ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

AFRICAN RAILWAY CENTER OF EXCELLENCE

Evaluation of Ballast Fouling Causes, Rate and Scheduling of Appropriate Maintenance (at Dire-Dawa Site)

A Thesis in Railway Engineering (Civil Infrastructure)

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Railway Engineering (Civil Infrastructure)

APPROVAL

The undersigned have examined the thesis entitled '**Evaluation of Ballast Fouling Causes, Rate, and Scheduling of Appropriate Maintenance (at Dire Dawa Site)**' presented by **Kawiso Benard**, a candidate for the degree of **Master of Science in Railway Engineering (Civil Infrastructure)** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled "**Evaluation of Ballast Fouling Causes, Rate and Scheduling of Appropriate Maintenance (at Dire Dawa Site)**" 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 referred.

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GSR/9475/10

ABSTRACT

The railway infrastructure is an integral part of the railway system that holds all the forces applied on the ground without excessive deformation. The system substructure faces a problem of contamination, disintegration and various sorts of deterioration summarized as ballast fouling. Ballast fouling damages the system properties by softening, deforming and void filling that causes the structure capability to withstand design forces, instability, and drainage issues. A novel of how to establish ballast fouling causes, degree and rate are jotted down in this research, to find solutions and minimize the effects of the problem and improve the maintenance too. Efforts have been taken to forecast the problem extent on the line with an aim to have planned maintenance and minimize the costs. From the particle size distribution and particle breakage analysis performed on samples from the track, the average contaminating material (< 9.5 mm) was approximately 16 % by weight with most affected sections fouled at 30 % and 33 %. The average Fouling Index FI for the tested section was found to be 16 % moderately fouled at a rate of 0.040 %/MGT with more than 29 % ballast particle, 26 % silt and clay particle and 45 % particle of sand by weight. The major causes of ballast fouling are wind, traffic loading, migration of fines from subgrade or external sources from the surrounding. After a period of one year and three months period of track use, there is a large variation in ballast grading with breakage index of 42 % material (<16 mm) the smallest sieve size. The planned maintenance schedule has a three-year cycle.

Keywords: Railway, Maintenance, Drainage, Sub-structure, Contamination, Fouling, Fouling Index.

DEDICATION

I dedicate this research to Addis Ababa Institute of Technology, Ethiopian Railway Cooperation, and maintenance team, African Railway Centre of Excellence and the entire staff body that always endeavored to lecture and share the necessary ideas.

To my family for the physical, financial and emotional support rendered. To the World bank organization that has arranged and funded this entire program.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Standards Testing Materials
AREMA	American Railway Engineering and Maintenance-of-way Association
BS	British Standards
LAA	Los Angeles Abrasion
ERC	Ethiopia Railway Corporation
AS	Australian Standard
AAR	Association of American Railroad
VCI	Void Contamination Index
PVC	Percentage Void Contamination
FI	Fouling Index
MGT	Million Gross Tones
V_V	Volume of void
BL	Ballast Life
PSD	Particle Size Distribution
CP	Canadian Pacific
TDR	Time Domain Reflecting
GPR	Ground Penetrometer Radar

CHAPTER 1 INTRODUCTION

1.1 Background

The railway track is one of the most important components in the railway system which consists of two parallel steel rails, anchored on perpendicular sleepers, these rails and sleepers lying on a foundation as seen in Figure 1.1. The purpose of the rail track structure is to provide a stable, safe and efficient guideway to train wheels running at various speeds with different axle loadings.

Selig and waters, [6] noted that ballasted track structures may be grouped into two categories: Superstructure and the substructure.

1.2 Track Superstructure

The superstructure consists of the rails, fastening system and the sleepers. Different components of the superstructure have different roles. Rails guide the train wheels evenly and continuously, transfer concentrated wheel loads to the sleepers, then to the track substructure and in some cases serve as electrical conductors for the signal circuit.

Fastening systems retain the rails against the sleeper thus resisting the vertical, lateral, longitudinal and overturning movements of the rail. Sleepers, on the other hand, receive the load from the rail and distribute it over the supporting ballast at acceptable ballast pressure levels, hold the fastening system to maintain proper track gauge and restrain the lateral, longitudinal and vertical rail movement by anchorage of the superstructure in the ballast.

Rail pads located between the rail and sleepers provide for the resiliency of the rail/sleeper system, damping of wheel induced vibrations, reduce rail or sleeper contact attrition and electrically insulate the track signal circuits, [6].

1.3 Track Substructure

The track substructure includes the ballast, sub-ballast, and subgrade layers that support the track superstructure of rails and ties. The main function of the track substructure is to support the applied train loads uniformly and without permanent deformation that might affect the track geometry therefore an influence on the track superstructure stability and performance including vehicle dynamics, [7]. The foundation is normally compressed soil, on top of which is a bed of ballast (aggregates) to distribute the load from the sleepers to the capping layer and formation soils according to Indraratna and Salim [1].

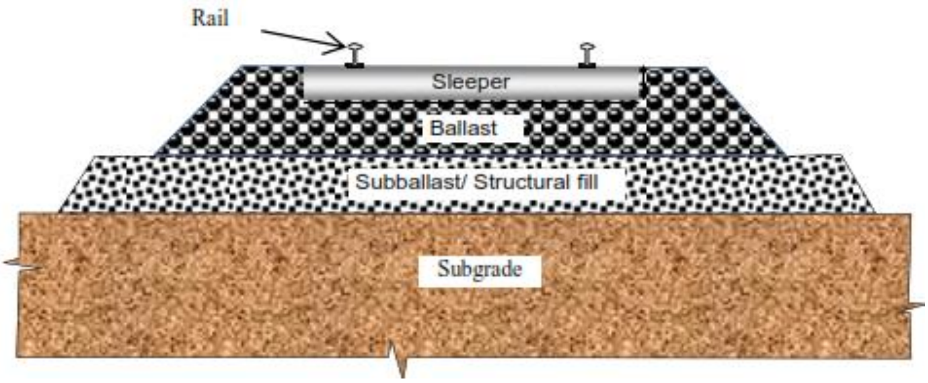

Figure 1.1 Typical Ballasted Railway Track Cross Section, [1].

A ballast bed performs two major roles in the railway network which are; drainage and load-bearing capacity. Rail ballast comprises of uniformly-graded coarse aggregates, produced from crushing locally available rocks such as granite, basalt, limestone, slag or gravel.

During railway operations, the rail track goes through a number of challenging difficulties among which is ballast fouling. Fouling is the accumulation of unwanted material on solid surfaces to the detriment of function. The fouling materials can consist of either living organisms (bio-fouling) or a non-living substance. Ballast fouling refers to the presence of finer particles in the ballast material from crushed aggregate, sleeper wear, fine particles from sub-grade or external (“surface spillage”) fines from freight and coal fouling. Also, ballast fouling can be caused by ballast breakdown, sleeper wear, infiltration of other materials from ballast surface or from the base of the ballast layer that fill its voids, [2]. Fouled ballast may also be defined as a ballast condition where voids in the ballast are filled with relatively finer materials or fouling agents like sand as shown in Picture 1.1, [3] Particles are assumed to be fouling if they are smaller than 9.5 mm (3/8 in.). Ballast material is said to be clean if the Fouling Index, FI < 1.0, [3].

Figure 1.2 Sand Fouled Ballast on the Left (Adigala) on Ethio-Djibouti Line and Clean Ballast on the Right.

Ballast fouling is often as a result of Ballast breakdown under repeated loading and vibrations in which contacts between ballast particles will be points at which each angular particle interacts with an adjacent particle to transfer the applied load. These small contact points deform substantially under loads to provide a high level of resilience, common to clean ballast layers. The high loads involved and the small area of contact cause each ballast particle to deform substantially, potentially resulting in the fracture of particles or wear at particle contacts when the applied stress approaches or exceeds the strength or due to repetitive tamping actions during maintenance and freezing of water in particles.

Also, ballast surface infiltration could be delivered with the ballast, dropped from trains, wind-blown; the accumulation of sand is one of the specific fouling conditions and key design challenges threatening the safety and affecting serviceability and maintenance of railways in arid and desert regions, for example, the Linhai-Ceke line in China, [4] running-water carried or splashing from adjacent wet spots. Sleeper wear due to sleeper-ballast interaction, underlying granular layer infiltration from old track bed breakdown, sub-ballast particle migration from inadequate gradation (silt and clay) or subgrade infiltration into ballast bed where sub ballast or another layer does not exist to act as a filter to separate the subgrade from the ballast.

The behavior of fouled ballast is often dominated by a small percentage of silt and clay that can create a fouling material that is plastic with a lubricating quality that will limit particle interlocking, thus cleaning is required. Unfortunately, this is a costly operation, [3].

According to Paderno (2010), the costs of ballast maintenance represents approximately 30 % of the annual track maintenance budget, [5].

Once the ballast is severely fouled that the ballast particles can no longer interact without mobilizing the weak structural response of the fouling material, the ballast function is compromised, [2].

At this point, the conditions of the rail track can be deteriorated eventually loses the ability to perform its desired functions considerably depending on the type of fouling material and the degree of fouling hence leading to soft and deformable ballast structure, poor drainage of water falling onto the track, reduction in the voids thereby leading to a considerable decrease in the movement of particles through the ballast, reduction in vertical stability (including uplift), lateral and longitudinal forces applied to the sleepers to retain the track in its required position, decrease in resilient modulus (strength) and energy absorption capacity, vegetation growth in the rail track, increased noise level and inadequate electrical resistance between rails, [2].

Generally, it decreases the drainage and load-bearing capacity of the ballast layer, [1] impact of ballast fouling on rail tracks as well. The track progressively moves vertically and laterally causing deviations from the desired geometry under repeated loading from traffic, [6].

Therefore, Ethiopia is one of the landlocked countries in the east African corridor with railway transport handling around 95 % of its cross-border trade through Djibouti, lines like Addis Ababa-Djibouti line, Awash-Hara Gebeya project and Hara Gebeya - Mekele projects have been funded to facilitate trade in the region. Therefore, this research focuses on finding out the potential causes of ballast fouling, levels of fouling and the rate at which fouling occurs in order to come up with appropriate maintenance measures to ensure that the system runs for its designed time and specification not forgetting the low life-cycle cost.

1.4 Problem Statement

In a life cycle of rail track system, many contaminations happen to the track components which affect the ability of the system to fulfill its duties as per the designs. One of the conditions is called fouling; on the track, it is dubbed ballast fouling. Ballast fouling affects the track structure by deforming and softening it which reduces the drainage ability of the track and the friction at inter-particle contact points; these releases some of the compressive interlocking forces thus reducing the stability of the ballast and hence deviations from the desired geometry of the entire track structure under repeated loading from traffic. It is so rampant in low lying areas where running water meets with the track, desert areas due to windblown sand, level crossings where the system interacts with other systems and humans but also happens in other sections due to ballast tamping and different track loading which causes ballast disintegrations. Ballast being a critical component in maintenance to avoid alignment issues and prolong the service life of the track, the effort has to be taken so as not to affect the drainage system and stability of the entire railway infrastructure.

1.5 Objectives

1.5.1 Aims and objectives

The main objective of this study is to clearly evaluate the causes/ sources of ballast fouling on the track substructure and to provide appropriate maintenance schedule to ensure the proper service life of the structure.

The specific objectives of this research are;

1. To evaluate the sources/causes of ballast fouling at Dire Dawa site Ethio-Djibouti line
2. To evaluate the degree and rate of ballast fouling at Dire Dawa site Ethio-Djibouti line
3. To propose an appropriate maintenance schedule based on evaluation results.

1.6 Scope of the Study

1.6.1 Geographical Scope

The case study for this research is Dire Dawa area along Addis Ababa Djibouti line and the source of materials used for carrying out the study (ballast material) was obtained from the premises of Ethio-Djibouti line at Dire Dawa site.

1.6.1.1 The geographical location of the Dire-Dawa site

Dire-Dawa lies between Mieso (Exclude)-Dewele section as shown in Figure 1.2 which is part of the new standard-gauge Railway Ethiopia/Sebeta-Djibouti/Nagda. The west starting point of the line is Mieso in central Ethiopia; the east end point is the border between Ethiopia and Djibouti to the east of Dewele. The west end of the section is connected to Sebeta-Mieso section, which finally ends at Addis Ababa, the capital of Ethiopia and the east end is connected to a railway in Djibouti, which forms a transport corridor of Djibouti port to the sea.

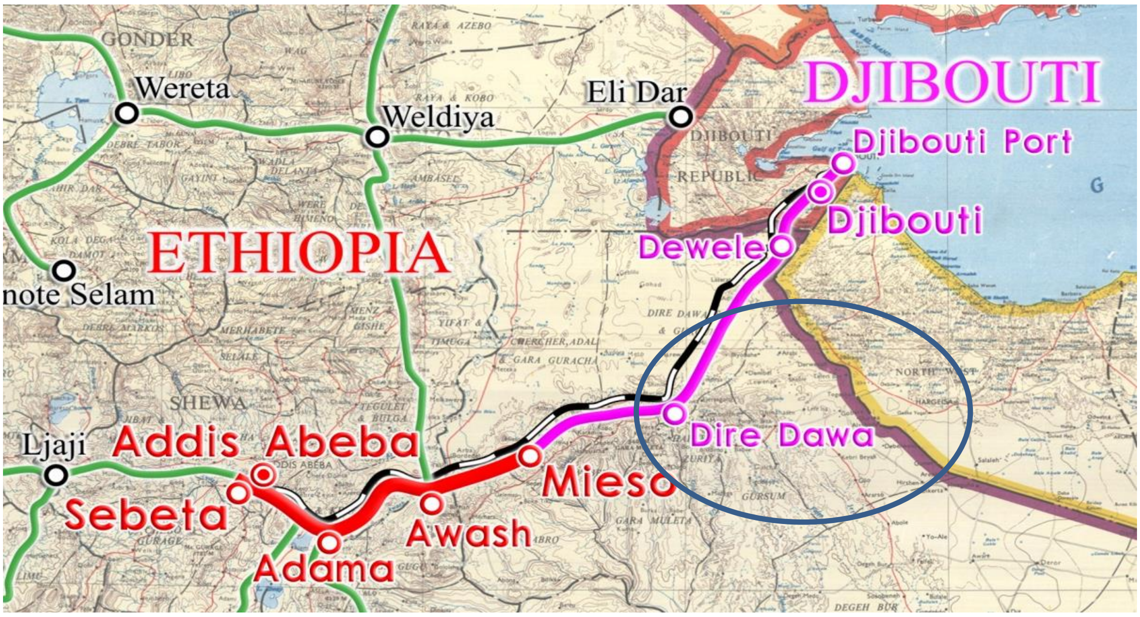

Figure 1.3 Geographical Location of (Dire-Dawa Site)

1.6.2 Content Scope

The study focuses on evaluating the sources of ballast fouling, levels or extent of fouling limited to FI methodologies, rate of ballast fouling on the track substructure and to provide planned maintenance measures or schedule to maintain the design period of the structure.

1.7 Research Questions

1) What are the most likely site-specific sources of ballast fouling at Dire-Dawa site?
2) What is the extent or degree of ballast fouling at Dire Dawa site?
3) What is the rate of ballast fouling at Dire-Dawa site?
4) What is the appropriate maintenance framework?

1.8 Thesis Structure

The thesis is presented in five (5) major chapters

Chapter one (1) consists of project background, problem statement, objectives, the scope of study and research questions.

Chapter two (2) is divided into eight sections: section (1) presents a brief review of the track structure, section (2) review on the ballast. Section (3) discusses ballast fouling and Section (4) presents a general literature review on the various methods used in ballast fouling quantification, section (5) rate of fouling and how it is calculated, section (6) summarized Overview of Ethio- Djibouti Railway Line and section (7) gives a brief summary of ballasted track maintenance and section eight shows a summary of particle breakage.

Chapter (3) consists of the methodology which includes the procedures of data collection, laboratory test standards, and procedures.

Chapter four (4) comprises of result presentation and discussions, chapter five covers conclusions and recommendations. Also, a list of references, sources of data for this thesis and appendix is attached.

1.9 Significance of the study

The study identifies the sources of ballast fouling, degree of fouling, rate of ballast fouling on the track substructure and provides appropriate maintenance framework for Dire-Dawa site along Ethio-Djibouti railway line. The variation of the ballast fouling causes for different railroads justifies the need for finding out the causes for specific sites. The research also estimates the ballast remaining usage period which is a key factor in estimating the probable maintenance or renewal period for railway operating industries.

