity values (horizontal and vertical) are then assigned to the layers as ballast type designations. Pressure or flow boundary conditions are then applied to the model to define the initial conditions for seepage analyses. Seepage analyses were performed for the sections shown in Table 3-21;

**Table 3-13 Selected Track Section For Seepage Analysis**

Section	Chainage	layer thickness (cm)	VCI Value
Diredewa	DK 126+950	15	30.81%
		10	32.85%
Adigala	DK 237+400	15	53.35%
		10	58.03%
Dewanle	DK 347+600	15	46.93%
		10	49.41%

### **3.8.1 Assumptions**

To simulate the seepage analysis for selected sections of the track, the following reasonable assumptions have been made.

The first assumption made in this study was the two dimensional steady state flow through ballasted track because flow can occur in both vertical and horizontal directions, therefore, a 2-D seepage analysis was conducted.

In this study  $k_h$  and  $k_v$  are assumed to be the same. Because for most large size granular materials, the hydraulic conductivity tends to isotropic. Therefore, the difference in values of  $k_h$  and  $k_v$  for coarse aggregates is significantly less than for those fine grained materials such as silt and clay. Hence,  $k_h=k_v$ =equivalent hydraulic conductivity of ballast for each layer has been used to simulate seepage analysis [28].

A hydraulic head equal to the track height was assumed at the top surface. This was another assumption made in this study.

In this study, erosion of fouled materials is neglected due to the minimum amount of rainfall in the areas which have been investigated.

### **3.8.2 Material Model**

In this study, the material model used for seepage analysis is saturated only material model because for ballast material linear Darcy's law is still valid. Darcy's law is developed after conducting tests of porous media at saturated state.

### **3.8.3 Boundary Condition**

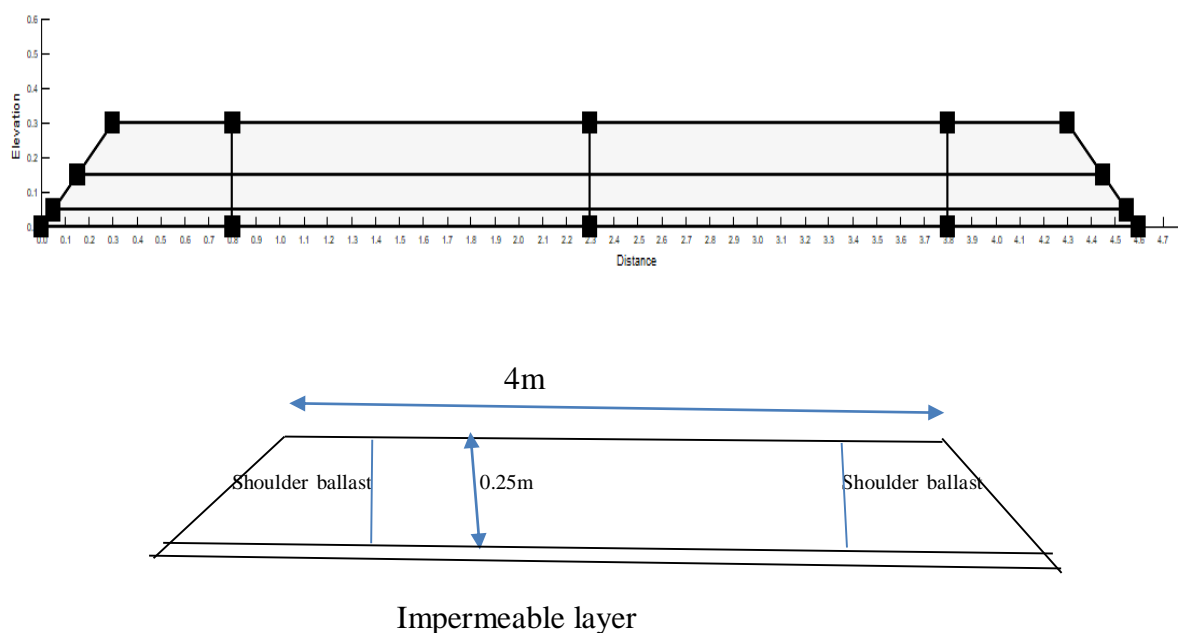
Two types of boundary conditions were applied to the finite element model. A free drainage boundary condition was used at the top of the shoulder ballast surface, along the centerline and at the bottom bed of ballast layer and an impermeable boundary was applied below the bottom bed of ballast.

### **3.8.4 Modelling**

Hydraulic conductivity values corresponding to different VCI values obtained from analytical model were used as input parameters in the analysis. A vertical cross section of a typical section track is used in the analysis as shown in Figure 3-14. The hydraulic conductivity values for each selected track sections have been sorted out from Appendix E and shown by Table 3-22.

To simulate this the real scenario at each sections is considered. The model considered as fouling track;

- The track is divided into two horizontal layers
- Hydraulic conductivity for each layer according to VCI values is accounted



**Figure 3-7 Vertical cross section of typical ballast layer used in seepage analysis**

**Table 3-14 Hydraulic Conductivity of selected track sections (Appendix E)**

Section	Layer	Material	Hydraulic conductivity (cm/sec)
<b>Diredewa</b>	1	Crushed ballast	5.62e-5
	2	Sand	4.5e-5
<b>Adigala</b>	1	Crushed ballast	5.93e-4
	2	Clay	1.7e-4
<b>Dewanle</b>	1	Crushed ballast	1.34e-4
	2	Clay	3.59e-5

**Table 3-15 Saturated hydraulic conductivity and saturated water content**

Material	Ksat (cm/sec)	$\Theta_s$	Mv (/kpa)
<b>Crushed ballast layer</b>	0.01	0.3	0.05e-3
<b>Sand</b>	1e-4	0.342	0.05e-3
<b>Clay</b>	1.3e-5	0.435	1.5e-3

### **3.9 Classification of Track Drainage**

Based on the available data, 122mm/24hr the maximum rainfall intensity in eastern Ethiopia. The corresponding critical flow rate is 1.7e-6 m/sec over the unit length of the track. From the seepage analysis, the maximum drainage capacity (Q) of the ballast layer can be determined for various levels and conditions of fouling. When track drainage capacity is equal to or lower than what is required for a given rainfall rate, then the fouled track is considered to be impermeable. In this context, a ratio between the computed track drainage capacity and the critical flow (Q/Qc) has been used as a dimensionless index to classify the drainage condition in this study.