CHAPTER 2 LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Introduction

Degradation of the railway track is a complex process that involves the influence of several factors that may condition its performance during the life cycle of the structure and consequently the durability of the track itself. Considering that a railway track structure deteriorates rapidly over time, knowing the degradation process will help in estimating the future state of track conditions and mitigating problems associated with operational safety. Thus, in order to make the management of railway infrastructure more efficient, it is essential to locate, in an early and more expeditious way, areas that need intervention actions according to Ana et al, ([7]. According to Sussmann et.al, [8] ballast material quality has a great influence upon ballast life and those methods to determine the resistance to such breakdown mechanisms also becomes very important. Chrismer further states that the selection of the economical ballast material depends upon such considerations as purchase price, material quality, hauling distance from the quarry, and track renewal methods to name but a few. However, "the issue of material quality and how it affects ballast life in track has been and still remains one of the most difficult issues to resolve", [9].

2.2 Ballast and Ballast fouling

2.2.1 Ballast

Ballast is defined as a layer of selected crushed stones, gravel, murram and or granular material placed at the top layer of the substructure in which the sleepers are embedded for distributing the load to the underlying layers, provision of drainage and as well as for longitudinal and lateral stability of the track , Ballast is also required to provide a level and hard bed for the sleepers to rest and enable maintaining the level and alignment of the track. Ballast is also necessary for the provision of elasticity and resilience to the track for proper riding comfort. [6], [1], [10].

Ballast section is the primary geotechnical component of a rail track foundation and the performance of ballast section depends on the four major geotechnical properties [11], [12].

- Characteristics of the constituting particles (size, shape, surface roughness, particle crushing strength and resistance to attrition, among others),
- Bulk properties of the granular assembly (particular size distribution, void ratio or density and degree of saturation),
- Loading characteristics (current state of stress, previous stress history and applied stress path) and,
- Particle degradation (combined effects of grain properties, aggregate characteristics and loading.

2.2.1.1 Ballast subdivisions

Selig and Water, [12] sub-divided ballast into four zones:

1. Crib; material between the sleeper,
2. Shoulder; material beyond the sleeper ends down to the bottom of the ballast layer,
3. Top ballast; upper portion of the supporting ballast which is distributed by tamping.
4. Bottom ballast; lower portion of supporting ballast layer which is not disturbed by tamping and which generally is the more fouled portion.

2.2.1.2 Properties of unfouled ballast

The Australian Standard (AS) 2753.7 states the general requirements and specifications of ballast, and the recommended grain size distribution through different standards may dictate different requirements based on the purpose of the railway line and the geotechnical conditions of the area. Specifications for unfouled ballast as recommended by AREMA (2013) and the Canadian Pacific Railroad (CPR) (Klassen et al. 1987) are as summarized in Table A.0,27.

2.3 Ballast Fouling

2.3.1 Introduction

Fouling is the term used to indicate contamination of ballast by the presence of fines or a condition where voids in the ballast are filled with relatively finer materials or fouling agents, [3] [13], [14]. It is expected that fresh and clean ballast will be placed during the construction of a track with fouling components not exceeding 1 % by weight. Fouling material is often most noticeable as muddy slurry. The fouling material and slurry most often consist mainly of ballast breakdown, Sussmann et.al [8].

During the service life of railway tracks, particle breakage, surface intrusion, and infiltration of fines from subgrade caused by traffic loading increase the number of fines in ballast, known as 'fouling'. Fouling increases plastic deformation of ballast which leads to deteriorate a track surface. To avoid progressive deterioration of the track, continuous and prompt maintenance is required when fouling approaches a critical level. Maintenance operations are scheduled on the basis of measured track deformation and the level of fouling, [15].

Typically, porosity in ballast is in the order of 35-50 %, so, fouling probably does not start to be significant until the fines increase to 10 % or higher, [16]. Fouling of ballast over time is the reason why tracks deteriorate and this is because as ballast is fouled, its performance decreases, resulting in higher settlement due to poor drainage of the track.

2.3.2 Causes of ballast fouling

The fouling of ballast is progressive and can be influenced by many factors. In cases in which no environmental or operational detritus contaminates the ballast, ballast breakdown can be expected and may initially enhance stability by retaining ballast particles in place. However, this is a temporary condition and either damage caused by partially blocked drainage or continued wear of the ballast will occur to destabilize the ballast. Sussmann et.al, [8].

According to Ana et.al, [7] the behaviour of ballast depends, among other factors, on its intrinsic characteristics, such as: the nature, shape and physical properties of the aggregates (porosity, hardness, wear resistance, alterability, etc.); the grading curve adopted (in particular, the percentage of fines); and the quantity of the gravel elements. With regard to the ballast fouling material, it is verified that there are some factors that contribute to its contamination, taking to poor service conditions. In general, the origin of these phenomena may be:

a) Traffic/operational factors, due to the imposed stresses, the sleepers tend to rise and settle back into the ballast layer, the impact caused by the dynamic stresses can overload the ballast and lead to breakage, sliding and abrasion of its particles;

b) Factors associated with soil characteristics, namely the change in the mechanical characteristics of the various elements;

c) Environmental factors (water content and soil temperature). It should be noted that for a correct evaluation of the railway track, it is necessary to take into account the influence of all these factors, not only its evolution / degradation in isolation, but mainly as a whole.

Selig and Waters, [6] noted that ballast fouling sources are site-specific and concluded from their study that ballast breakage, surface intrusion is the most significant source of fouling which contributes more than three-quarters of total fouling content that's around (76 %), upward migration of material from lower granular layers of the subgrade and roadbed contributing (13 %).

Sussmann et.al [8], showed that the main source of ballast fouling was caused by the mechanical wear of the ballast through repeated train loading. The ballast-to-ballast particle contact area varies from when the ballast is freshly placed and loose (Figure 2.1a) to increased particle contact as the ballast rearranges and reorients into a more stable structure on initial compaction (Figure2.1b). The consolidated ballast is the desired condition in which ballast can remain in a stable orientation for an extended period of time and traffic (Figure 2.1c). Further loading can deteriorate the ballast to the point at which the particles degrade and the voids fill. As the void space fills, the ballast structural matrix that has carried the load and distributed the load to the lower layers begins to shed load to the weaker material in the void space as the ballast particles are forced apart by the fouling material and the ballast structural performance degrades. Maintenance intervention will not substantially change this figure because ballast tamping will result in completely loosened ballast that will need to recompact and consolidate (Figure 2.1d) if a stable, consolidated ballast layer is to develop.

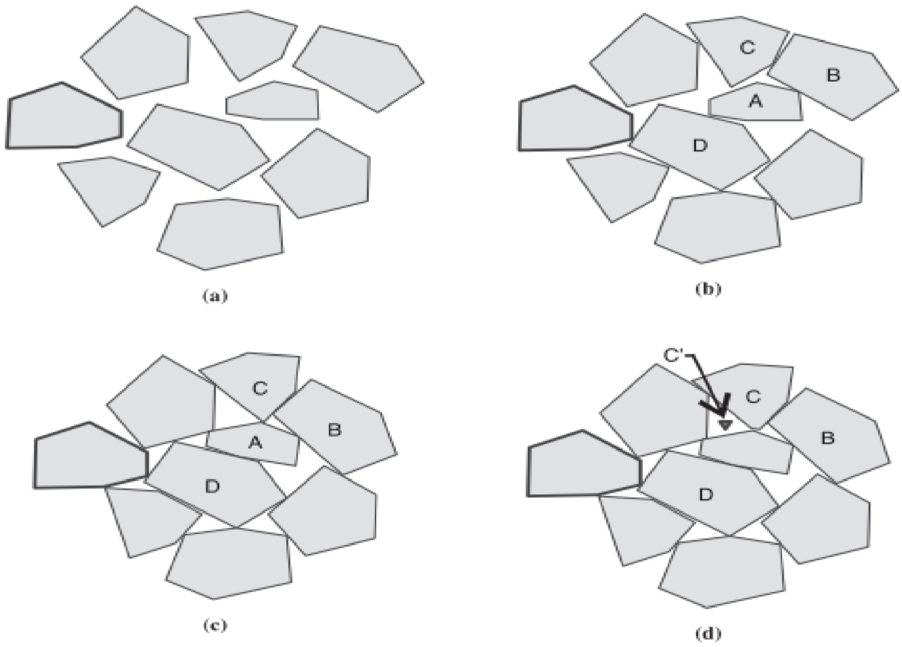

Figure 2.1 Stages of Ballast Compaction and Breakdown: (a) new ballast placement, (b) initial ballast compaction, (c) well- compacted ballast typical of consolidated track, (d) ballast breakdown

Table 2.1 British Railway Sources of Fouling by Selig and Waters

No	Sources	Degradation	
		kg/sleeper	% of total
1.	Delivery with ballast (2 %)	29	7
2.	Tamping: 7 insertions during renewal and 1 tamp/year for 15 years at 4 kg/tamp	88	20
3.	Attrition from various causes including traffic and concrete sleeper wear (traffic loading: 0.2 kg/sleeper/million tons of traffic)	90	21
4.	External input at 15 kg/year (wagonspillage:4.0 kg/sqm/yr) Airborne dirt:0.8 kg/sqm/yr	225	52
	Total	432	100

Also, studies conducted by the Association of American Railroads (AAR), [17] using Petrographic analysis indicated that 75-90 % of the fouling material accumulated during 300 million gross tones (MGT) was from ballast breakdown, and the remainder, from external sources, [5].

In Australian coal freight tracks, Feldman and Nissen [18] stated that coal fine intrusion account for 70-95 % of the fouling materials in ballasted rail tracks and 5-30 % from other sources, [1], [4] in low-lying Coastal areas where the subgrade is usually saturated, the finer silt and clay particles get pumped up into the ballast layer as 'slurry' under train loading, when trains operate in the absence of a properly graded filtration layer underneath the ballast layer, [1], [6], [19]. Further studies suggest that fines also develop due to edges of the ballast stone breaking off as a consequence of sleeper loading under traffic. After one million tonnes of traffic, 3.6 kg of fines per sleeper develop under a 16 tone axle and 5.2 kg under a 32 ton axle and during cleaning (tamping process) results to accumulation of 1.8-3.9 kg of fine therefor this indicts that the fines due to tamping can be regarded in addition to traffic loading, [20].

Ballast performance has been observed to be significantly worse with fine material less than 9.5 mm in the ballast compared to coarse-fouling material (material > 9.5 mm), [6] as these finer particles accumulate in the ballast layer, they tend to interfere with the ballast performance by retaining water hence reducing drainage, creating the appearance of mud in the presence of water. The behavior of fouled ballast is further degraded if the fouling material behaves plastically, [21] the effect of fouled ballast on-track performance is dramatic.

Sussmann et al. (2001a) studied the effects of track condition and stiffness. Sussmann 2007 on track geometry profile deterioration rates and found that the geometry deteriorated most rapidly at spots where fouled ballast and drainage problems existed along the track. In general, fouling material in the ballast contributes to some degree of ballast drainage problems, settlement, and increased track maintenance, [13].

From the above, the most common sources of fouling material are due to crushing of ballast caused by traffic loading though the quantity is dependent on the use of the train and the environmental or geographical and geotechnical nature of the area. Other sources also include; Contaminants shipped with the ballast or material mixed with the ballast while it is handled or installed, Material dropped or spilled on the track from the wagons, Windblown material, Soil penetrating the ballast from below (subgrade or roadbed), Tie or concrete sleepers wear or other deteriorated track materials. In summary, around 76 % of ballast fouling originates from the fracture and abrasion of ballast particles, followed by 13 % of infiltration from sub-ballast, 7 % infiltration from the surface, 3 % from subgrade intrusion, and 1 % from sleeper wear, [22] as summarized in Figure 2.2.

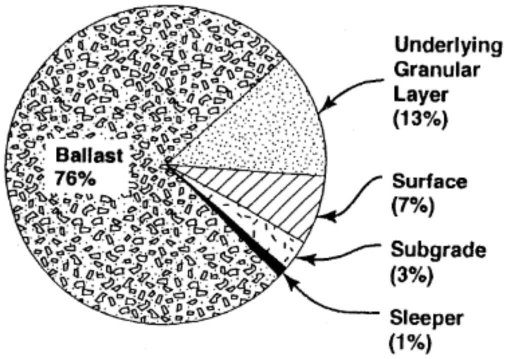

Figure 2.2 Sources of Ballast Fouling Evaluated by Selig and waters 1995, [6].

A definitive assessment of the source of ballast fouling has therefore, been recommended to do tests to assess the source and nature of the fouling material since it varies for every region, [13]. Hence the aim of carrying out this research.

2.3.3 Effects of ballast fouling on drainage

Research conducted by Selig and waters shows that ballast fouling reduces the drainage capacity of the ballast layer. As the ballast voids become full due to accumulated fine particle, the amount of water flow within the particle and void space is reduced, this results to trapping of water in the track structure and potentially saturating the track. He also noted that an FI of 30 % is the breakpoint at which track drainage becomes substantially more impeded by fouling, [8].

2.3.4 Methods of Measuring of ballast fouling

The methods of measuring ballast fouling are categorized into two and that is field investigation and laboratory technics,

2.3.4.1 Field investigation

Ground Penetrating Radar (GPR):

Ground penetrating radar is a non-destructive evaluation technique that uses electromagnetic radiation in the micro- wave band of the radio spectrum, and detects the reflected signals from subsurface structures. GPR can be used in a variety of media, including rock and soil to provide continuous information about the track subsurface conditions.

However, in situations where it is expensive and not available, traditional methods requiring direct visual inspection and selective excavation of the ballast samples for investigation is necessary, [23].

Time domain reflecting (TDR)

In TDR measurements, the relative dielectric permittivity of the material between the probes can be determined by measuring the travel time between the electrical pulse reflected at the top of the probe and the electrical pulse reflected from the end of the probe, [15].

2.3.4.2 Laboratory testing

Laboratory testing techniques include, Void Contamination Index, Percentage Void Contamination, Relative Ballast Fouling Ratio, and Fouling Index.

Void Contaminant Index (VCI):

Void contamination index (*VCI*) proposed by, [24] includes the effect of void ratio, specific gravity, and gradation of fouling material and is defined as:

Tennakoon, [24] stated that a value of *VCI* = 50 % indicates that half of the total ballast voids are occupied by the fouling material.

Percentage void contamination (PVC)

According to Feldman and Nissen, [18] defined the Percentage Void Contamination (*PVC*) as the ratio of the bulk volume of fouling material to the volume of voids of ballast when it is clean. New ballast contains approximately 40-45 % voids, [25].

Relative Ballast Fouling Ratio ($R_{(b\text{-}f)}$)

$R_{(b\text{-}f)}$ is defined as the ratio of the dry weight of fouling particles passing through a 9.5 mm sieve to the dry weight of ballast particle retained on a 9.5 mm sieve. It is calculated using equation 2:3 [2] reported that it will be less time consuming using $R_{b\text{-}f}$ to measure ballast fouling as compared to another method currently being used and hence practicing track engineer will find it very attractive. However limited experimental evidence has been given to their findings. A detailed description and definition of the different fouling categories in $R_{b\text{-}f}$, are presented in Table 2.3.

Table 2.2 Relative Ballast Fouling Ratio R_{b-f}, [2].

Category	R (b-f) %
Clean	<2
Moderately clean	2≤10
Moderately fouled	10≤20
Fouled	20≤50
Highly fouled	≥50

Fouling Index

Fouling index is the measure of fine particles content in the ballast material. Selig and Waters proposed the FI to quantify the degree of ballast fouling numerically.

$$FI = P_4 + P_{200} \quad \text{......} \quad 2.1$$

Where:

P4 is percentage passing No. 4 (4.75 mm) sieve

P_{200} is percentage passing sieve No. 200 (0.075 mm).

However, research conducted by, [26] indicates that Selig's criteria of computing for FI gave a lower degree of fouling for field ballast due to lower limits of ballast classifications in some standards, therefore, proposed a more practical fouling index based on diameter ratios as to formulate better ballast cleaning strategy

Therefore, for this research Selig's fouling index, [26] shall be adopted since it has been proved relatively accurate and common technic used by many researchers in the current railway industry. The FI_D or FI will be chosen to base on the standard that was used for grading the Addis Ababa Djibouti line ballast.

Table 2.3 Classification Criteria for Fouled Ballast, [27].