**Table 3-16 Track Drainage Classification**

Section	Q (m <sup>3</sup> /sec)	Qc (m <sup>3</sup> /sec)	Remark	Drainage Category
Diredawa	8.21e-6	1.70e-06	1<Q/Qc<10	Acceptable drainage
Diredawa	4.55e-06	1.70e-06	1<Q/Qc< 10	Acceptable drainage
Diredawa	7.70e-06	1.70e-06	1<Q/Qc<10	Acceptable drainage
Aigala	2.55e-7	1.70e-06	0.1<Q/Qc<1	Poor drainage
Adigala	4.25e-7	1.70e-06	0.1<Q/Qc<1	Poor drainage
Adigala	5.27e-7	1.70e-06	0.1<Q/Qc<1	Poor drainage
Dewanle	8.5e-07	1.70e-06	0.1<Q/Qc<1	Poor drainage
Dewanle	1.02e-6	1.70e-06	0.1<Q/Qc<1	Poor drainage
Dewanle	1.53e-6	1.70e-06	0.1<Q/Qc<1	Poor drainage

To determine the critical degree of fouling current drainage conditions on those sites especially at Adigala and Dewanle, 2D seepage analysis has been done by assuming different VCI values. The seepage analysis shows when VCI reaches at 35%, the drainage category has changed to poor condition. Table 3-25 shows the different values of VCI to determine the critical degree of fouling.

**Table 3-17 Critical VCI Value Determination**

VCI (%)	Drainage
0	Good
20	Good
25	Acceptable
30	Acceptable
35	Poor
40	Poor
45	Poor
50	Poor

**CHAPTER 4 RESULTS AND DISCUSSIONS**

**4.1 Laboratory Test Result**

The ballast material should resist the effects coming from chemical, mechanical and environmental. To attain this the ballast material should be naturally crushed aggregate with angular, having sharp and cuboidal shape. In this study, the ballast material which has been tested was crushed Igneous rock aggregate mainly Basalt with an average specific gravity of 2.8 which particles ranging from 16 to 63 mm.

But the gradation of ballast samples on track didn't completely fulfill ASTM requirements whereas the gradation of ballast on the quarry had fulfill the requirements in some extent. This implies the quality of ballast material used on those selected sections of Ethio-Djibouti line was not good.

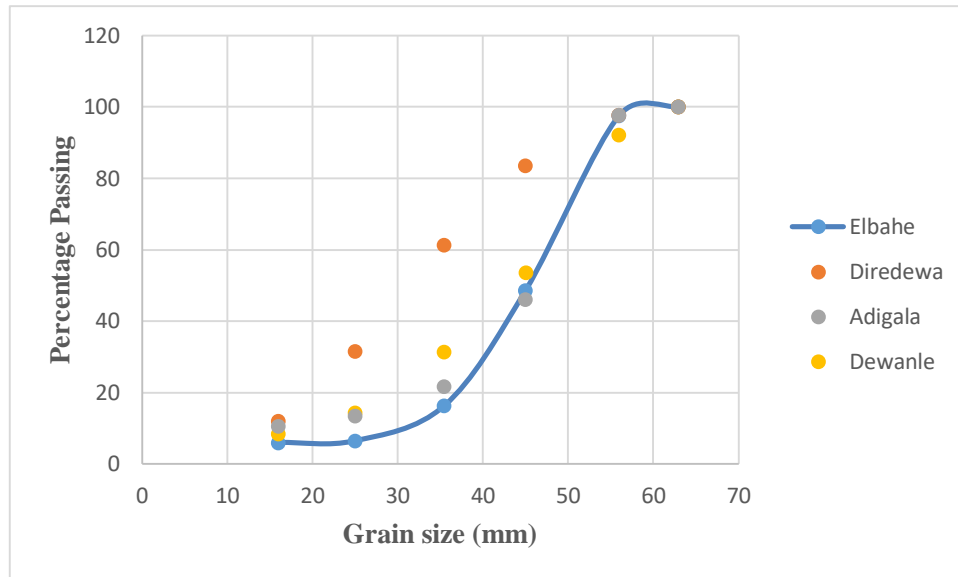
**Table 4-1 Specification Limits as per ASTM**

Sieve size (in)	Sieve size (mm)	ASTM C131 specification limit
2.5	63.5	100
2	50.8	90-100
1.5	38.1	50-80
1	25.4	10-35
0.75	19.05	0-10
0.5	12.7	0-5

**Table 4-2 Average Gradation of Ballast Samples**

Sieve opening (mm)	Percentage Passing (%)			
	Elbahe	Diredawa	Adigala	Dewanle
16	6.075	12	10.586	8.43
25	6.555	31.568	13.578	14.43
35.5	16.413	61.328	21.738	31.5
45	48.553	83.578	46.174	53.634
56	97.54	97.822	97.702	92.264
63	100	100	100	100

Figure 4-1 shows the ballast gradation difference between the quarry site Elbahe and samples from the track of Diredawa, Adigala and Dewanle. This will help to predict the extent of fouling and deterioration of ballast with respect to service life time of ballast.



**Figure 4-1 Comparison of gradation curve for quarry site and track ballast**

During this study, three sets of samples were taken from each of the three selected sites of the line and also at the ballast quarry site for Los Angeles Abrasion test. There was a big gap in LAA test results of fresh ballasts at quarry and ballasts samples on the track. Within two years' operation time of the line a difference of such amount is unexpected. For the selected section of the line surface ballast gradation were designed in conformity with the requirements in Table 4-3;

**Table 4-3 Design Requirements of Ballast Materials at Ethio-Djibouti Railway Line**

Property	Parameter	Technical Index
Abrasion resistance and impact resistance	Los Angeles abrasion, LAA (%)	$27 \leq LAA < 32$
	Standard aggregate impact toughness, IP	$10 < IP \leq 95$
	Stone abrasion-resistant hardness coefficient K (dry grinding)	$17 < K \text{ (dry grinding)} \leq 18$
Crushing resistance	Standard aggregate crushing ratio, CA (%)	$9 \leq CA < 14$
	Percentage of crushed ballast aggregate, CB (%)	$18 \leq CB < 22$
Water permeability	Permeability coefficient, Pm ( $10^{-6}$ cm/s)	$3 < Pm \leq 4.5$
Water permeability	Compressive strength of stone powder test module, $\sigma$ (MPa)	$0.4 \leq \sigma < 0.55$
	Stone powder liquid limit, LL (%)	$20 \geq LL > 16$
	Stone powder plastic limit, PL (%)	$11 \geq PL > 9$
Atmospheric corrosion resistance	Loss rate after immersion in sodium sulfate solution (%)	$< 10$

**Table 4-4 Recommended Test Results based on AREMA and ASTM**

Test indicator	Building material	
	Basalt	Limestone
Volume density (g/cm <sup>3</sup> )	≥2.60	≥2.60
Volumetric weight (kg/m <sup>3</sup> )	≥1400	≥1400
Water absorbing capacity (%)	≤1.0	≤2.0
Los Angeles rate of wear (%)	≤25	≤30
Loss factor of immersion in sodium sulfate solution (%)	≤5	≤5
Needle or flaky grains (%)	≤5	≤5
Elongation index or flakiness index (%)	≤25	≤25
Rate of crushing of ballast aggregate (%)	≤25	≤25

**Table 4-5 Comparison of LAA and CV Test Results on Quarry Site and Track**

Selected sites	LAA values	CV values
Quarry site (Elbahe)	11.88%	17.75%
Diredawa	29.13%	27.5%
Adigala	49.1%	46.75%
Dewanle	41.33%	34%

The laboratory test results on fouling materials at each sections revealed that, fine materials existed on the track sections have different particle size and properties. In Diredawa the dominant fine material has found to be coarse sand while in Adigala and Dewanle sections clay materials are the main fouling materials. The fine materials are incorporated with the ballast material on track which has an effect on its drainage performance.

## **4.2 Mechanism of Ballast Fouling**

When ballast is not functioning correctly, the track strength will be not adequate and thus affects track stability. There is a variation in track stability failure which varies from rapid deterioration with little warning to slow and progressive deterioration with predictable maintenance options. Ballast related degradation and deterioration is under progressive one. This progressive failure gives visual evidence to provide the corresponding maintenance measurements.

In this study, the fouling materials are the result of ballast breakdown under load the high velocity wind in the areas. The fouled ballast problems areas that are investigated contain crushed ballast (gravel) from ballast breakdown combined with fine grained clay particles that resulted from wind blow onto the track. Fines pumping into the ballast from subgrade is insignificant in the investigated areas.

If the conditions in the line will continue with this circumstance, the ballast voids will completely have filled with fouling material, causing the ballast particles to lose contact with each other and essentially “float” within the fouling material. This can cause complete loss in ballast support and the track will be unable to perform the functions.

### **4.3 Degree of Ballast Fouling**

Among fouling indices, VCI is more sensitive to the changes of the fouling type and extent which is more realistic. Void Contamination Index(VCI) is the only fouling characterization method that incorporates the specific gravity of the fouling material. Ballast fouling has to be evaluated by a more rational parameter called VCI which considers type of fouling material. Laboratory tests such as specific gravity of ballast and proper field sampling procedure have been done to accurately evaluate the fouling condition unlike assessment of fouling based on mass based fouling indices such as FI.

The fouling particles fill the voids and prevent the drainage of the ballast. In order to evaluate the effects of fouling materials and the trapped water (by fouling) on the performance of the ballast under loading, this study has used this important parameter.

According to the conducted laboratory tests and field investigations on selected sites of Diredewa, Adigala and Dewanle, the ballast is filled with fine particles. The field investigation result has showed, for each sampling trenches there is a significant mass of fine particles passing 9.5 mm sieve size which was an evidence to say the ballast is fouled on those selected sites. The results from rate of fouling determination has also confirmed, the extent of ballast fouling is significant especially in Adigala and Dewanle. The following Table 4-1 is the summary showing percentage of voids filled by fine particles in each respective sections

**Table 4-6 Percentage of Void filled by fine particles**

<b>Section</b>	<b>Average Percentage of Void filled by fines</b>
Dire dewa	30.84%
Adigala	54.12%
Dewanle	43.70%

#### **4.4 Effect of Fouling on Drainage**

Ballast fouling problems will degrade the track performance and demand additional maintenance. To prevent or minimize these problems, adequate drainage is imperative in ballasted tracks. To achieve this and to get ballasted track having good drainage performance, many investigation works should be expected for the new planned tracks as well as the one which are giving operation. Regular inspection and assessment works focusing on railway ballast can minimize the risk of drainage problems on ballasted track. In this study except Diredeewa section, the fouling materials are highly plastic clay which will have a devastated effect on ballast material during its remaining life time. This will impend the drainage capacity of the track.

To increase the drainage capacity of the track maintenance method which is recommended in this study is ballast shoulder cleaning because it reduces track fouling and increases ballast life time service.

Shoulder cleaning should be done before the VCI value reaches 35% because the drainage capacity have changed to poor condition if VCI exceeds 35%.

## **CHAPTER 5 CONCLUSIONS AND RECCOMENDATIONS**

### **5.1 Conclusions**

Study of two dimensional flow was imperative for investigating the influence of the degree of fouling on the overall hydraulic conductivity of fouled ballast. In this study, the drainage condition of the track has been proposed based on typical high rainfall intensity in the areas investigated and the corresponding track drainage capacity. Generally, the following conclusions were drawn from this study;

- The results of this study showed that ballast materials at selected sites of Dire dawa track section of Addis-Djibouti line has fouled by coarse sand materials while Adigala and Dewanle track sections has fouled by clay material. Especially at Adigala more than half of the voids are filled with fines based on VCI results.
- The results have confirmed that hydraulic conductivity values decreased with increasing Void Contamination Index Value according to analytical approach method.
- It has been shown that the drainage conditions of selected sites at Diredawa has fallen under acceptable condition while Adigala and Dewanle sections of Addis-Djibouti line are under poor drainage category according to the classification made based on criteria used in this study.
- The result revealed that shoulder cleaning should be done before VCI reaches 35%.