Fouling index			**Classification**
$FI_P = P_{0.075} + P_4$	$FI_D = \frac{D_{90}}{D_{10}}$	$FI = P_{0.075} + P_4$ (Selig and waters, 1994)	
<2	<2.1, and $P_{13.2}$≤1.5 %	<1	Clean
2≤10	2.1<4	1≤10	Moderately clean
10≤20	4<9.5	10≤20	Moderately fouled

Fouling index			Classification
$FI_P = P_{0.075} + P_4$	$FI_D = \frac{D_{90}}{D_{10}}$	$FI = P_{0.075} + P_4$ (Selig and waters, 1994)	
20≤40	9.5≤40	20≤40	Fouled
≥45	≥45, $P_{13.2}$≤140 %, $P_{13.2}$ >5 %	≥40	Highly fouled

2.3.5 Rate of Ballast Fouling

Fouling rate refers to the frequency of occurrence of ballast fouling or the rate at which the ballast material gets contaminated. The fouling rate can be calculated by dividing the average value of the Fouling Index (FI) by the life of the ballast material.

$$\text{Fouling rate} = \frac{\text{Fouling Index (FI)}_{\text{Average}}}{\text{Life of ballast}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

Feldman, [18] came up with a method of estimating the ballast material cleaning cycle for the given section of railway track. The same technique was used to predict the allowable ballast life using the Fouling Index (FI) and the method requires thorough monitoring of ballast material and it suggests that samples should be taken for every two-kilometer interval along the section of interest on the track. It also suggests that a three-year testing program would be required in order to obtain clear variations in the rate of fouling. The ballast-cleaning cycle can be calculated by dividing the fouling limit for highly fouled ballast by the rate of fouling for the track section.

2.3.6 Ballast life

Ballast life refers to the period when the ballast aggregates are in a sound mechanical and physical state to serve the desired functions without fragmentation. Ballast life expires when the voids between the particles become filled with fines to the extent that permeability is basically lost and the ability to maintain a track lift after tamping or under traffic loading is greatly diminished, [13]. The major causes of ballast degradation are fragmentation and wear processes during environmental and traffic exposure which in turn leads to settlement and increased expenses for maintenance of the track to regain stability, [4] the resistance to ballast fragmentation is assessed by application of the Los Angeles Abrasion test and the resistance to wear due to grinding is estimated by the Micro-Deval abrasion test and Mill-abrasion test.

To determine the life of ballast material, different researchers have come up with several methods which include the use of abrasion number (An) which is equal to the Los Angeles Abrasion results for a ballast material plus five times the results of the Mill Abrasion (MA) test or Micro-Deval abrasion (M_{DE}) test for the same ballast material, [28].

$$Abrasion\ number = LAA + 5 * M_{DE} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.3$$

According to, (25) life of ballast can be obtained from the equation,

$$Life\ of\ ballast = 10^6\ exp(8.08 - 0.0382A_n) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2.4$$

A correction factor of 1.5428 for wooden sleepers and 1.029 for concrete sleepers is introduced on the answer obtained by Equation 2.9 while calculating the final durability of the ballast material, [27].

where Life of the ballast is expressed in accumulated traffic flow (Million Gross Tones) MGT. Further studies performed by Klassen et al. (1987) show a comprehensive study that aimed to quantify ballast life for Canadian Pacific Rail where a number of samples under the ties were obtained, graded and ballast life in MGT was obtained based on grading and abrasion number. From the same data, a computer simulation model called BALLAST2, [9] was developed which assumes a linear relationship between ballast breakdown with traffic.

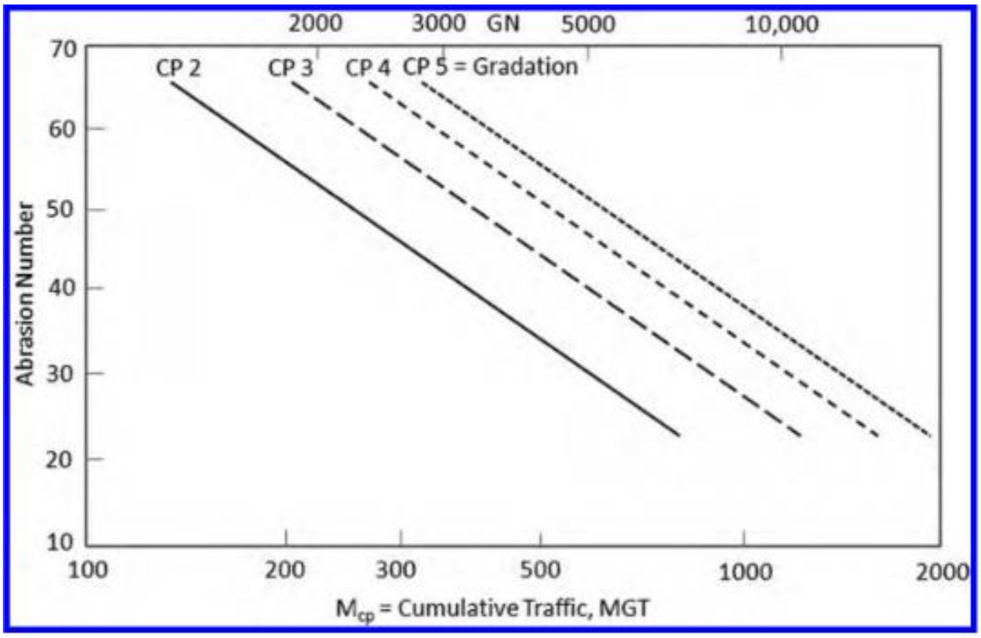

Figure 2.3 Ballast life in MGT based on ballast gradation and Abrasion Number, [13].

Therefore, from the literature, the Figure 2.3 and Equation 2.9 can be used to compute for ballast life with a known abrasion number of the ballast material.

2.3.7 Los Angeles Abrasion Test

Los Angeles Abrasion is a test performed to assess the crushing resistance and particle strength to resist breakage under ties. The testing is done as per ASTM Standard C535 or ASTM method C 131-66.

2.3.8 Micro-Deval and Mill Abrasion (MA) Test

The MA is a test that provides a measure of abrasion resistance of ballast and is an indicator of ballast hardness, [13]. Studies by Raymond, Diyaljee 1979, [29] have shown that there is no clear difference between the Micro-Deval and the Mill abrasion test results for the same rock type.

It suggests that both tests are used to assess the wear characteristics of the ballast material, [27] and give partially the same results. The test concept is based on the Micro-Deval abrasion test (ASTMD 6928) and (BS EN 1097-1) for aggregate crushing and abrasion but is performed without crushing.

For this study due to the absence of the test equipment in the region (Ethiopia) for either of the two (Mill Abrasion and Micro-Deval), the existing Micro-Deval test results shall be adopted for the same rock type. In reference to the preliminary design review of Dire-Dawa railway section, [30] the line is seated on weathered soil of basaltic igneous rock which completely distributes in the whole line and it suggests that the rock type used on the project was igneous rock which due to its availability in the region.

Therefore, the Micro-Deval values of an igneous rock will be collected from the various studies that have been conducted to compute for the abrasion number in this study due to scarcity of the testing equipment.

2.3.8.1 Igneous rocks

These are rocks formed from the cooling and crystallization of lava or magma (molten rock) they include intrusive or extrusive, mafic or felsic. The examples include; Granite**,** Basalt, Syenite, Diorite, Gabbro, Peridotite, Pegmatite, Felsite and dolomite among others,[31]. According to studies conducted by, [27], [31], [32], [33] they obtained the Micro-Deval values for igneous rocks as shown in Table 2.5.

Table 2.4 Micro-Deval Test Values for Igneous Rock, [27], [31], [32], [33].

Serial No.	Source	Material type	Micro-Deval value (%)
1	Granite mountain	Igneous	3.5
2	Hanson	Igneous	6.5
3	Jobe	Igneous	10.7
4	Jobe	Igneous	9.6
5	Martin M	Igneous	7.3
6	Martin M	Igneous	6.4
7	Martin M	Igneous	7.0
8	Akos Torok	Basalt	9.2
9	Martin M	Igneous	5.0
10	Vulcan	Igneous	8.8
11	Jordan	Igneous	6.5
12	Upper valley	Igneous	5.8
13	Bay	Igneous	3.6
14	Trinity	Igneous	7.2
15	Earth and Environmental Science	Trachy basalt	4.86
16		Granite	5.1
17		Granite	4.9
18		Granite	7.3
19		Dolomite	10.6

Generally, Micro-Deval levels from various abrasion testing methods show soft limestones and sandstone test between 20-35 % loss (fail), Hard limestones and dolomite test between 8-15 % loss (pass), Hard igneous rock and basalts test between 4-8 % loss (pass), Quartz type stones test between 8-16% loss (pass), Granite type rocks are mostly dependent on whether the rock is weathered (fractures easily) although they can range from 7-25 % loss (pass or fail). Testing is the only way to know if stone being used in construction can withstand the abrasion when hauled/handled/spread and weathered, [34]. Therefore, due to absence of the testing equipment, the average shall be used to obtain an approximate Micro-Deval for the Ethiopian igneous rock for the case of this research.

2.4 Ballasted Track Maintenance

Maintenance refers to restoring the infrastructure to its designed function ability. Maintenance strategy can either be preventive or corrective, Preventive is the maintenance conducted before a detected fault and corrective is after a detected fault. It is intended to reduce the probability of failure or degradation of an item's functioning, [35]. Therefore, the focus of this research is to propose a preventive form of maintenance.

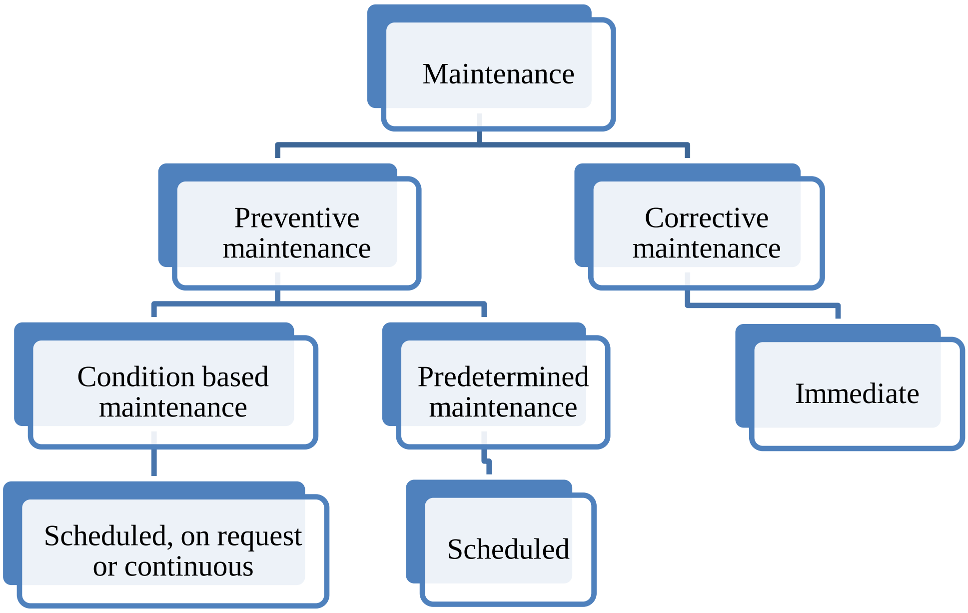

Figure 2.4 Maintenance Strategy, [35].

Why preventive maintenance?

- Increased efficiency of the maintenance activity
- Security and comfort to passengers since the railway track behavior is monitored and measures are taken before actual breakdown.
- Gives better planning for the availability of the required material and machines.
- Failure risks are reduced due to planned monitoring and rectification measures which gives a high utilization level of the facility.

In order to reduce ballast fouling, ballast cleaning, undercutting, and replacement with fresh ballast should be carried out. Tamping being one of the most effective ways of restoring track geometry as involves lifting the sleeper to the desired level and inserting tamping tines into the ballast with the lifted sleeper between each pair of tines, this forces the ballast material underneath the sleeper base to fill the voids, [36]. Tamping can be beater packing, mechanized handheld packing tool or on track mechanized tamping machine. Other maintenance techniques include shovel packing or stone blowing which is also dived into manual or mechanized, [37]. However, tamping loosens and damages the ballast, leading to breakdown, loss of strength and stiffness of the layer hence does not reduce fouling. It is estimated that a tamper generates around 2 to 4 kg of fines per sleeper for one tamping insertion, whereas only 0.5 kg of fines per sleeper is produced by an equivalent stone-blowing cycle, [38].

Therefore, the availability of stone blower and the undercutting machine would be of great advantage. The frequency of ballast undercutting is linked to its quality which changes continually due to the generation of fine particles (fouling) caused by attrition and ballast degradation due to traffic or tamping, [25] during ballast undercutting, the fouled ballast is extracted and replaced with new ballast material. Research has also found that cleaning ballast shoulders can provide improved drainage from the crib area and washing away of some of the fouling material provided the crib ballast FI is not highly fouled (FI less than 30 %), [13].

2.5 Particle Breakage

The breakage index measures the extent of particle breakage with a lower value of zero indicating no particle breakage and higher value of 100 %, indicating all particles are broken below the smallest sieve size used.

Indraratna and Salim presented that particle breakage can be quantified using Marsal's breakage index Bg. From gradations of fresh and ballasts exposed to traffic, the changes in particle gradation, the difference in percentage retained on each sieve size;

$$\Delta w_k = w_{ki} - w_{kf} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.5$$

Where; Wki is the percentage retained on sieve size k before test and Wkf is the percentage retained on the same size after test. The Breakage Index (Bg) is the sum of all positive values $\sum \Delta Wk$, [3].

CHAPTER 3 MATERIALS AND METHODOLOGY

3.1 Ballast Material Source

Ballast material was obtained from Ethio-Djibouti railway line between chainage 125 – DK 129 and Elbahe at chainage 147 as shown in Figure 3.1.

Figure 3.1 Elbahe Quarry Ballast Sources

3.2 General Overview of Ethio- Djibouti Railway Line

3.2.1 Meteorological Characteristics

Ethiopia is located in East Africa with many plateaus in its territory. Although it is located in the tropics, owing to a large difference in latitude span and altitude, the temperature in each area is uneven. In general, the climate of the country mainly is a tropical savannah climate, while some regions are plateau mountain climate and tropical desert climate. On the whole, most areas are of mild climates with average annual temperature ranging between 10°C and 27°C. The average annual temperature is 16°C, 20.6°C and 23.3°C in the capital city, Mieso and Dire Dawa respectively. Generally, the temperature is highest from March to May and relatively 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 between 1000 to 1500 mm and 250 to 500 mm in depressions and valleys, [30].

3.2.2 General track technical information

Ethio-Djibouti main lines is a standard gauge line (1435 mm) that adopts the sub-heavy standard ballast track and jointed track with Rail: 50 kg/m, 25mU71Mn hot-rolled new rails with bolt holes, Sleepers and fastener used are of new type II pre-stressed concrete used in normal sections, and 1680 sleepers laid per kilometer with Elastic rod type I fastening on the line The track bed parameters are in Table A.1 and A.2, [30].

3.3 Data Collection

In this study, the aim is to determine the sources of fouling using a Fouling Index (FI), levels of fouling rate and prediction of the maintenance schedule at Dire Dawa site.

The type of data to collect

a. Information on sources of ballast fouling
b. Ballast quality specifications as used during construction stage in the study area.
c. Ballast samples for study and analysis from Dire Dawa site Ethio-Djibouti line (on track) and quarry
d. Ethio-Djibouti line substructure design information.

3.4 Field investigation

3.4.1 Visual inspection

This was done manually by moving along the railway line before taking the ballast samples from the track to observe and identify the most likely causes of ballast fouling by the help of camera photos were captured to give a sight view of what is on the ground. During this process, various spots of severely damaged ballast combined with sand related particles were observed on the truck from kilometers DK 125 to kilometer DK129 with relatively high percentages of ballast sizes ranging between 25 mm to fine particles. Total contamination of the ballast material around level crossings by dust like material (loam soils, silt and clay components) were observed which is most likely to be a threat during rainy seasons. A few areas on the truck were observed to be covered by vegetation components around kilometer DK 128. The drainage condition in some areas is bushily covered with tall grass and shrubs as shown in the picture below. The objective of the visual inspection was to have a general view of the track conditions including the drainage and give a basis for taking samples for further laboratory investigations. Figures 3.2, 3.3 are some of the photos captured during the field inspection process.

Figure 3.2 Fouling Ballast on the Left and Sand Contamination Spots on the Right Side

Figure 3.3 Contaminated Ballast at Level Crossing on the Left and Bushy Drainage on the Right.

3.4.2 Field sampling

Geotechnical classification and trenching of the study area were carried out to meet a specific list of study criteria. The random sampling method developed had to ensure capturing of the necessary fine material, coarse ballast, so as to obtain a uniform representative sample for grain size characterization. While sampling, the excavation was always between 20 cm and 25 cm which is the thickness of the ballast bed. To minimize conflicts with the management team or Authorities and not to interfere with the train operations since there was no stand by maintenance teams to replace and tamp the ballasts, maximum of two-three trenching sites were located in each kilometer. The sampling was done on left and right shoulder along the track. During sampling, fouled spots were noticed in most of the sites containing broken ballasts and sand fine particles as shown in Figure 3.4.

Figure 3.4 Fouled Ballast During Sample Excavation

3.4.3 Ballast sample collection procedure from the track

Tools used in sampling included Pick-axe, Spade, Sampling bags, Tape measure and Camera

An adequate ballast sample of around 40 kg and 60 kg was collected from every trench so as to have an appropriate sample for grading.

A total of fifteen samples were collected in a stretch of five kilometers

By the help of laborers, trenches of approximately 20 cm width by 25 cm deep were dug to extract the ballast sample.

The material was packed into the sampling bags using a handheld spade. Care was taken so as to minimize material loss or dropping during packaging.

The packed Sample bags were closed and stored in a safe location to prevent any loss of sampled material.

After the excavation of the ballast samples, the trenches were backfilled with nearby ballast materials to permit normal train operations and avoid unnecessary accidents.

The sampling method applied was manual and simple, affordable on small scale and does not damage or affect the track components but time-consuming and slightly expensive if it's on large scale research.

However, the best method would have been the use of mechanical backhoes with maintenance teams to replace and tamp the ballast layer after sample excavation to enable normal operations of the line.

Figure 3.5 Extraction of Sample on the Left and Measuring of the Sampling Depth on the Right

3.5 Laboratory Assessment of Ballast Samples

After field investigation or visual field inspection, laboratory test on the ballast samples was conducted to determine the grain size distribution as shown in Picture 3.6 and Abrasion characteristics of the material. The results were recorded in order to be used in the correlation between the initial at (Quarry or before application of traffic) and analysis of the current track condition from the ballast material perspective. The tests included course or Large pan sieving (63 mm, 56 mm, 45 mm, 35.5 mm, 25 mm and 16 mm) as used in the Chinese Standard for ballast gradation and fine sieving to identify particles that are <9.5 mm (fouling material). The grading was performed on both samples from Quarry site and from the track, Abrasion test was also conducted to assess the wear and degradation characteristics of the material and to obtain the Los Angele Abrasion (LAA) values that will be used in the calculation of the rate of fouling using numerical equations. To have a clear relationship, the Chinese standard was adopted in addition to ASTM. The results from gradation were tabulated and the particle size distribution charts plotted for course material. In the laboratory, all samples were visually examined and described according to ASTM D2488 to identify the different soil components.

3.5.1 Laboratory grading to classify the different fouling components

For ballasts, the fouling material is considered to be any particle that passes the smallest end of the gradation curve that are not desired for effective track performance and it differs with different standards.

In Chinese grading, the smallest sieve size end is 16 mm and only permits (0-5 %) passing, therefore, any quantity above 5 % passing 16 mm sieve size is not desired therefore these particles were graded and classified to get percentages passing 9.5 mm (fouling material) and also identify the different compositions in the material as shown in Picture 3.7.

The classification was done as according to USCS system to identify the compositions in the contaminant for example sand, gravel (crushed ballast), silt and clay for sources grouping.

Table 3.1 Different Classification Systems for Soil Particle Sizes

Soil Type	USCS Symbol	GRAIN SIZE RANGE (mm)			
		USCS	AASHTO	USDA	MIT
Gravel	G	76.2 - 4.75	76.2 – 2	> 2	> 2
Sand	S	4.75 – 0.075	2 – 0.075	2 – 0.05	2 – 0.06
Silt	M	Fines < 0.075	0.075 – 0.002	0.05 – 0.002	0.06 – 0.002
Clay	C		< 0.002	< 0.002	< 0.002

The Fouling Index (FI) was calculated using $FI = P_4 + P_{200}$

Where,

P_4 percentages passing sieve size 4.75 mm

P_{200} percentages passing sieve size 0.075 mm

The level of fouling was described as in Table 3.2 Classification criteria for fouled ballast material by Selig and waters.

Table 3.2 Classification Criteria for Fouled Ballast

Fouling index			Classification
$FI_P = P_{0.075} + P_{4.75}$	$FI_D = \frac{D_{90}}{D_{10}}$	$FI = P_{0.075} + P_{4.75}$ (Selig and waters, 1994)	
<2	<2.1, and $P_{13.2}$≤1.5 %	<1	Clean
2≤10	2.1<4	1≤10	Moderately clean
10≤20	4<9.5	10≤20	Moderately fouled
20≤40	9.5≤40	20≤40	Fouled
≥45	≥45, $P_{13.2}$≤140 %, $P_{13.2}$ >5 %	≥40	Highly fouled

3.5.2 Determination of the rate of ballast fouling

According to Ionescu, (24) the rate of ballast fouling can be calculated mathematically by dividing the average value of the fouling index (FI) by the ballast life (BL).

$$Rate\ of\ fouling = \frac{FI_{Average}}{Ballast\ life\ (BL)} \quad \ldots \quad 3.1$$

Where LB = M_{CP} is the ballast life as cumulative traffic in million gross tonnes (MGT). As calculated from the Canadian Pacific method. Ballast life can alternatively be computed from the CP graphical method as shown in Figure 2.3.

$$M_{cp} = 10^{a} \quad \ldots \quad 3.2$$

$$a = [(-0.017)(A_n - 60)] + 2.5 \quad \ldots \quad 3.3$$

A_n is an abrasion number of the ballast material calculated from,

$$A_n = LAA + 5 * MA, or \quad M_{DE} \quad \ldots \quad 3.4$$

Where:

LAA is Loss Angeles Abrasion value (%)

MA is Mill Abrasion value (%)

M_{DE} is Micro-Deval abrasion value (%).

The method also uses a Canadian Pacific rail ballast chart which has varying gradations CP2, CP3, CP4, and CP5 to obtain the ballast life based on the ballast gradation and abrasion number. To use the Canadian Pacific rail chart, the Chinese gradations shall be superimposed on to the CP so as to locate where it lies and estimate the ballast life.

Therefore, this gives two values of ballast life by mathematical calculation and graphical interpretation.

Using equation 2.9, a check can be done to compare the life of ballast obtained from the graph.

Where 1.029 is a factor for concrete sleeper effect on the durability of the ballast material, [27].

3.5.3 Los Angeles Abrasion Testing

LA Abrasion testing was performed to assess the wear characteristics of the ballast rock type. Testing was done as per ASTM Standard C535. The test also provides a measure of crushing resistance, used to evaluate ballast particle strength and characteristics to resist the breakage under the tie when loaded with traffic.

A total sample weight of 10 kg was weighed with 5 kg of the sample between 50.8 mm and 38.1 mm, 5 kg of the sample between 38.1 mm and 25.4 mm particle diameter as per the standard.

The sample was placed in the Los Angeles abrasion apparatus with 12 steel balls each 1.5 kg and automatically rotated for 1,000 revolutions in a steel drum as shown in Picture 3.8.

The rotation of the drum was done at a rate of 32 rpm with the ballast and the steel balls resulting in the crushing and wearing effect of the ballast.

After the 1000 revolutions, the test sample was removed and sieved through 1.7 mm sieve and the mass retained weighed which is subtracted from the original total mass to obtain the mass of the crashed ballast. The LAA value is taken as the percentage of fines produced during the test to the original sample weight.

Calculation of Los Angeles Abrasion value

Let L1 be the original weight of the sample

L2 be the weight of the sample after test

$$LAA = \frac{L1 - L2}{L1} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

3.5.4 Superimposing the Chinese standard on to the grading standards, Cp rail ballast.

The quarry samples were graded in the laboratory and the results of the cumulative mass passing plotted on the Chinese gradations envelopes.

The average cumulative mass of the same quarry result was calculated to get the average cumulative mass passing (%) for the four quarry samples.

The average cumulative masses were superimposed by plotting the average cumulative masses passing (%) on to the CP Rail ballast gradation standards to determine where the grading lies of the CP2, CP3, CP4, and CP5. The plotted graphs are presented in Figures 4.13, 4.14, 4.15 and 4.16

From the plots, the Chinese standard gradation or the quarry gradation results lie between gradations CP4 and CP5 of the Canadian Pacific hence a reference line for the quarry is marked.

Using the calculated abrasion number of the ballast, the ballast life is read off from the chart by drawing a straight line from the calculated ballast abrasion number to the marked line where the ballast gradation lies within the chart.

3.5.5 Determination of Specific Gravity, Void Ratio and Volume of Void

The test procedure is as per BS812, [39].

Table 3.3 Bulk Specific Gravity of the Ballast

Bulk Specific Gravity				
	Test	1	2	3
A	Mass of oven dry sample in air (g)	1609.20	1611.10	1611.80
B	Mass of pycnometer filled with water water (g)	1698.10	1734.20	1691.70
C	Mass of Pycnometer +SSD Sample+water	2900.70	2825.20	2912.30
D	Mass of SSD sample	1831.10	1698.30	1881.60
Gsb	Bulk specific gravity	2.911	2.795	2.845
	Average Gsb	2.85		

Specific gravity Gsb = 2.85

Table 3.4 Unit Weight of the Ballast

Unit weight of Ballast Material				
	Test number	1	2	3
A	Weight of empty container (kg)	1.67	1.670	1.67
B	Weight of container plus ballast (kg)	10.72	11.68	11.18
C	Weight of container plus water full (kg)	6.56	6.56	6.56
	Weight of ballast sample (kg)	9.05	10.01	9.51
	Volume of water (m^3)	0.005	0.005	0.005
	Unit weight (kg/m^3)	1850.7	2047.0	1944.8
	Average unit weight (γ_w) (kN/m^3)	19.5		

$$\Upsilon_d = \frac{Gs * \gamma_w}{1+e} \dots \dots \dots \dots 3.6$$

$$19.48 = \frac{2.85 * 9.8}{1+e}$$

e = 0.434

where $V_T = 0.005m^{3,}$ obtained by measuring the volume of the container used.

V_T is the total volume

$$Vv = \frac{0.434 * 0.005}{1 + 0.43} \dots \dots \dots \dots 3.7$$

$Vv = 0.0015m^3$

Therefore, volume of void as a ratio of the total volume,

$$Vv = \frac{0.0015}{0.005} = 0.302 \dots \dots \dots \dots 3.8$$

3.6 Particle Breakage

The breakage index of fresh ballast and ballast exposed to traffic is calculated using equation 2.10

The breakage index (Bg) is the sum of all positive values $\sum \Delta Wk$,

$$\Delta w_k = w_{ki} - w_{kf}$$

Where; Wki is the percentage retained on sieve size k before traffic loading

Wkf is the percentage retained on the same size after traffic loading.

3.7 Appropriate maintenance schedule

Assumptions

Assume the same fouling conditions hence constant rate of fouling throughout the year

Assume constant traffic loading per year.

The volume of voids within new/clean ballast constitutes approximately 0.41 – 0.45 of the total volume of ballast within a track, [18], [8].

Table 3.5 Unit weight-volume relationships of ballast

Ballast condition	FI	Unit weight (kN/m^3)	Void ratio	Void volume
Loose	0	16.01	0.68	0.41
Consolidated	0	17.62	0.53	0.35
Fouled	20	20.02	0.35	0.26
Failing	40	20.16	0.25	0.20

From Equation 3:9, the volume of void for 1.4 years (the period for which the railway line has operated to the ballast testing date) is 0.3026 therefore for twelve months (one year) is 0.35.

$$\frac{1.2}{1.4} * 0.3026 = 0.26 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. 3.9$$

Therefore, (0.303-0.2594) = 0.044 to get for one year

1.2 indicates twelve months, 1.4 indicates fourteen months.

Since the volume of voids for fresh ballast is 0.41 and reduced to 0.35 after one year of operation, for constant fouling condition this means a drop of 0.06 in the volume of voids per year.

For a change in Fouling Index,

If after 1.2 years of track usage the FI=16 %, for any period the FI can be calculated as follows

$$FI(k) = \frac{k\_(year)}{1.2} * FI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.10$$

Where FI(k) is the fouling index for a given year (k).

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 Results for Particle Size Analysis (Coarse Ballast Material)

This consists of nine sets of gradation data from both the quarry site and the ballast obtained from the track. In the analysis, a comparison will be made between the quarry gradation results which represent the initial condition of the ballast material or the grading of fresh ballast as was used during construction and the current ballast state on track to finding out the amount of degradation that has taken place. In addition, particle breakage index is performed to obtain the changes in sizes after traffic load on the track.

Table 4.1 Chinese Ballast Gradation Envelope as used on Ethio-Djibouti Line

The side length of square-mesh sieve (mm)	16	25	35.5	45	56	63
Mass percentage passing the sieve (%)	0 – 5	5 – 15	25 - 40	55 - 75	92 - 97	97 - 100

4.2 Results and plots for Elbahe Ballast Quarry as used during construction

Table 4.2 Sample (1) Result for PSD Elbahe Quarry.

BALLAST PARTICLE-SIZE ANAYSIS						
Elbahe Quarry at DK 147			Total Mass (gm)	50000		
Sampling Date: 20/02/19			Testing Date: 21/02/19			
Sieve Size (mm)	Chinese Grading envelope (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass passing (%)
	lower	upper				100
63	97	100	0.0	0.0	0.0	100
56	92	97	1200.0	1200.0	2.4	98
45	55	75	19110.0	20310.0	40.6	59
35.5	25	40	15130.0	35440.0	70.9	29
25	5	15	11730.0	47170.0	94.3	6
16	0	5	2510.0	49680.0	99.4	1
pan			0.0	49680.0	99.4	1

Table 4.2 represents the results from gradation for the quarry sample, more gradation results for sample 2, 3 and 4 are shown in the appendix Table, A.0.3, A.0.4 and A.0.5.

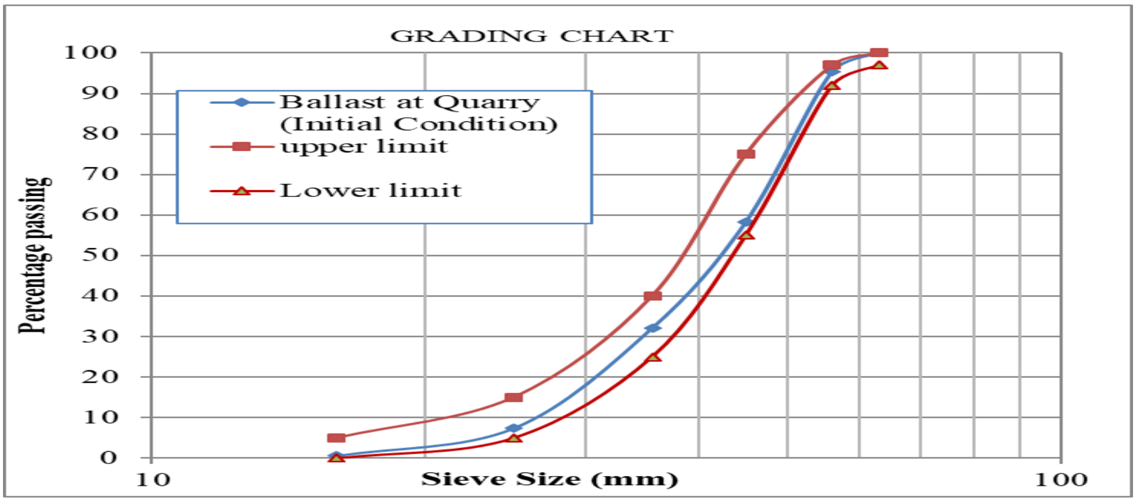

Figure 4.1 Grading Chart for Elbahe Quarry Sample (2)

Figures 4.1, A.0.1, A.0.2, and A.0.3 are plotted from gradation results in Tables 4.2, A.0.3, A.0.4 and A.0.5

From Figures (4.1, A.0.1, A.0.2, and A.0.3), the averagely initial condition of the ballast gradation from Elbahe Quarry source lies within the grading envelope. This means that the ballast materials are clean and satisfy the grading requirements as per the recommendation.