### **5.2 Recommendations**

Shoulder cleaning is recommended before VCI value reaches 35% because if the degree of fouling exceeds 35% the drainage condition will be changed to poor category.

A new and modified ballast maintenance schedule is recommended which fits the level of fouling on those selected sections. Further more detail investigation on ballast fouling must be done by taking more number of samples and conducting variety of tests over a wide coverage to see effects on ballast drainage capacity, shear strength of ballast, track settlement and total track performance.

## **Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line**

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Experimental machines to determine the ballast permeability properties are however costly to fabricate and are not available indeed. Hence test machines are availability and other additional studies on ballast fouling for different newly constructed railway projects in the country will enable other researcher interested in this area to set maintenance schedules based on predicted life span of ballast.

To evaluate the track drainage capacity at higher level of accuracy, a more sophisticated numerical model having a larger number of discretized ballast layers with a wider variation of corresponding VCI values will be required.

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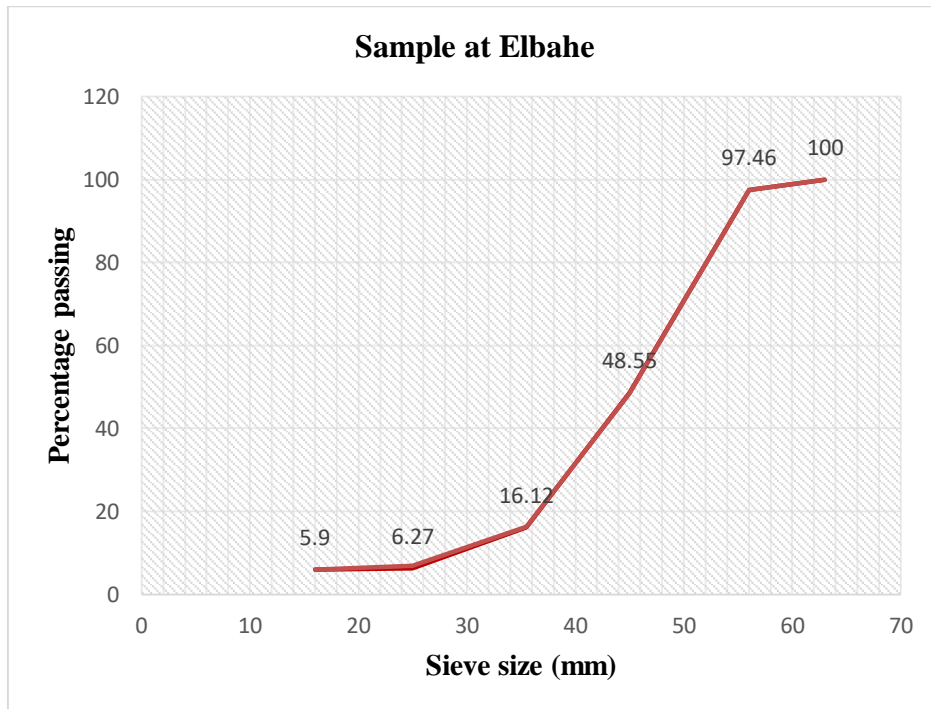
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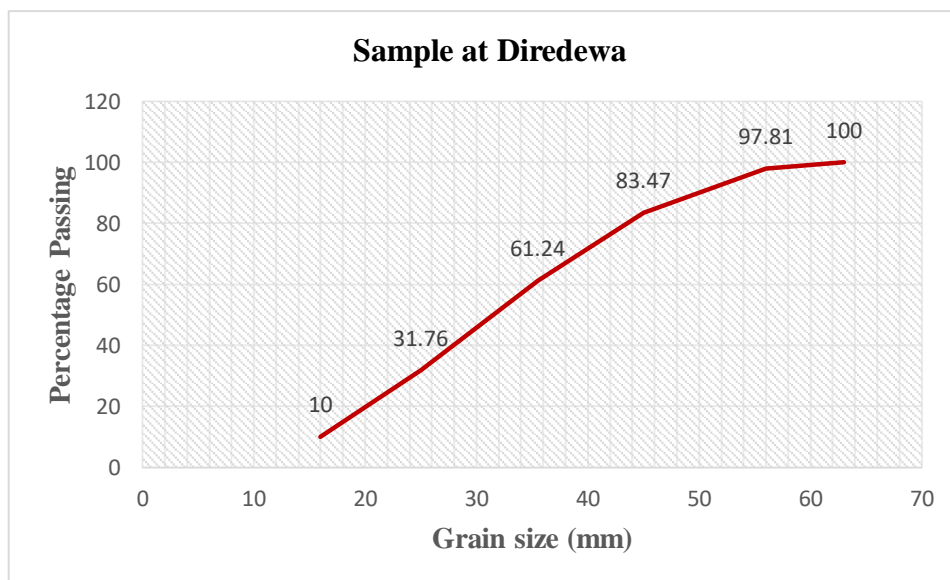
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**APPENDIX A**