4.3 Results and plots for On-Track Ballast (Current condition)

Table 4.3 Ballast Particle Size Distribution Results for Chainage 125+650

BALLAST PARTICLE-SIZE ANAYSIS						
DK 125+650			Initial dry Mass (gm)	50000		
Sampling Date: 16/02/19			Testing Date: 18/02/19			
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100.0
63	97	100	320	320	1	99
56	92	97	620	940	2	98
45	55	75	8430	9370	19	81
35.5	25	40	10290	19660	39	61
25	5	15	13410	33070	66	34
16	0	5	12490	45560	91	9
pan			3790	49350	99	1

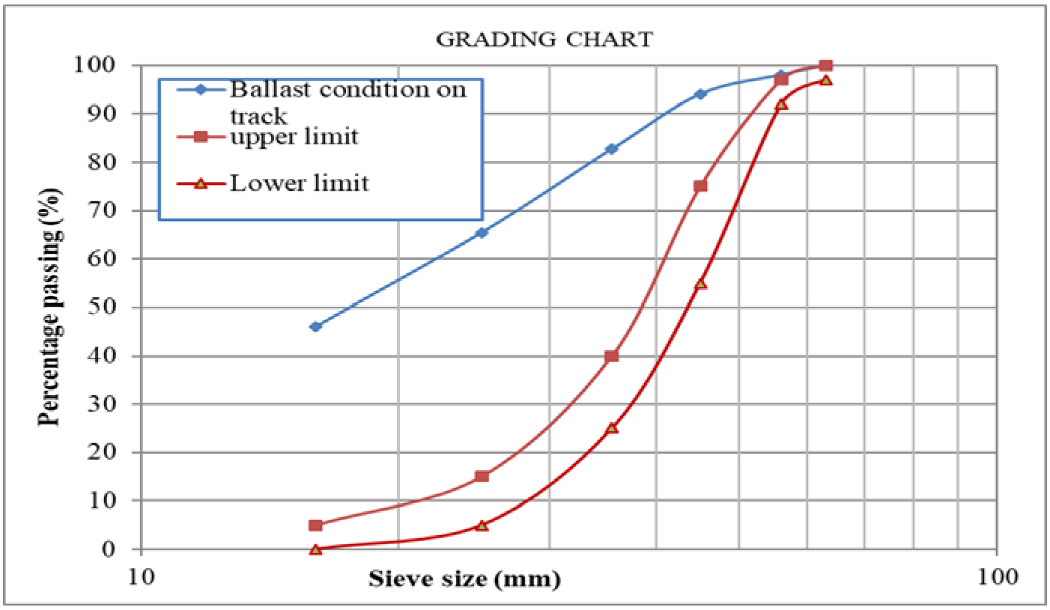

Figure 4.2 On Track Ballast Grading Chart for DK 127+800

Table 4.3 represents the results from gradation for the on-track sample at chainage 125+650, more gradation results for samples between chainages 126+480 to chainage 129+800 are shown in the appendix Tables, A.0.6, A.0.7, A.0.8, A.0.9, A.10, and A.11

Figures 4.2, A.0.4, A.0.5, A.0.6, A.0.7, A.0.8, and A.0.9 are plotted from gradation results in Table 4.3, and Appendix Tables, A.0.6, A.0.7, A.0.8, A.0.9, A.10, and A.11

Figures 4.2, A.0.4, A.0.5, A.0.6, A.0.7, A.0.8, and A.0.9 show a wide variation in gradation from the initial specified envelope due to ballast breakdown by traffic loading and tamping with particle Breakage Index ranging from 27.2 % to 60.0 % and the average Breakage Index of 42 % as calculated from Table 4.4.

The variation in breakage index is due to tamping activities that have been carried out in some sections to restore the track alignment hence causing breakage of the ballast particles.

4.4 Particle Breakage Analysis

The results are generated from the gradation of the fresh ballasts and the ballasts after traffic loading and tamping maintenance action using equation 2.10.

Table 4.4 Particle Breakage Index Analysis

Breakage Index Analysis															
Sieve Size	Wki	Wkf	ΔWk	Wkf	ΔWk	Wkf	ΔWk	Wkf	ΔWk	Wkf	ΔWk	Wkf	ΔWk	Wkf	Δ
		DK 126+480		DK 125+650		DK 127+250		DK 127+800		DK 128+100		DK 128+700		DK 129	
(mm)	%														
63	0.0	0.0	0.0	0.6	-0.6	0.0	0.0	0.0	0.0	2.0	-2.0	0.8	-0.8	0.0	
56	3.2	2.4	0.9	1.2	2.0	4.8	-1.6	2.0	1.3	3.3	-0.1	1.9	1.4	1.9	
45	39.2	18.2	21.0	16.9	22.4	5.3	33.9	4.0	35.2	11.4	27.8	20.4	18.8	21.8	
35.5	28.7	23.5	5.2	20.6	8.1	14.0	14.7	11.3	17.4	13.4	15.3	18.2	10.5	20.1	
25	24.4	24.2	0.2	26.8	-2.4	16.8	7.6	17.3	7.1	17.4	7.0	20.8	3.6	19.2	
16	4.1	21.6	-17.5	25.0	-20.9	18.8	-14.7	19.4	-15.3	15.8	-11.7	21.9	-17.8	25.3	-
pan	0.1	9.6	-9.5	7.6	-7.5	39.9	-39.8	45.8	-45.7	35.2	-35.1	15.3	-15.2	11.5	-
Bg =ΣΔWk positve values			27.2		32.5		56.3		61.0		50.1		34.3		
Average Bg = 42.0%															

4.5 Laboratory Grading to Classify the Different Fouling Components and Calculation of the Fouling Index (FI).

From Table A.0.12, the percentage of particles passing 9.5 mm sieve size which forms the fouling material is 4% consisting of Silt and Clay (particles < 0.075 mm), Sand (particles between 4.75 mm to 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling Index (FI) is calculated from Equation 2:4

$FI = P_4 + P_{200}$ where:

P_4 is percentage passing the 4.75 mm (No.4) sieve,

P_{200} is percentage passing the 0.075 mm, however a sieve of 0.063mm has been used in this research due to absence of 0.075 mm size.

$P_4 = 3.02$

$P_{200} = 1.83$

$$\mathrm{FI}(1) = 3.02 + 1.83 = 5\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .4.1$$

Therefore, at DK 125+650, the ballast material is moderately clean since the fouling index of 5 % is within 1 ≤ 10 % as in Table 2.4.

From Table A.0.13, the percentage of particles passing 9.5 mm sieve size which forms the fouling material is 5.24 % consisting of Silt and Clay (particles < 0.075 mm), Sand (particles between 4.75 mm – 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling Index (FI) is calculated from Equation 2:4

$P_4 = 2.66$

$P_{200} = 1.04$

$$\text{FI}\ (2) = 2.66 + 1.04 = 4\ \% \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.2$$

Therefore, at DK 126+480, the ballast material is moderately clean since the Fouling Index of 4 % lies between 1 ≤ 10 % as in Table 2.4.

From Table A.0.14, the percentage of particles passing 9.5 mm sieve size which forms the fouling material is 30.49 % consisting of Silt and Clay (particles < 0.075 mm), Sand (particles between 4.75 mm – 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling Index (FI) is calculated from equation 2:4

$P_4 = 23.21$

$P_{200} = 5.19$

$$FI(3) = 25.55 + 5.14 = 28\ \% \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.3$$

Therefore, at DK 127+250 according to Selig and Waters, the ballast material is fouled in reference to Table 2.4 since the fouling index of 28% lies between 20 ≤ 40 % hence restoration measures need to be taken for the proper functionality of the ballast in this section.

From Table A.0.15, the percentage of particles passing 9.5 mm sieve size which forms the fouling material is 32.86 % consisting of Silt and Clay (particles < 0.075 mm), Sand (particles between 4.75 mm – 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling index (FI) is calculated from Equation 2:4

$P_4 = 25.55$

$P_{200} = 5.14$

$$FI(4) = 25.55 + 5.14 = 30\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.4$$

Therefore, at DK 127+800 according to Selig and Waters, the ballast material is fouled in reference to Table 2.4 since the fouling index of 30 % lies between 20 ≤ 40 % hence measures should be taken to restore the ballast condition in this section.

From Table A.0.16, the percentage of particles passing 9.5 mm sieve size which forms the fouling material is 25.50 % consisting of Silt and Clay (particles < 0.075 mm), Sand (particles between 4.75 mm – 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling index (FI) is calculated from Equation 2:4

$P_4 = 18.5$

$P_{200} = 5.0$

$$FI(5) = 4.78 + 4.13 = 24\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.5$$

Therefore, at DK 128+100 according to Selig and Waters, the ballast material is fouled in reference to Table 2.4 since the fouling index of 24 % lies between 20 ≤ 40 % hence maintenance measures needed to restore the ballast condition in this section.

From Table A.0.17 the percentage of particles passing 9.5 mm sieve size which forms the fouling material is 11 % consisting of Silt and Clay (particles < 0.075 mm), Sand (particles between 4.75 mm – 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling index (FI) is calculated from Equation 2:4

$P_4 = 8.68$

$P_{200} = 4.09$

$$FI(6) = 4.78 + 4.1 = 13\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.6$$

Therefore, at chainage 128+700 according to Selig and Waters, the ballast material is moderately fouled in reference to table 2.4 since the Fouling Index of 13 % lies between 10 ≤ 20 % hence maintenance work needed to remove the fouling contents.

From the Table A.0.18, the percentage of particles passing 9.5 mm which form the fouling material is 7.87 % consisting of silt and clay (particles < 0.075 mm), Sand (particles between 4.75 mm – 0.075 mm) and Gravel or broken Ballast material (particles > 4.75 mm).

The Fouling Index (FI) is calculated from Equation 2:4

$P_4 = 5.32$

$P_{200} = 2.41$

$$\text{FI}(7) = 5.32 + 2.41 = 8\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 4.7$$

Therefore, at DK 129+150 according to Selig and Waters, the ballast material is moderately clean in reference to Table 2.4 since the Fouling Index lies between 1 ≤ 10 % hence the material is still in relatively good functioning conditions.

The average of the fouling index FI= [FI (1) + FI (2) + FI (3) + FI (4) + FI (5) + FI (7) + FI (7)]/7

$$FI = 16\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 4.8$$

As calculated in Equation A.0.1

Using Selig and Waters classification criteria for fouled ballast in Table 3:3, the ballast material in section DK 125-DK129 is moderately fouled in reference to Table 2.4 since the average Fouling Index FI= 16 % between the range 10 ≤ 20 % hence maintenance measures need to be taken to restore the facility to avoid the probable damages that may be caused by ballast fouling.

Therefore, the degree or extent of fouling is moderate in reference to Table 2.4 hence an answer to objective (2) of this research.

4.6 Calculation of Fouling Components as a Percentage of the Total < 9.5 mm Sieve Size

Using the USCS Classification system, the percentages of the components of fouling material which includes broken ballasts or gravel, sand silt and clay are computed as follows.

Table 4.5 Calculation of the fouling contents using ASTM

Soil type	USCS Symbol	Grain Size (mm)
Gravel	G	76.2 to 4.75
Sand	S	4.75 to 0.075
Silt and Clay	M/C	Fines < 0.075

From Table A.0.19,

Gravel =100 - 62 = 38 %

Sand = 62-16

= 46 %

Silt and clay =16 %, percentage < 0.063 mm

From Table 4.5, Gravel is the material between 76.2 to 4.75,

Sand is the material between 4.75 to 0.075 or 0.063 mm and silt and clay material percentage < 0.063 mm.

Therefore, percentage of Fouling ballast breakdown for chainage 125+650 was found to be 38 % sand being the highest with 46 %, silt, and clay 16 %.

The percentages of fouling for the chainages 126+480 to chainage 129+150 are summarized in Table 4.6.

4.7 Summary of the Fouling Percentages for Gravel, sand, Silt, and Clay

Table 4.6 Summary of the fouling percentages for Gravel, sand, Silt, and Clay

Soil Type	Fouling Percentages (%) for Different Chainage							Average (%) for each Component
DK	DK 125+650	DK 126+480	DK 127+250	DK 127+800	DK 128+100	DK 128+800	DK 129+150	
Gravel	38	24	22	34	29	21	35	29.0
Sand	46	59	62	10	56	45	39	45.3
Silt and Clay	16	17	15	56	14	34	26	25.4

Table 4.7 is a summary of the fouling percentages for Tables A.0.19, A.0.20, A.0.21, A.0.22, A.0.23, A.0.24, and A.0.25

From Table 4.7, the average percentage fouling due to ballast breakdown was found to be 29 % sand being the highest with 45 %, silt and clay 25.49 % for chainage 125-DK129. Sand (45 %) which could be due to the wind blowing from the surrounding or tipped while loading at quarry sites.

Gravel (29 %) due to traffic loading and tamping action that cause ballast breakage

Silt and Clay (26 %) which could be due to the wind blowing from the surrounding, tipped while loading due to poor ballast material loading from quarry sites or from subgrade intrusion.

4.7.1 Causes of Fouling

From the analysis in Table 4.7, the causes of fouling at Dire Dawa site include,

Wind blow with sand contributing 45 % of the fouling material

Traffic loading and tamping contributing to 29 % broken ballast material

Subgrade intrusion contributing to 25 %

Therefore, the major source of ballast fouling in Dire Dawa along Ethio-Djibouti line is wind.

4.8 Calculation of the Los Angeles Abrasion Value

4.8.1 Los Angeles Abrasion for quarry material

Let L1 be the original weight of the sample before the test

L2 be the weight of the sample retained on 1.7 mm sieve size after test, using Equation 3:4,

Table 4.7 Summary of Los Angeles Abrasion for Quarry Ballast Material

Mass	Sample 1	Sample 2	Sample 3	Sample 4
L1 (kg)	10	10	10	10
L2 (kg)	8.22	8.20	8.21	8.3
LAA (%)	17.8	18	17.9	17.1
$LAA_{average}$	17.7 %			

Therefore, the average Los Angeles value for quarry samples 1, 2,3, and 4 is,

$$LAA_{average} = 17.7\ \%$$

4.8.2 LAA for on track ballast material

Using equation 3:4,

Table 4.8 Summary of Los Angeles Abrasion for on Track Ballast Material

Mass	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
L1 (kg)	10	10	10	10	10
L2 (kg)	8.101	7.6	7.98	7.26	8.11
LAA (%)	19	24.5	21.1	27.4	19
$LAA_{average}$ (%)	22.2				

Therefore, the average value of the LAA for on track samples as calculated from Equation 4.10

$$LAA_{average} = 22.2\ \%$$

From the Los Angeles Abrasion analysis, a degradation is also observed because initially before the application of traffic on the ballast (Quarry sample) the average Los Angeles Abrasion is 17.7 % which shows strong sound aggregates and after the application of traffic (on track samples) the average is 22.2 % with a drop of 4.5 % from the original condition hence an evidence of degradation.

4.8.3 Calculation of Abrasion Number An

From the literature review, abrasion number is equal to LAA+5*M_{DE} therefore, using equation 2:8, the abrasion number (An) can be computed.

Average Micro-Deval value = 6.8 % as calculated in Equation A.0.2

Therefore, abrasion number; $(An) = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 22.17 + 5 * 6.835\ \%$

$$An = 56.3\ \%$$

The abrasion number of 56.3 % will be used in calculation of the ballast life.

4.8.4 Superimposing the Chinese Standard on To the Gradation Standards, Cp Rail Ballast.

Table 4.9 Cumulative Percentage Mass Passing for Quarry (Q) Samples 1,2,3 and 4

Sieve Size (mm)	Cummulative Mass Passing (%) for Elbahe Quarry DK				Average Cumulative Mass Passing (%)
	Q1	Q2	Q3	Q4	4
63	100.0	100.0	100	100	100.0
56	97.6	95.4	97.3	97	96.8
45	59.3	58.2	55.1	70	60.7
35.5	28.9	32.0	25.5	38	31.1
25	5.4	7.3	0.67	14	6.8
16	0.4	0.5	0.26	4	1.3
pan	0.4	0.5	0.02	0	0.2

The average cumulative percentage mass passing for quarry samples 1, 2, 3 and 4 were plotted on the Canadian Pacific rail (CP) envelopes (CP2, CP3, CP4, CP5).

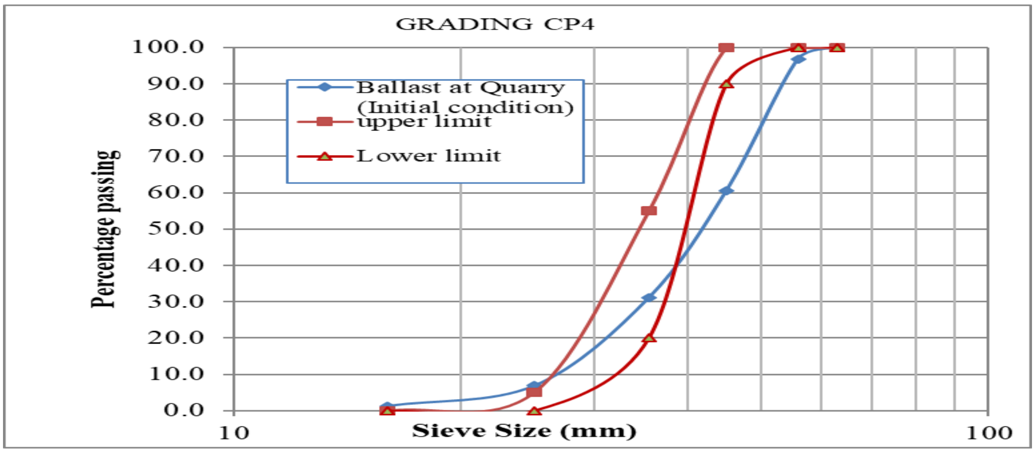

Figure 4.3 Average of Cumulative Mass Passing Plotted on CP4

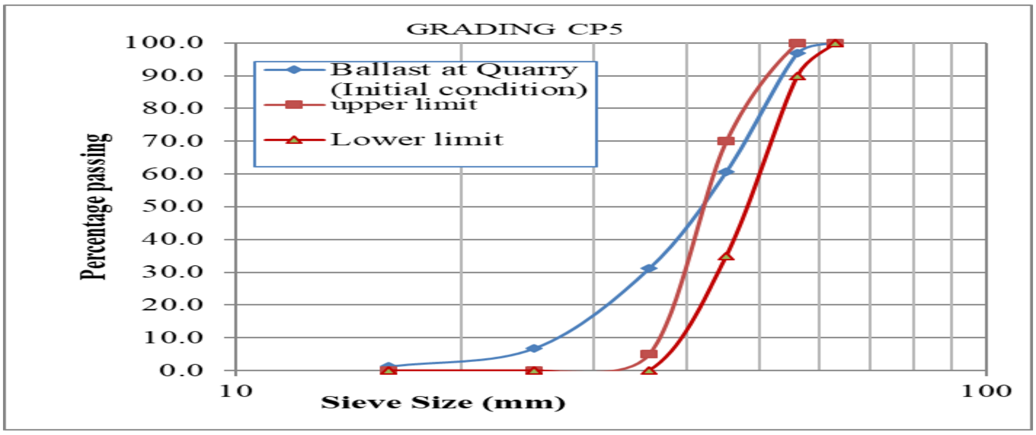

Figure 4.4 Average of Cumulative Mass Passing Plotted on CP5

As seen from the plots in figures 4.3, 4.4, A.0.11 and A.0.12 the cumulative mass passing for the quarry results doesn't fit in the envelops CP2, CP3, but it partially fits into CP4 and CP5.

Therefore, from the plots, the reference line for the cumulative mass shall be drawn between CP4 and CP5 for estimations of the ballast life. Using the abrasion number of 56.3 % as calculated, the cumulative traffic can be got from the plot of Ballast life (in MGT) based on ballast gradation and Abrasion Number. (Data from Chrismer, 1994).

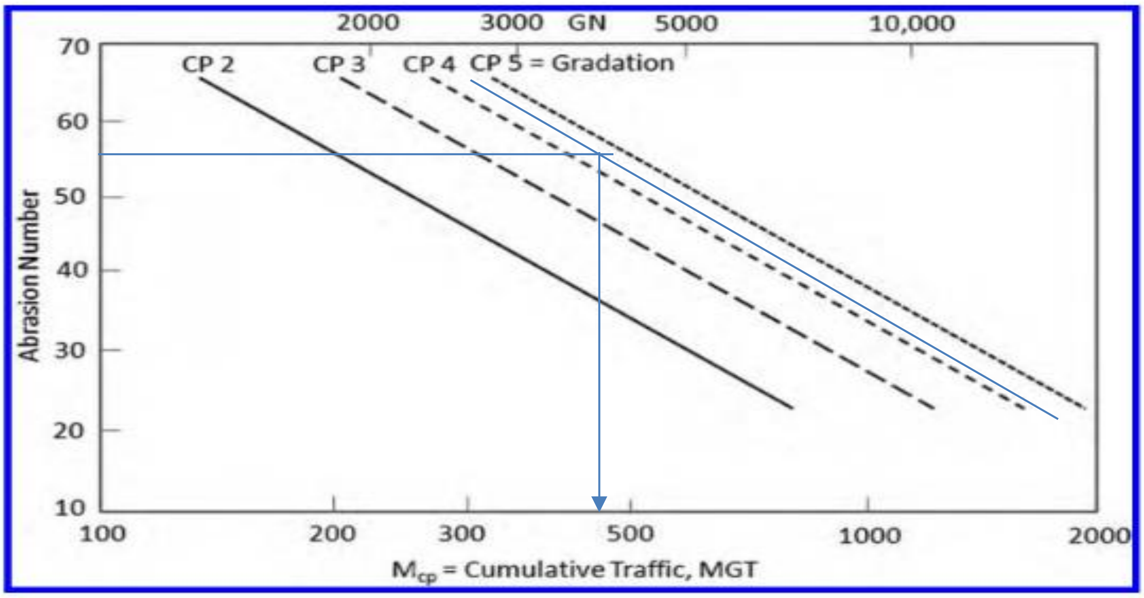

Figure 4.5 Ballast Life (in MGT) Based on Ballast Gradation and Abrasion Number. (Data from Chrismer, 1994.

From Figure 4.5 above, the ballast life is estimated to be 410MGT

Using equation 2:6,

$$Fouling\ rate = \frac{Fouling\ Index\ (FI)_{Average}}{Life\ of\ ballast} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.9$$

$$\text{Average FI} = 16\ \%$$

The ballast life is approximately 410 MGT as read from the graph

Using equation 2:9,

$$Life\ of\ ballast = 1.029 * [10^6\ exp(8.08 - (0.0382 * 56.344))]$$

Ballast life =386.2 MGT

To minimize errors, the average of the two values of ballast life from graph and equation is computed.

Ballast life is taken as average of 410 MGT and 386.2 MGT

=398.1 MGT

Therefore, Fouling rate is equal to 0.04 %/MGT calculated using Equation 4.11

Based on the fouling rate, the maintenance schedule can be predicted by assuming constant reduction in the volume of the void of the ballast and increment in the fouling index on the railway line.

4.9 Appropriate maintenance schedule guidelines

Table 4.10 Predicted Time in Years with Varying Volume of Void and FI

Time (year)	Volume of voids	FI	Remark based on *Vv*	Remark based on FI
0	0.41-0.45	<2	Loose	Clean
1	0.35	13.29	Consolidated	Moderately fouled
1.2	0.30	15.95	Consolidated	Moderately fouled
2	0.28	26.58	Fouled	Fouled
3	0.22	39.88	Failing	Fouled
4	0.16	>40	Failing	Highly fouled
5	0.93	>50	Failed	Highly fouled
6	0.30	>50	Failed	Highly fouled

During facility usage, inspection should be conducted every month to identify any evidence of fouling, vegetation growth, ballast breakage, and sand pours by wind.

Testing should be done at six months intervals to provide sufficient information about the condition and extent of fouling and level of void volume this is because after one year and two months period of track use as per this research, the FI equal to 16% which is a moderately fouled state and volume of void of 0.30 the minimum field void level below which the ballast layer is considered fouled as in table 4.9, therefore, ballast shoulder cleaning recommended to improve the drainage and washing away of some of the fouling material from the crib area.

After two years of track usage, the railway ballast undercutting or any form of renewal has to be performed to restore the functionality of the ballast this is because the FI is approximately equal to 26.6 % and V_V equal to 0.28 which both indicate fouled state in reference to Table 4.9.

If undercutting or any form of ballast renewal is not performed within 3 years the ballast will deteriorate to a level where it needs to be fully replaced and formation work may also be required which is safety threatening to the users and very expensive since its time consuming and involves total suspension of the track operations.

Table 4.11 Showing Summary of the Proposed Maintenance Schedule.

Maintenance activity	**Time (year)**						
	0	0.5	1	1.5	2	2.5	3
Inspection	x	x	x	x	x	x	x
Removal of vegetation	x	x	x	x	x	x	x
Testing of ballast samples			x		x		x
Shoulder cleaning			x		x		x
Sand removal	x	x	x	x	x	x	x
Undercutting							x
Replacement							x

Note: x is used to mean that action should be taken at that specified interval.

Findings

With a known average load capacity or tonnage per year on the track, a maintenance schedule or cycle can be developed in relation to the volume of voids and the rate of ballast fouling. The allowable ballast life or cleaning cycle is calculated as,

$$Allowable\ ballast\ life = \frac{Volume\ of\ void\ (Vv)}{Fouling\ rate\ (FR)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.10$$

From the allowable ballast life, the remaining track usage period is computed which can be a reference point for the maintenance engineer to plan and schedule for ballast maintenance.

$$Remaining\ ballast\ usage\ period = \frac{Allowable\ ballast\ life}{Average\ tonnage\ per\ year} \dots\dots\dots\dots\dots\dots\dots\dots\dots 4.11$$

Table 4.12 Estimated Ballast Remaining Usage Period at Dire Dawa site

	BL (MGT)		MGT/yr		
	398.1		571.3		
Time (year)	Vv	FI	FR %/MGT	Allowable Ballast Life (MGT)	Remaining Usage Period (year)
				100	
0	0.41	2	0.01	8160.6	14.3
1	0.35	13.7	0.03	1010.5	1.8
1.2	0.30	16.0	0.04	756.2	1.3
2	0.28	25.4	0.06	443.0	0.8
3	0.22	37.0	0.09	236.6	0.4
4	0.16	48.6	0.12	127.8	0.2

yr is used to mean a year in Table 4.10.

From Tables 4.10, the clean ballast had a fouling index of < 2 % and the volume of the void of 0.41 and estimated service period of 14.3 years, but after one year of use with the traffic of 571.3 MGT/year, the ballast material suffered a large degradation rate with fouling index of 13.7 % from the initial 2 % and reduction of the volume of the void from 0.41 to 0.35 (moderately fouled) and the remaining ballast service period reduced to approximately two years.

CHAPTER 5 CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

This research presents an evaluation of the various sources of ballast fouling, degree of fouling, the rate at which it occurs and estimated maintenance period. The causes of ballast fouling in Dire Dawa are wind blow, traffic loading and tamping, and subgrade material intrusion. The causes contained more than 29 % particle of ballast, 26 % particle of silt and clay and 45 % particle of sand. The degree of fouling material (< 9.5 mm) was approximately 16.7 % by weight which is moderately fouled condition with worst sections fouled at 30.5 % and 32.9 %. The rate of fouling was at 0.04 %/MGT. After a period of one year and approximately three months track usage, there is a large variation in ballast gradation with breakage index of 42 % meaning on average, only 58 % of the ballast is larger than 16 mm the minimum sieve size used hence at this rate of degradation, almost half of the ballast material will be less than 16 mm by the end of the two years of track use. The proposed maintenance schedule is every year in order to ensure quality track operation.

5.2 Recommendations

Continuous data collection and testing programs to assess the causes and levels of fouling should be adopted by Dire Dawa site along Ethio-Djibouti and other railway industries to come up with predetermined maintenance works which reduce risk of abrupt track failure since the fouling components vary in different regions.

The idea of ballast shoulder cleaning should be adopted since it provides improved drainage from the fouled ballasts so long as the crib ballast FI < 30% as indicated in the literature review.

Further investigations need to be conducted on how to control windblown sand along with railway infrastructures since it is one of the major sources of the fouling components.

REFERENCES

[1] N. Tennakoon, B. Indraratna, and S. Nimbalkar, "Impact of Ballast Fouling on Rail Tracks," *Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance*, vol. 104, pp. 1–11, 2014.

[2] P. Anbazhagan, S. Lijun, I. Buddhima, and R. Cholachat, "Model track studies on fouled ballast using ground penetrating radar and multichannel analysis of surface wave," *Journal of Applied Geophysics*, vol. 74, no. 4, pp. 175–184, 2011.

[3] B. Indraratna and W. Salim, "Mechanics of ballasted rail tracks: a geotechnical perspective." p. 226, 2005.

[4] N. Tennakoon, B. Indraratna, C. Rujikiatkamjorn, S. Nimbalkar, and T. Neville, "The role of ballast-fouling characteristics on the drainage capacity of rail substructure," *Geotechnical Testing Journal*, vol. 35, no. 4, pp. 1–4, 2012.

[5] J. J. Pires and A. G. D. Dumont, "Railway Ballast Degradation," *15th Swiss Transport Research Conference*, p. 25, 2015.

[6] J. M. Selig, Ernest T and Water, "Track geotechnology," pp. 12–19, 1995.

[7] A. M. Marques, S. Fontul, and A. Paixão, "Ballast fouling evaluation with ground penetrating radar," *MATEC Web of Conferences*, vol. 211, p. 12004, 2018.

[8] T. R. Sussmann, M. Ruel, and S. M. Chrismer, "Source of Ballast Fouling and Influence Considerations for Condition Assessment Criteria," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2289, no. 1, pp. 87–94, 2012.

[9] S. Vitton, T. Drive, K. Breitenbucher, and W. Ottawa, "Assessment of Aggregate Sources in Michigan for High Speed Railroad Ballast Final Report."

[10] S. Chandra, *Chandra, Satish_ Agarwal, M. M.-Railway Engineering-Oxford University Press (2007).pdf*. 2007.

[11] P. Anbazhagan, T. P. Bharatha, and G. Amarajeevi, "Study of Ballast Fouling in Railway Track Formations," *Indian Geotechnical Journal*, vol. 42, no. 2, pp. 87–

99, 2012.

[12] E. Selig and D. Cantrell, "Track Substructure Maintenance--From Theory to Practice," *American Railway Engineering …*, no. 812, 2001.

[13] D. Li, J. Hyslip, T. Sussmann, and S. Chrismer, "Railway Geotechnics," *Railway Geotechnics*, 2015.

[14] R. Bruzek, T. D. Stark, S. T. Wilk, H. B. Thompson, and T. R. Sussmann, "Fouled Ballast Definitions and Parameters," p. V001T01A007, 2016.

[15] A. Ebrahimi, D. Fratta, and J. M. Tinjum, "Detection of Fouling in Ballast by Electromagnetic Surveying," *AREMA 2008 Annual Conference & Exposition*, pp. 1–21, 2010.

[16] C. M. P. E.T.Selig, T.S Yoo, "M e c h a n ic s o f B a lla s t C o m p a c t io n Volume I : Technical Review of Ballast Compaction and Related Topics," 1982.

[17] A. R. April and AAR, "A Short History of U . S . Freight Railroads," no. April, pp. 1–5, 2014.

[18] F. Feldman and D. Nissen, "Alternative testing method for the measurement of ballast fouling: percentage void contamination," *CORE 2002: Cost Efficient Railways through Engineering*, no. Civil, pp. 101–111, 2002.

[19] B. Indraratna, H. Khabbaz, W. Salim, and D. Christie, "Geotechnical properties of ballast and the role of geosynthetics in rail track stabilisation," *Proceedings of the Institution of Civil Engineers - Ground Improvement*, vol. 10, no. 3, pp. 91–101, 2006.

[20] B. Lichtberger, *Track Compendium*. 2005.

[21] W. Loon, "Mechanics of Railway Ballast Behaviour," 2004.

[22] D. Pfeiffer, "Records Relating to North American Railroads National Archives and Records Administration," 2001.

[23] A. M. Zarembski, G. T. Grissom, and T. L. Euston, "On the Use of Ballast Inspection Technology For the Management of Track Substructure,"

Transportation Infrastructure Geotechnology, vol. 1, no. 1, pp. 83–109, 2014.

[24] B. INDRARATNA, N. TENNAKOON, S. NIMBALKAR, and C. RUJIKIATKAMJORN, “Behaviour of clay-fouled ballast under drained triaxial testing,” *Géotechnique*, vol. 63, no. 5, pp. 410–419, 2012.