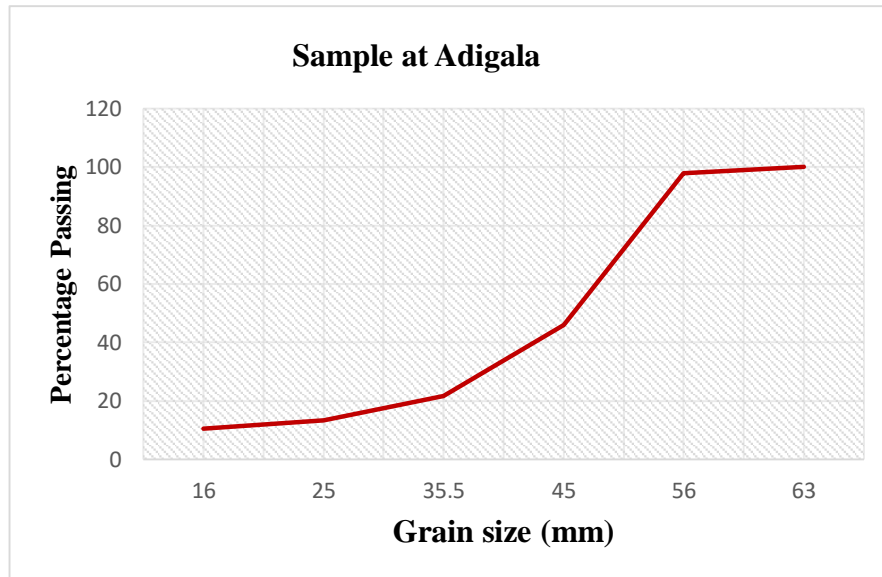
**Gradation curve of ballast at each section**



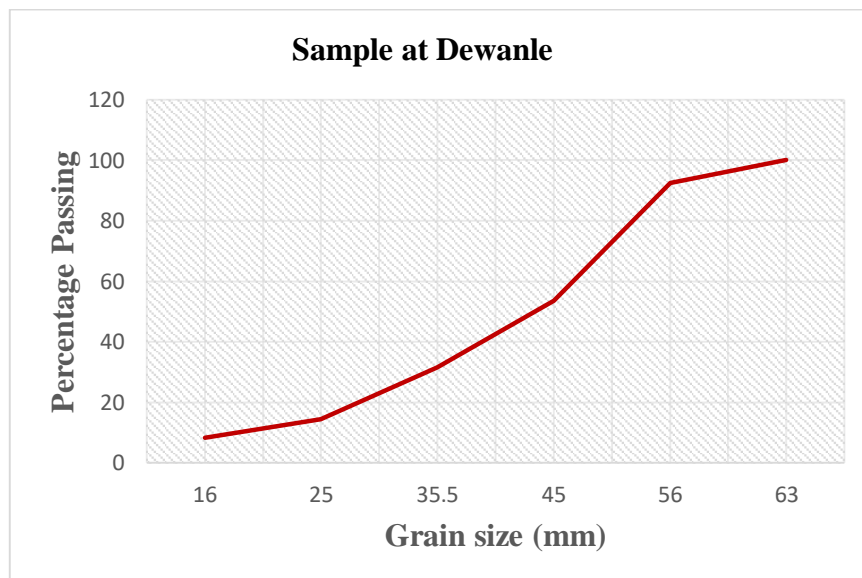
**Figure 5-1 Gradation curve of ballast at Elbahe Site**



**Figure 5-2 Gradation curve of ballast at Diredawa site**



**Figure 5-3 Gradation of ballast at Adigala site**



**Figure 5-4 Gradation of ballast at Dewanle site**

**APPENDIX B**

Los Angeles Abrasion test results

**Table 5-1 LAA Test Results at Elbahe Quarry Site**

Sample No.	Sample Weight		L A A (%)	
	G <sub>1</sub> (g) Weight before Abrasion	G <sub>2</sub> (g) Weight after Abrasion	L A A = $\frac{M1 - M2}{M1} \times 100$	Average
1.	10000	8850.50	11.49%	<b>11.88%</b>
2.	10000	8765.34	12.35%	
3.	10000	8821.45	11.79%	

**Table 5-2 LAA Test Results at Melka Jebdhu (Diredewa)**

Sample No.	Sample Weight		L A A (%)	
	G <sub>1</sub> (g) Weight before Abrasion	G <sub>2</sub> (g) Weight after Abrasion	L A A = $\frac{G_1 - G_2}{G_1} \times 100$	Average
1.	10000	7206	27.94%	<b>29.13%</b>
2.	10000	6918	30.82%	
3.	10000	7137	28.63%	

**Table 5-3 LAA Test Results at Adigala Track Section**

Sample No.	Sample Weight		L A A ( % )	
	G <sub>1</sub> (g) Weight before Abrasion	G <sub>2</sub> (g) Weight after Abrasion	L A A = $\frac{G_1 - G_2}{G_1} \times 100$	Average
1.	10000	5150.78	48.49%	<b>49.1%</b>
2.	10000	5096.23	49.04%	
3.	10000	5025.58	49.74%	

**Table 5-4 LAA Test Results at Dewanle Track Section**

Sample No.	Sample Weight		L A A ( % )	
	G <sub>1</sub> (g) Weight before Abrasion	G <sub>2</sub> (g) Weight after Abrasion	L A A = $\frac{G_1 - G_2}{G_1} \times 100$	Average
1.	10000	5740.3	42.59%	<b>44.33%</b>
2.	10000	5395.6	46.05%	
3.	10000	5564.76	44.35%	

**APPENDIX C**

**Procedures for determination of VCI in the field**

The ballast is excavated in two layers so that the fouled ballast layer is properly identified. The procedures for the case of two layers in this study;

1. Remove the first ballast layer and measure its thickness and the total ballast sample taken.
2. Sieve the whole ballast measured on the first ballast layer using 9.5 mm sieve size to calculate the mass of ballast passing and retaining 9.5mm sieve.
3. Remove the second ballast layer and measure its thickness and the total ballast sample taken from the second layer.
4. Determine the dry weights of the clean ballast ( $M_{b1}$ ,  $M_{b2}$ ) and the dry weights of the fouling material ( $M_{f1}$  and  $M_{f2}$ ) for layer 1 and 2 respectively.
5. Determine the specific gravities of ballast particle ( $G_{sb}$ ) and fouling material ( $G_{sf}$ )
6. Calculate the void ratio by formula.
7. Then determine VCI for each site and for each layer.