[25] Q. Competition, “Final Aurizon Network Review Of Ballast Undercutting,” no. November, 2015.

[26] D. Ionescu, “Ballast Degradation and Measurement of Ballast Fouling,” *7th Railway Engineering Proceedings*, vol. 2, no. February, pp. 12–18, 2005.

[27] V. Ramūnas, A. Vaitkus, A. Laurinavičius, D. Čygas, and A. Šiukščius, “Prediction of Lifespan of Railway Ballast Aggregate According To Mechanical Properties of It,” *The Baltic Journal of Road and Bridge Engineering*, vol. 12, no. 3, pp. 203–209, 2017.

[28] S. Caleb Douglas, “Ballast Quality and Breakdown during Tamping,” pp. 940–955, 2013.

[29] S. El-badawy, J. Valentin, and I. Congress, *Sustainable Solutions for Railways and Transportation Engineering*. 2018.

[30] C. F. S. and D. Institute, “Preliminary design meiso-dawanle ethiopian railway,” 2013.

[31] E. B. Tuncay, Ş. Kilinçarslan, and F. Yağmurlu, “Investigation of Usability as Aggregate of Different Originated Rocks,” *IOP Conference Series: Earth and Environmental Science*, vol. 44, no. 2, 2016.

[32] A. R. HOARE, “FEASIBILITY OF USING THE MICRO-DEVAL TEST METHOD AS AN AGGREGATE PRODUCTION QUALITY CONTROL TOOL,” 2003.

[33] Á. Török, “Engineering Geology for Society and Territory - Volume 8,” *Engineering Geology for Society and Territory - Volume 8*, vol. 5, pp. 115–118, 2014.

[34] M. Flock, “Brookside labs Micro-Deval Aggregate Abrasion Testing,” 1960. .

[35] C. LACKHOVE *et al.*, “AUTOMAIN Augmented Usage of Track by Optimisation of Maintenance , Allocation and Inspection of Railway Networks,” 2013.

[36] 1Grace L. Tsebo Simo and Christiane Simo Lezin Seba Minsili, Madja Doumbaye Jérémie, “Preventive Maintenance of Railway Tracks : Ballast Performance Anticipation in the Cameroon Railway Preventive Maintenance of Railway Tracks : Ballast Performance Anticipation in the Cameroon Railway,” no. march, 2012.

[37] P. Claisse and C. Calla, “Rail ballast: conclusions from a historical perspective,” *Proceedings of the Institution of Civil Engineers - Transport*, vol. 159, no. 2, pp. 69–74, 2006.

[38] G. D’Angelo, N. Thom, and D. Lo Presti, “Laboratory Simulation of Field Loading Conditions and Maintenance Operations,” *International Conference Railway Engineering 2015*, 2015.

[39] C. M. Laboratory, “Laboratory Testing Manual 2000,” *Laboratory Testing Manual, Central Materials Laboratory*, vol. 9987–889, pp. 1–320, 2000.

APPENDIX

Table A.0.1 Track bed Parameters

Property	Parameter	Technical Index
Abrasion resistance and impact resistance	Los Angeles abrasion, LAA (%)	27≤LAA<32
	Standard aggregate impact toughness, IP	10<IP≤95
	Stone abrasion-resistant hardness coefficient K (dry grinding)	17<K (dry grinding) ≤18
Crushing resistance	Standard aggregate crushing ratio, CA (%)	9≤CA<14
	Percentage of crushed ballast aggregate, CB (%)	18≤CB<22
Water permeability	Permeability coefficient, Pm (10-6 cm/s)	3<Pm≤4.5
Water permeability	Compressive strength of stone powder test module, σ (MPa)	0.4≤σ<0.55
	Stone powder liquid limit, LL (%)	20≥LL>16
	Stone powder plastic limit, PL (%)	11≥PL>9
Atmospheric corrosion resistance	Loss rate after immersion in sodium sulfate solution (%)	<10
Stability	Density (g/cm^3)	>2.55
	Unit weight g/cm3	>2.5
Soft grains	Uniaxial compressive strength in saturated condition (MPa)	Content of soft grains is less than 10% (mass ratio)

Table A.0.2: Track Bed Parametters for Ethio-Djibouti Line [27]

<table>
<tr><th colspan="3">Item</th><th>Value (Diredawa to Dawanle)</th></tr>
<tr><td colspan="3">The top width of the single-track bed (m)</td><td>3.1</td></tr>
<tr><td rowspan="3">Permeable soil and hard rock subgrades</td><td rowspan="2">Soil subgrade</td><td>Surface ballast (cm)</td><td>25</td></tr>
<tr><td>Bottom ballast (cm)</td><td>20</td></tr>
<tr><td colspan="2">Permeable soil and hard rock subgrade (cm)</td><td>30</td></tr>
<tr><td colspan="3">Bridge (cm)</td><td>≥25</td></tr>
<tr><td colspan="3">Side slope of the track bed</td><td>1.1.75</td></tr>
</table>

Table A.0.3 Sample (2) Results for Particle Size Distribution of Ballast Elbahe Quarry

<table>
<tr><th colspan="8">BALLAST PARTICLE-SIZE ANAYSIS</th></tr>
<tr><td colspan="3">Elbahe Quarry at DK 147</td><td>Total mass (gm)</td><td>56000</td><td></td><td></td></tr>
<tr><td colspan="3">Sampling Date: 20/02/19</td><td colspan="3">Testing Date: 21/02/19</td><td></td></tr>
<tr><td rowspan="2">Sieve Size (mm)</td><td colspan="2">Standard Specification Passing (%)</td><td>Mass Retained (gm)</td><td>Cummulative Retained (gm)</td><td>Cummulative Mass Retained (%)</td><td>Mass passing (%)</td></tr>
<tr><td>lower</td><td>upper</td><td></td><td></td><td></td><td>100</td></tr>
<tr><td>63</td><td>97</td><td>100</td><td>0</td><td>0</td><td>0</td><td>100</td></tr>
<tr><td>56</td><td>92</td><td>97</td><td>2600</td><td>2600</td><td>5</td><td>95</td></tr>
<tr><td>45</td><td>55</td><td>75</td><td>20890</td><td>23490</td><td>42</td><td>58</td></tr>
<tr><td>35.5</td><td>25</td><td>40</td><td>14700</td><td>38190</td><td>68</td><td>32</td></tr>
<tr><td>25</td><td>5</td><td>15</td><td>13900</td><td>52090</td><td>93</td><td>7</td></tr>
<tr><td>16</td><td>0</td><td>5</td><td>3810</td><td>55900</td><td>100</td><td>0</td></tr>
<tr><td>pan</td><td></td><td></td><td>0</td><td>55900</td><td>100</td><td>0</td></tr>
</table>

Table A. 0.4 Sample (3) Results for Particle Size Distribution of Ballast Elbahe Quarry

BALLAST PARTICLE-SIZE ANAYSIS						
Elbahe Quarry at DK 147			Total mass (gm)	50670		
Sampling Date: 20/02/19			Testing Date: 21/02/19			
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass passing (%)
	lower	upper				100
63	97	100	0	0	0	100
56	92	97	1350	1350	3	97
45	55	75	21380	22730	45	55
35.5	25	40	15000	37730	74	26
25	5	15	12600	50330	99	1
16	0	5	210	50540	100	0
pan			0	50540	100	0

Table A.0.5 Sample (4) Results for Particle Size Distribution of Ballast Elbahe Quarry

BALLAST PARTICLE-SIZE ANAYSIS					
BALLAST TEST RECORD Elbahe			Total mass (gm)	82890	
	Sampling Date: 14/02/19			Testing Date: 15/02/19	
Sieve Size (mm)	Standard Requiurement (%) Passing		Mass of particles Passing (kg)	Mass Particles Passing (%)	Cummulative Mass Passing (%)
	lower	upper			
63	97	100	2450	3	100
56	92	97	4570	6	97
45	55	75	24900	30	70
35.5	25	40	24900	30	38
25	5	15	17800	21	14
16	0	5	8280	10	4
pan			0	0	0

Table A.0.0.6 Ballast PSD Results for Chainage 126+480

BALLAST PARTICLE-SIZE ANAYSIS						
DK 126+480			Total mass (gm)	51240		
Sampling Date: 16/02/19			Testing Date: 18/02/19			
Sieve Size (mm)	Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100
63	97	100.0	0	0	0	100
56	92	97.0	1220	1220	2.38	98
45	55	75.0	9320	10540	20.57	79
35.5	25	40.0	12060	22600	44.11	56
25	5	15.0	12390	34990	68.29	32
16	0	5.0	11050	46040	89.85	10
pan			4920	50960	99.45	1

Table A.0.7 Ballast PSD Results for Chainage 127+250

BALLAST PARTICLE-SIZE ANAYSIS						
DK 127+250			Total mass (gm)	55100		
	Sampling Date: 17/02/19			Testing Date: 18/02/19		
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100
63	97	100	0	0	0.00	100
56	92	97	2640	2640	4.79	95
45	55	75	2920	5560	10.09	90
35.5	25	40	7690	13250	24.05	76
25	5	15	9240	22490	40.82	59
16	0	5	10370	32860	59.64	40
pan			21980	54840	99.53	0.5

Table A.0.8 Ballast PSD Results for Chainage 127+800

BALLAST PARTICLE-SIZE ANAYSIS						
DK 127+800			Total mass (gm)	50910		
	Sampling Date: 17/02/19			Testing Date: 18/02/19		
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100
63	97	100	0	0	0	100
56	92	97	1000	1000	2	98
45	55	75	2030	3030	6	94
35.5	25	40	5740	8770	17	83
25	5	15	8810	17580	35	65
16	0	5	9880	27460	54	46
pan			23340	50800	100	0.2

Table A.0.9 Ballast PSD Results for Chainage 128+100

BALLAST PARTICLE-SIZE ANAYSIS						
DK 128+100			Total mass (gm)	53800		
Sampling Date: 19/02/19			Testing Date: 22/02/19			
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100
63	97	100	1100	1100	2	98
56	92	97	1800	2900	5	95
45	55	75	6100	9000	17	83
35.5	25	40	7200	16200	30	70
25	5	15	9400	25600	48	52
16	0	5	8500	34100	63	37
pan			18900	53000	99	1

Table A.0.10 Ballast PSD Results for Chainage 128+700

BALLAST PARTICLE-SIZE ANAYSIS						
DK 128+700			Total mass (gm)	51500		
Sampling Date: 19/02/19			Testing Date: 22/02/19			
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100
63	97	100	420	420	1	99
56	92	97	960	1380	3	97
45	55	75	10530	11910	23	77
35.5	25	40	9350	21260	41	59
25	5	15	10720	31980	62	38
16	0	5	11270	43250	84	16
pan			790	44040	86	14

Table A.0.11 Ballast PSD Results for Chainage 129+800

BALLAST PARTICLE-SIZE ANAYSIS						
DK 129+150 and DK 129+800			Total mass (gm)	51300		
	Sampling Date: 19/02/19			Testing Date: 19/02/19		
Sieve Size (mm)	Standard Specification Passing (%)		Mass Retained (gm)	Cummulative Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
	lower	upper				100
63	97	100	0	0	0	100
56	92	97	970	970	2	98
45	55	75	11200	12170	24	76
35.5	25	40	10310	22480	44	56
25	5	15	9800	32280	63	37
16	0	5	13000	45280	88	12
pan			5900	51180	100	0

Table A.0.12 Fine Particle-Size Analysis DK 125 +650

FINE PARTICLE-SIZE ANALYSIS				
DK 125+650	Total mass (gm)	50000		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (kg)	Cummulative Mass Retained (kg)	Cummulative Mass Retained (%)	Mass Passing (%)
				9
9.5	2500	2500	5	4.0
4.75	490	2990	6	3.0
2.36	200	3190	6	2.6
1.18	127	3317	7	2.4
0.3	126	3443	7	2.1
0.063	142	3585	7	1.8
pan	194	3779	8	1.4

Table A.0.13 Fine Particle-Size Analysis DK 126 +480

FINE PARTICLE-SIZE ANALYSIS				
DK 126+480	Total mass (gm)	51240		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (kg)	Cummulative Mass Retained (kg)	Cummulative Mass Retained (%)	Mass Passing (%)
				10.1
9.5	2490	2490	4.9	5.2
4.75	1320	3810	7.4	2.7
2.36	316	4126	8.1	2.0
1.18	205	4331	8.5	1.6
0.3	189	4520	8.8	1.3
0.063	12	4532	8.8	1.3
pan	28	4560	8.9	1.2

Table A.0.14 Fine Particle-Size Analysis DK 127 +250

FINE PARTICLE-SIZE ANALYSIS				
DK 127+250	Total mass (kg)	55100		
Sampling Date: 17/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Cumulative Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
				40
9.5	5240	5240	10	30.5
4.75	4010	9250	17	23.2
2.36	2950	12200	22	17.9
1.18	1400	13600	25	15.3
0.3	2610	16210	29	10.6
0.063	2970	19180	35	5.2
pan	2710	21890	40	0.3

Table A.0.15 Fine Particle-Size Analysis DK 127 +800

FINE PARTICLE-SIZE ANALYSIS				
DK 127+800	Total mass (gm)	50910		
Sampling Date: 17/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
				46
9.5	6690	6690	13	32.9
4.75	3720	10410	20	25.6
2.36	1496	11906	23	22.6
1.18	1599	13505	27	19.5
0.3	3448	16953	33	12.7
0.063	3850	20803	41	5.1
pan	2249	23052	45	0.7

Table A.0.16 Fine Particle-Size Analysis DK 128 +100

FINE PARTICLE-SIZE ANALYSIS				
DK 128+100	Total mass (gm)	53780		
Sampling Date: 19/02/19			Testing Date: 22/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Mass Retained (%)	Mass Passing (%)
				36.6
9.5	5950	5950	11.1	25.5
4.75	3770	9720	18.1	18.5
2.36	1650	11370	21.1	15.5
1.18	2100	13470	25.0	11.6
0.30	1440	14910	27.7	8.9
0.063	2100	17010	31.6	5.0
pan	1500	18510	34.4	2.2

Table A.0.17 Fine Particle-Size Analysis DK 128 +700

FINE PARTICLE-SIZE ANALYSIS				
DK 128+700	Total mass (gm)	51500		
Sampling Date: 19/02/19			Testing Date: 22/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
				16.0
9.5	2680	2680	5.2	10.8
4.75	1090	3770	7.3	8.7
2.36	110	3880	7.5	8.5
1.18	1100	4980	9.7	6.3
0.30	1084	6064	11.8	4.2
0.063	70	6134	11.9	4.1
pan	1700	7834	15.2	0.8

Table A.0.18 Fine Particle-Size Analysis DK 129 +150

FINE PARTICLE-SIZE ANALYSIS				
DK 129+150	Total mass (gm)	51330		
Sampling Date: 19/02/19			Testing Date: 22/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Mass Passing (%)
				12
9.5	2120	2120	4.1	7.9
4.75	1310	3430	6.7	5.3
2.36	180	3610	7.0	5.0
1.18	240	3850	7.5	4.5
0.30	170	4020	7.8	4.2
0.063	900	4920	9.6	2.4
pan	150	5070	9.9	2.1

$$\text{Average FI} = \frac{4.85 + 3.70 + 28.40 + 30.69 + 23.50 + 12.77 + 7.73}{7} \ldots\ldots\ldots\ldots\ldots\ldots\ldots A.0.1$$

$$M_{DE} = \frac{3.5 + 6.5 + 10.7 + 9.6 + 7.3 + 6.4 + 7.0 + 9.2 + 5.0 + 8.8 + 6.5 + 5.8 + 3.6 + 7.2 + 4.86 + 5.1 + 4.9 + 7.3 + 10.6}{22} \ldots\ldots A.0.2$$

Table A.0.19 Percentages of Fouling Components DK 125+650

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 125+650	Total Mass of Material < 9.5 mm (gm)	1290		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100
9.5	0	0	0	100
4.75	490	490	38	62
2.36	200	690	53	47
1.18	127	817	63	37
0.3	126	943	73	27
0.063	142	1085	84	16
pan	194	1279	99	1

Table A.0.20 Percentages of Fouling Components DK 126+480

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 126+480	Total Mass of Material < 9.5 mm (gm)	2410		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100
9.5	0	0	0	100
4.75	1320	1320	55	45
2.36	316	1636	68	32
1.18	205	1841	76	24
0.3	189	2030	84	16
0.063	120	2150	89	11
pan	220	2370	98	2