$$VCI = \frac{1 + ef}{eb} * \frac{G_{sb}}{G_{sf}} * \frac{MF}{Mb} * 100$$

For instance, VCI value of Diredeewa section at Change of DK 123+700 at the first layer with given material properties of  $ef=1.157$ ,  $eb=0.88$ ,  $G_{sb}=2.82$ ,  $G_{sf}=2.65$  and mass of total ballast taken at this layer= $1.59\text{kg}$ , and after sieving using 9.5 mm sieve  $M_b=1.43\text{kg}$  and  $M_f=0.16\text{ kg}$  then VCI calculated as;

$$VCI = \frac{1 + 1.157}{0.88} * \frac{2.82}{2.65} * \frac{0.16}{1.43} * 100\%$$

$$VCI = 29.18\%$$

**Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line**

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**APPENDIX D**

Section	Chainge	layer thickness(cm)	Gsb	Gsf	eb	ef	mb (kg)	mf (kg)	VCI (%)	
Diredewa	DK 126+700	15	2.82	2.65	0.88	1.157	1.43	0.16	29.18%	
		10	2.82	2.65	0.88	1.157	1.42	0.17	31.23%	
	DK 126+950	15	2.8	2.63	0.88	1.157	1.44	0.17	30.81%	
		10	2.8	2.63	0.88	1.157	1.43	0.18	32.85%	
	DK 127+200	15	2.79	2.61	0.88	1.157	1.42	0.16	29.52%	
		10	2.79	2.61	0.88	1.157	1.41	0.18	33.45%	
	DK 127+450	15	2.8	2.63	0.88	1.157	1.43	0.15	27.37%	
		10	2.8	2.63	0.88	1.157	1.42	0.17	31.24%	
	DK 127+700	15	2.83	2.65	0.88	1.157	1.43	0.15	27.46%	
		10	2.83	2.65	0.88	1.157	1.41	0.19	35.27%	
	Adigala	DK 237+150	15	2.81	2.62	0.8	1.269	1.42	0.24	51.41%
			10	2.81	2.62	0.8	1.269	1.4	0.25	54.32%
DK 237+400		15	2.79	2.63	0.8	1.269	1.41	0.25	53.35%	
		10	2.79	2.63	0.8	1.269	1.4	0.27	58.03%	
DK 237+650		15	2.8	2.61	0.8	1.269	1.42	0.24	51.43%	
		10	2.8	2.61	0.8	1.269	1.41	0.26	56.11%	
DK 237+900		15	2.81	2.6	0.8	1.269	1.43	0.25	53.59%	
		10	2.81	2.6	0.8	1.269	1.42	0.26	56.13%	
DK 238+150		15	2.8	2.61	0.8	1.269	1.4	0.24	52.16%	
		10	2.8	2.61	0.8	1.269	1.39	0.25	54.73%	
Dewanle		DK 347+100	15	2.84	2.61	0.74	1.106	1.41	0.18	39.53%
			10	2.84	2.61	0.74	1.106	1.4	0.19	42.03%
	DK 347+350	15	2.81	2.65	0.74	1.106	1.42	0.19	40.38%	
		10	2.81	2.65	0.74	1.106	1.41	0.2	42.81%	
	DK 347+600	15	2.83	2.64	0.74	1.106	1.43	0.22	46.93%	
		10	2.83	2.64	0.74	1.106	1.42	0.23	49.41%	
	DK 347+850	15	2.82	2.63	0.74	1.106	1.43	0.21	44.81%	
		10	2.82	2.63	0.74	1.106	1.42	0.2	42.98%	
	DK 348+100	15	2.84	2.64	0.74	1.106	1.43	0.21	44.96%	
		10	2.84	2.64	0.74	1.106	1.42	0.2	43.12%	

**Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line**

**APPENDIX E**

Section	Chainge	layer thickness(cm)	Kb (m/s)	Kf (m/s)	VCI (%)	K (m/s)	
Diredewa	DK 126+700	15	0.0375	$1.995 \times 10^{-5}$	29.18	$6.8 \times 10^{-5}$	
		10	0.0375	$1.585 \times 10^{-5}$	31.23	$5.08 \times 10^{-5}$	
	DK 126+950	15	0.0375	$1.738 \times 10^{-5}$	30.81	$5.62 \times 10^{-5}$	
		10	0.0375	$1.479 \times 10^{-5}$	32.85	$4.5 \times 10^{-5}$	
	DK 127+200	15	0.0375	$1.91 \times 10^{-5}$	29.52	$6.46 \times 10^{-5}$	
		10	0.0375	$1.514 \times 10^{-5}$	33.45	$4.51 \times 10^{-5}$	
	DK 127+450	15	0.0375	$2.34 \times 10^{-5}$	27.37	$8.52 \times 10^{-5}$	
		10	0.0375	$1.55 \times 10^{-5}$	31.24	$4.95 \times 10^{-5}$	
	DK 127+700	15	0.0375	$2.24 \times 10^{-5}$	27.46	$8.16 \times 10^{-5}$	
		10	0.0375	$1.26 \times 10^{-5}$	35.27	$3.58 \times 10^{-5}$	
	Adigala	DK 237+150	15	0.0375	$3.3 \times 10^{-4}$	51.96	$6.29 \times 10^{-4}$
			10	0.0375	$2.24 \times 10^{-4}$	54.9	$3.85 \times 10^{-4}$
DK 237+400		15	0.0375	$3.16 \times 10^{-4}$	53.35	$5.93 \times 10^{-4}$	
		10	0.0375	$1 \times 10^{-4}$	58.03	$1.7 \times 10^{-4}$	
DK 237+650		15	0.0375	$3.24 \times 10^{-4}$	51.43	$6.22 \times 10^{-4}$	
		10	0.0375	$1.55 \times 10^{-4}$	56.11	$2.75 \times 10^{-4}$	
DK 237+900		15	0.0375	$3.1 \times 10^{-4}$	53.59	$5.75 \times 10^{-4}$	
		10	0.0375	$1.514 \times 10^{-4}$	56.13	$2.69 \times 10^{-4}$	
DK 238+150		15	0.0375	$3.39 \times 10^{-4}$	52.16	$6.43 \times 10^{-6}$	
		10	0.0375	$2.1 \times 10^{-4}$	54.73	$3.82 \times 10^{-4}$	
Dewanle		DK 347+100	15	0.0375	$1.78 \times 10^{-3}$	39.67	$4.2 \times 10^{-3}$
			10	0.0375	$6.31 \times 10^{-4}$	42.03	$1.47 \times 10^{-3}$
	DK 347+350	15	0.0375	$1 \times 10^{-3}$	40.38	$2.39 \times 10^{-3}$	
		10	0.0375	$5.25 \times 10^{-4}$	42.81	$1.12 \times 10^{-3}$	
	DK 347+600	15	0.0375	$6.31 \times 10^{-5}$	46.93	$1.34 \times 10^{-4}$	
		10	0.0375	$1.78 \times 10^{-5}$	49.41	$3.59 \times 10^{-5}$	
	DK 347+850	15	0.0375	$3.16 \times 10^{-5}$	44.81	$7.05 \times 10^{-5}$	
		10	0.0375	$3.16 \times 10^{-4}$	42.98	$7.27 \times 10^{-4}$	
	DK 348+100	15	0.0375	$2.69 \times 10^{-5}$	44.96	$5.92 \times 10^{-5}$	
		10	0.0375	$4.79 \times 10^{-4}$	43.12	$1.1 \times 10^{-3}$	

**APPENDIX F**

The average rainfall intensity in the investigated areas ranges from 55mm/24hr to 122mm/24hr. Taking the maximum one which is 122mm/24hr which corresponds to 5.08mm/hr. This rainfall intensity used for critical flow rate over a unit length of a track as;

$$Q_c = CiA$$

Where C= runoff coefficient =0.3 (for unimproved areas)

A= Drainage area with unit length track

A= length of track\* width of track

$$= 1m * 4m = 4m^2$$

$$i= 1.412 * 10^{-6} m/sec$$

$$Q_c = 0.3 * 1.412 * 10^{-6} \frac{m}{s} * 4m^2$$

$$Q_c = 1.7 * 10^{-6} m^3/s$$

**APPENDIX G**

**Table 5-5 Typical Values of the Coefficient of Volume Compressibility,  $m_v$  (after Carter 1983)**

Type of clay	Description	$m_v$		
		$(\times 10^{-3} \text{m}^2/\text{kN})$		
		Lower Limit	Upper Limit	Average
Heavy over-consolidated boulder clays, stiff weathered rocks and hard clays	Very low compressibility		0.05	
Boulder clays, marls, very stiff tropical red clays	Low compressibility	0.05	0.1	0.075
Firm clays, glacial outwash clays, lake deposits, weathered marls, firm boulder clays, normally consolidated clays at depth and firm tropical red clays	Medium compressibility	0.1	0.3	0.2
Normally consolidated alluvial clays such as estuarine and delta deposits, and sensitive clays	High compressibility	0.3	1.5	0.9
Highly organic alluvial clays and peats	Very high compressibility	1.5		

## Assessment and Evaluation of Ballast Fouling and Its Effect on Drainage Performance of ballast; A case study on Addis-Djibouti Line

**Table 5-6 Rainfall intensity data for Ethiopian cities**

Meteo-stations	<i>H</i> (m a.s.l.)	<i>P</i> (mm) annual	CV (%) annual	<i>P</i> (mm) <i>belg</i>	<i>P</i> (mm) <i>kirent</i>	<i>P</i> (mm) <i>bega</i>	<i>k/a</i> %	<i>I</i> <sub>max</sub> mm/24 h	<i>I</i> <sub>p</sub> mm/24 h	<i>T</i> <sub>r</sub> 100 mm/ 24 h (years)	MFI
Adami Tulu	1,636	756.8	27	186.2	447.6	123.0	59.1	47.4	81.9	68.6	93.9
Addis Ababa	2,354	1,204.8	18	238.4	863.5	102.9	71.7				186.1
Adigudum	2,095	490.5	49	52.5	428.5	9.5	87.4				127.1
Al Damazin	470	691.0		56.0	596.0	39.0	86.3				137.3
Alamata	1,520	750.4	24	219.9	387.1	143.4	51.6	52.8	96.0	32.4	106.2
Alemaya	2,047	802.9	26	248.4	431.0	123.5	53.7	56.4	118.0	15.3	95.0
Arba Minch	1,285	931.9	17	375.9	236.6	319.4	25.4				99.7
Aseb	14	45.4	127	6.1	20.6	18.7	45.4				7.5
Asela	2,430	1,225.5	17	321.6	762.8	141.1	62.2				150.2
Asmara	2,325	512.3	34	87.8	375.7	48.8	73.3				109.7
Awasa	1,750	951.5	16	292.9	472.6	186.0	49.7				99.3
Azezo	1,966	1,153.0		146.0	914.0	93.0	79.3				220.7
Bahir Dar	1,770	1,413.2	17	105.0	1,189.8	118.4	84.2				293.7
Belet Uen	198	259.0		138.0	21.0	100.0	8.1				53.7
Bilate	1,500	744.2	23	240.3	326.9	176.9	43.9				78.9
Borciota	1,062	505.0		122.0	309.0	74.0	61.2				76.4
Burao	970	195.0		102.0	62.0	31.0	31.8				33.0
Butajira	2,000	1,118.1	19	377.7	560.6	179.8	50.1				121.1
Comar	764	920.0		90	785	45.0	85.3				180.5
Debre Marcos	2,515	1,325.5	11	208.9	970.1	146.5	73.2				204.4
Dengeco	2,111	750.5	22	249.6	429.0	71.9	57.2	53.8	98.8	21.0	103.6
Derbiga el Agemsa	1,644	678.0		239.0	340.0	99.0	50.1				80.4
Desse	2,250	1,207.1	16	244.6	789.5	173.0	65.4	54.9	94.0	47.0	189.4
Dire Dawa	1,260	638.7	27	220.2	313.6	104.9	49.1	54.8	122.3	18.1	78.3
Djibouti	21	188.0	71	41.59	17.52	128.9	9.3				24.8
Elidar	423	153.1	40	29.0	99.1	25.0	64.7	27.8	55.0		26.5
Fitche	2,750	1,125.2	12	183.0	826.0	116.2	73.4	51.4	90.9	42.8	226.2
Gambela	484	1,114.1	22	187.3	697.6	229.2	62.6	89.4	181.4		139.7
Gedaref	599	579.7	16	15.8	525.2	38.7	90.6				146.6
Gewane	627	521.9	21	135.3	268.7	117.9	51.5	29.1	31.6		71.8
Gina Ager	3,160	1,693.2	20	415.3	977.0	300.9	57.7	74.3	170.8	6.4	216.9
Goba	2,743	943.7	20	292.4	412.2	239.1	43.7				98.9
Gode	295	236.9	61	135.0	8.4	93.5	3.6	58.4	174.0	7.0	50.7
Gonder	1,967	1,131.9	18	139.4	878.4	114.1	77.6	52.4	99.1	40.9	206.7
Gore	2,002	2,101.3	23	439.7	1,261.9	399.7	60.1	62.1	107.7	24.9	247.4
Hargeysa	1,347	350.0		120.0	210.0	20.0	60.0				50.6
Hayk	2,030	1,174.0	17	280.9	717.1	176.0	61.1	62.1	132.8	16.5	176.4
Jijiga	1,644	721.3	39	249.9	329.2	142.3	45.6				75.6
Jimma	1,725	1,500.5	13	401.1	821.0	278.4	54.7	53.0	105.7	39.5	164.4
Kassala	502	278.6	43	13.0	229.0	36.6	82.2	49.0	104.9		56.2
Kebri Dehar	549	325.3	49	170.4	20.6	134.3	6.3	59.4	128.0	11.8	77.7
Kobo	1,610	725.8	22	151.5	411.8	162.5	56.7	53.2	101.5	18.3	97.7
Koka Dam	1,595	698.8	48	135.6	496.0	67.3	71.0				112.3
Kombolcha	1,903	1,043.6	15	221.3	663.1	159.2	63.5				160.9
Konso	1,053	805.6	14	358.2	153.0	294.4	19.0	55.2	96.9	28.4	86.2



**Figure 5-5 Crushing Value Test for Ballast**



(a)



(b)



(c)

**Figure 5-6 Photos during field investigation for VCI determination a) highly fouled area  
b)sampling in between the main track c) sampling in shoulder ballast**

APPENDIX H

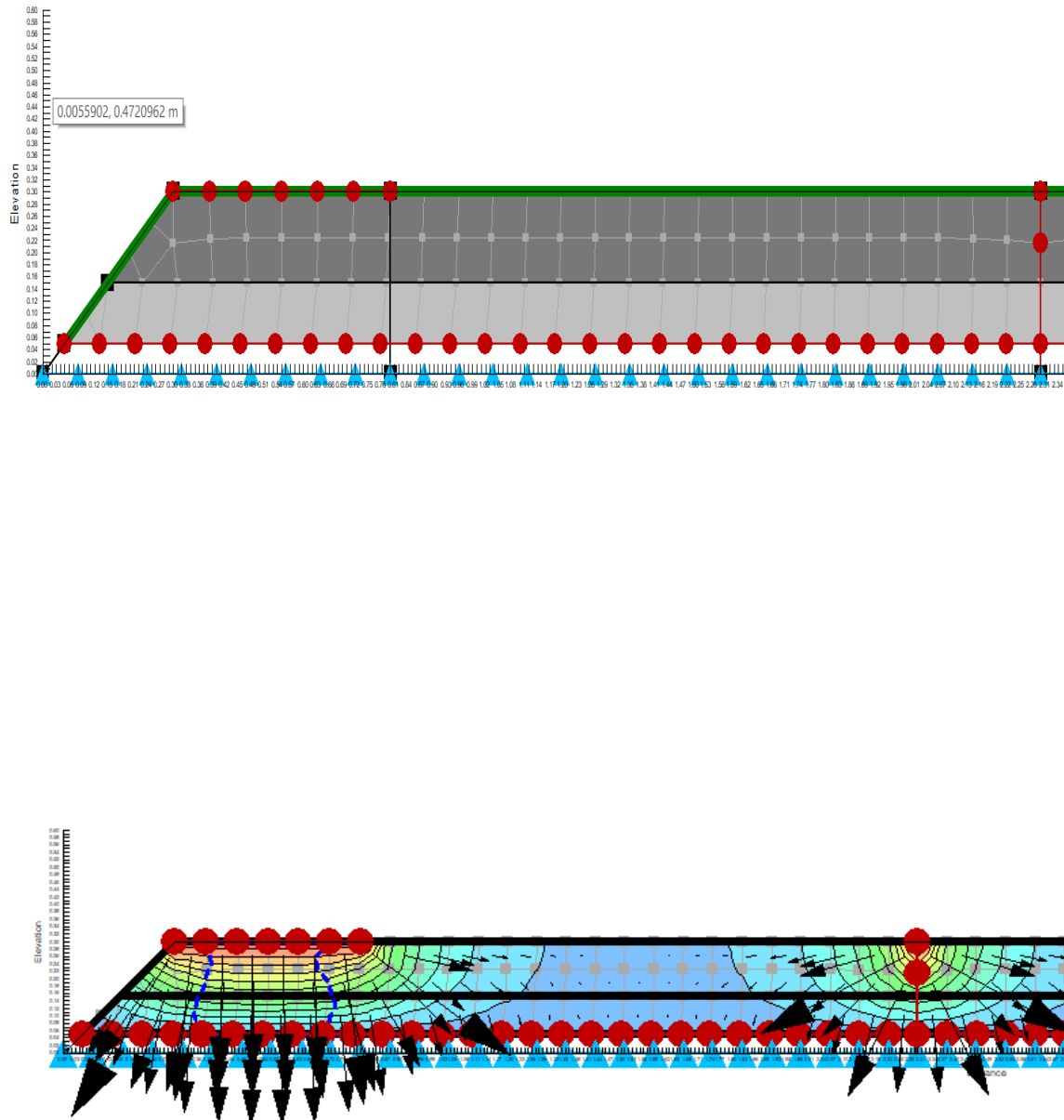


Figure 5-7 Vertical cross section of the typical ballast layer used in seepage analysis  
Discretization of one-half track