Table A.0.21 Percentages of Fouling Components DK 127+250

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 127+250	Total Mass of Material < 9.5 mm (gm)	16710		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100
9.5	0	0.0	0.0	100
4.75	4010	4010.0	24.0	76
2.36	2950	6960.0	41.7	58
1.18	1400	8360.0	50.0	50
0.3	2610	10970.0	65.6	34
0.063	2970	13940.0	83.4	17
pan	2710	16650.0	99.6	0

Table A.0.22 Percentages of Fouling Components DK 127+800

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 127+800	Total Mass of Material < 9.5 mm (gm)	16650		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100.0
9.5	0	0	0.0	100.0
4.75	3720	3720	22.3	77.7
2.36	1496	5216	31.3	68.7
1.18	1599	6815	40.9	59.1
0.3	3448	10263	61.6	38.4
0.063	3850	14113	84.8	15.2
pan	2249	16362	98.3	1.7

Table A.0.23 Percentages of Fouling Components DK 128+100

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 128 +100	Total Mass of Material < 9.5 mm (gm)	12930		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100
9.5	0	0	0.0	100
4.75	3770	3770	29.2	71
2.36	1650	5420	41.9	58
1.18	2100	7520	58.2	42
0.3	1440	8960	69.3	31
0.063	2100	11060	85.5	14
pan	1500	12560	97.1	3

Table A.0.24 Percentages of Fouling Components DK 128+700

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 128+700	Total Mass of Material < 9.5 mm (gm)	5210		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100
9.5	0	0	0.0	100
4.75	1090	1090	20.9	79
2.36	110	1200	23.0	77
1.18	1100	2300	44.1	56
0.3	1084	3384	65.0	35
0.063	70	3454	66.3	34
pan	1700	5154	98.9	1

Table A.0.25 Percentages of Fouling Components DK 129

PARTICLE-SIZE ANALYSIS FOR FOULING MATERIAL				
DK 129	Total Mass of Material < 9.5 mm (gm)	3790		
Sampling Date: 16/02/19			Testing Date: 18/02/19	
Sieve Size (mm)	Mass Retained (gm)	Cummulative Mass Retained (gm)	Cummulative Mass Retained (%)	Weight Passing (%)
				100
9.5	0	0	0.0	100
4.75	1310	1310	34.6	65
2.36	180	1490	39.3	61
1.18	240	1730	45.6	54
0.3	170	1900	50.1	50
0.063	900	2800	73.9	26
pan	150	2950.0	77.8	22

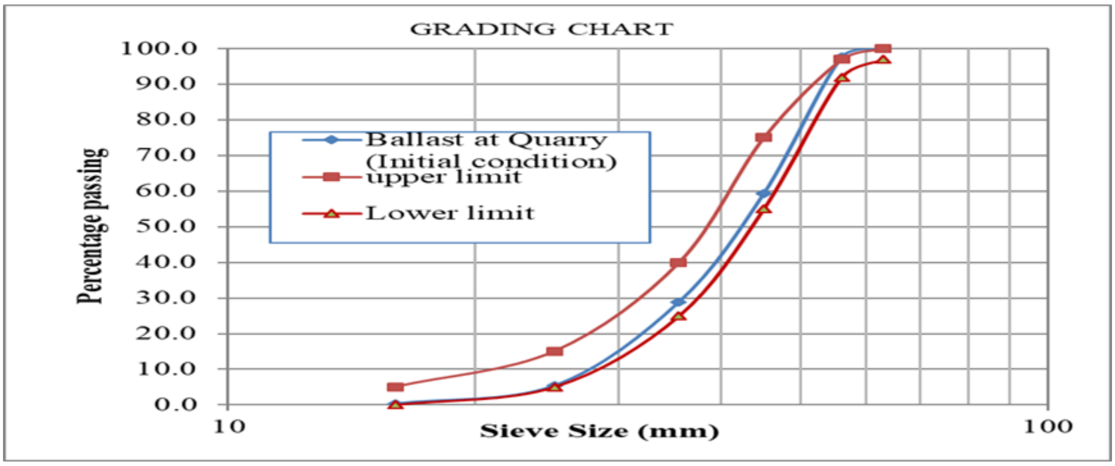

Figure A.0.1 Grading Chart for Elbahe Quarry Sample (1)

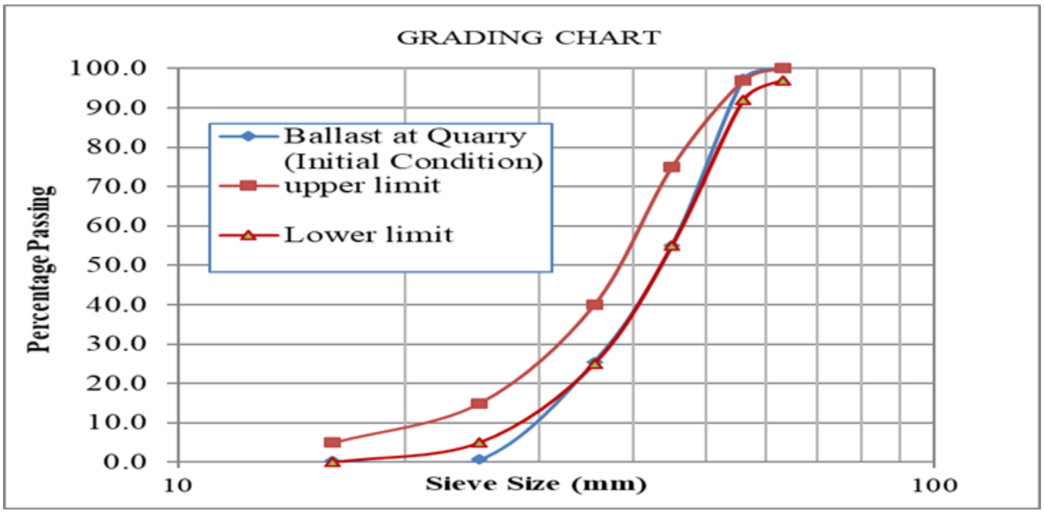

Figure A.0.2 Grading Chart for Elbahe Quarry Sample (3)

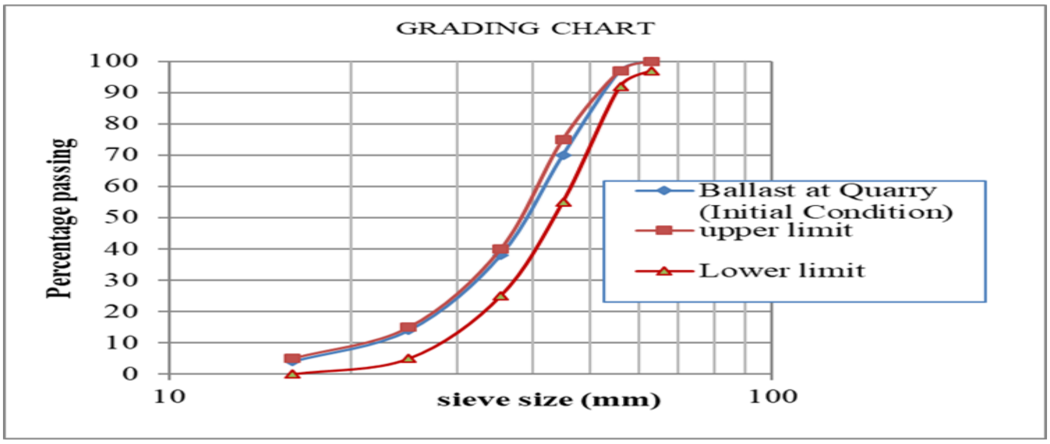

Figure A.0.3 Grading Chart for Elbahe Quarry Sample (4)

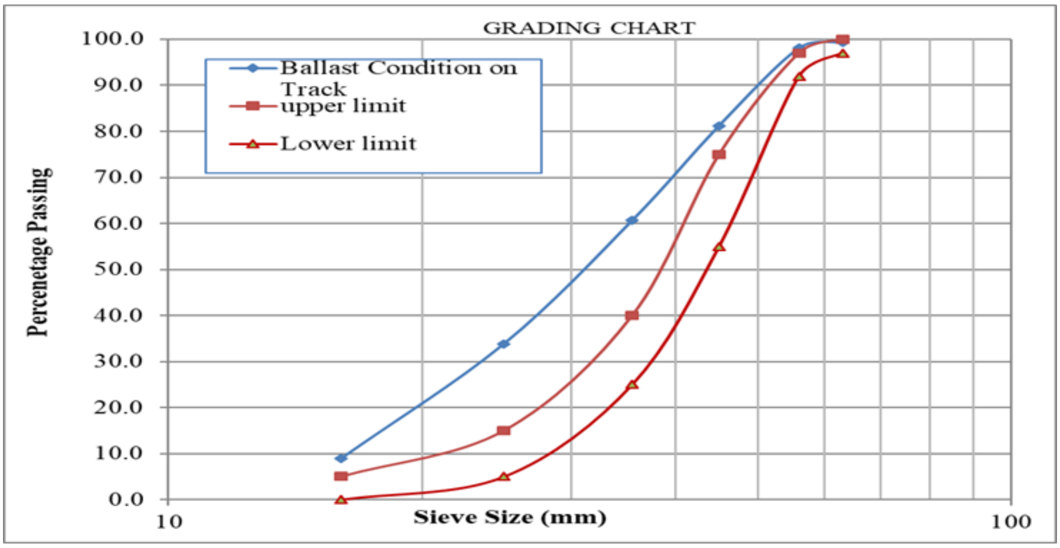

Figure A.0.4 On Track Ballast Grading Chart for chainage 125+650

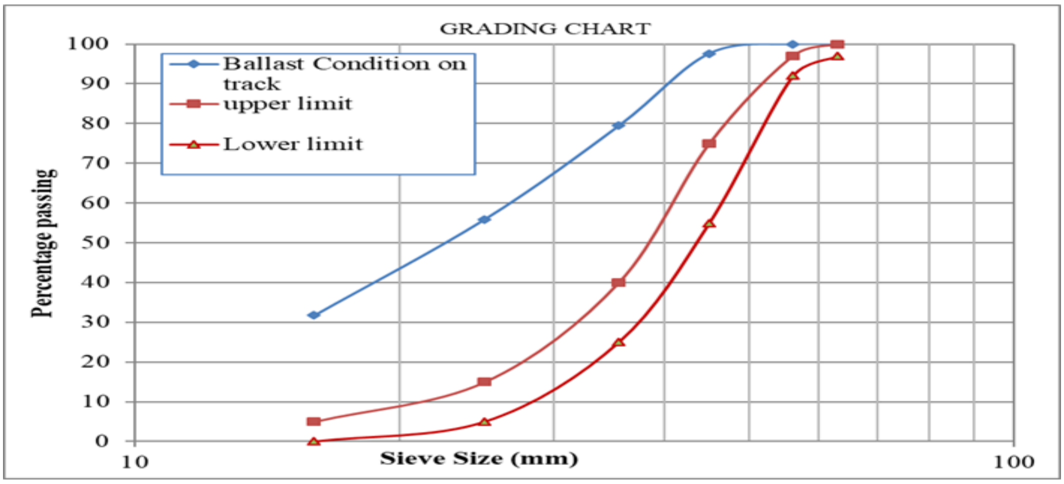

Figure A.0.5 On Track Ballast Grading Chart for DK 126+480

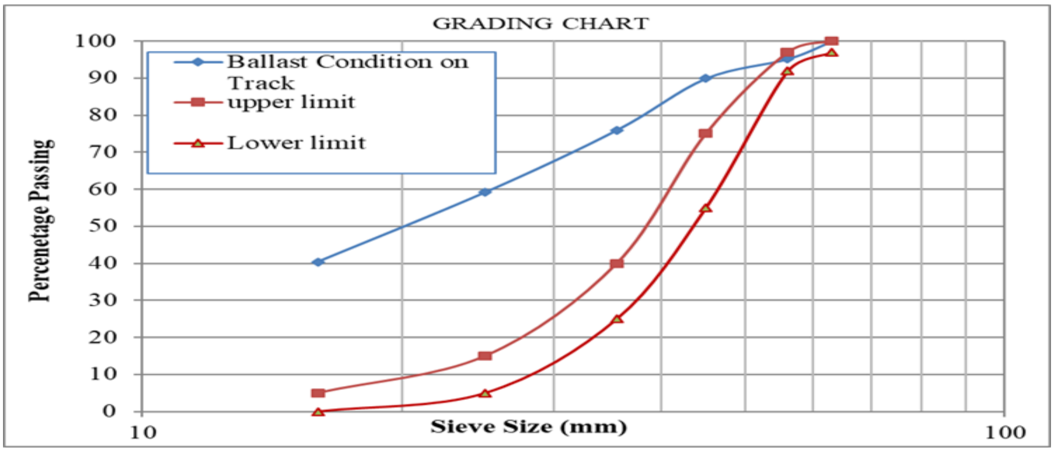

Figure A.0.6 On Track Ballast Grading Chart for Chainage 127+250

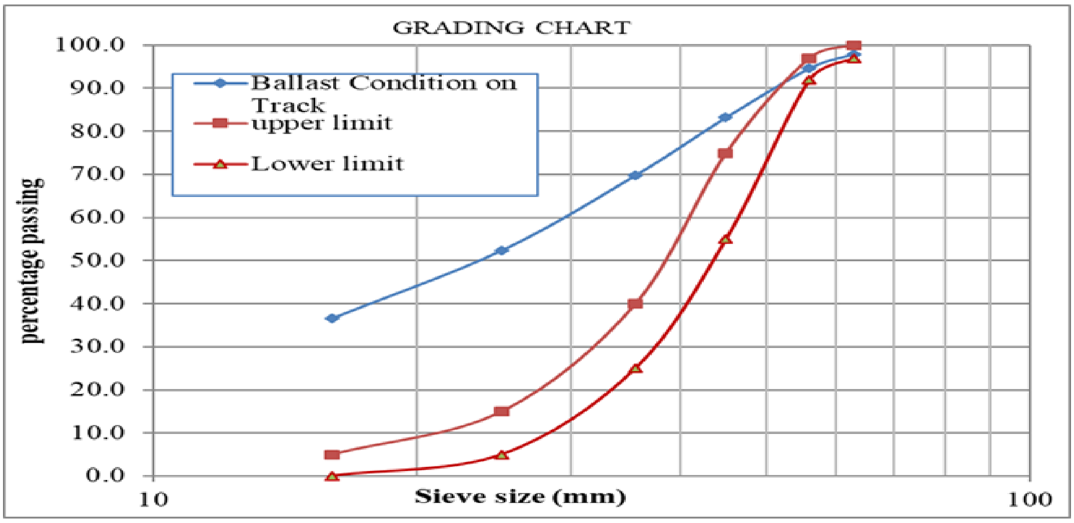

Figure A.0.7 On Track Ballast Grading Chart for DK 128+100

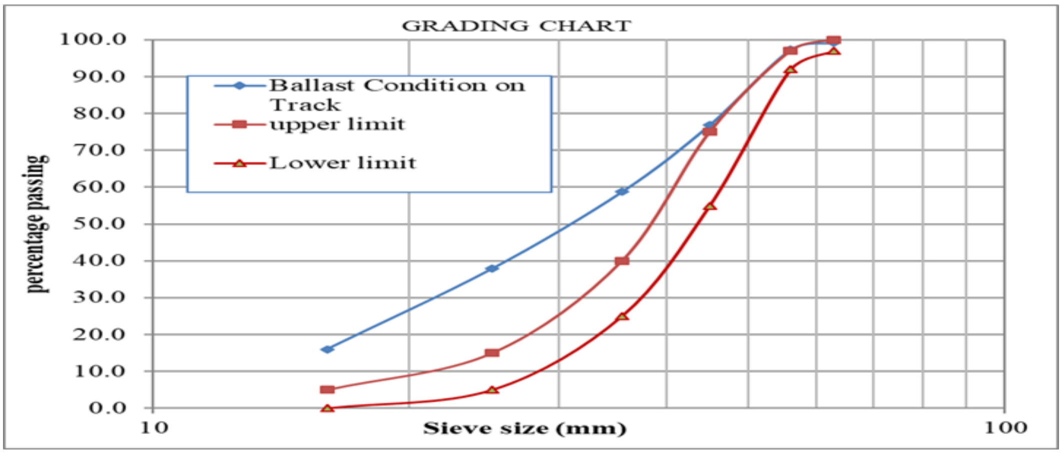

Figure A.0.8 On Track Ballast Grading Chart for DK 128+700

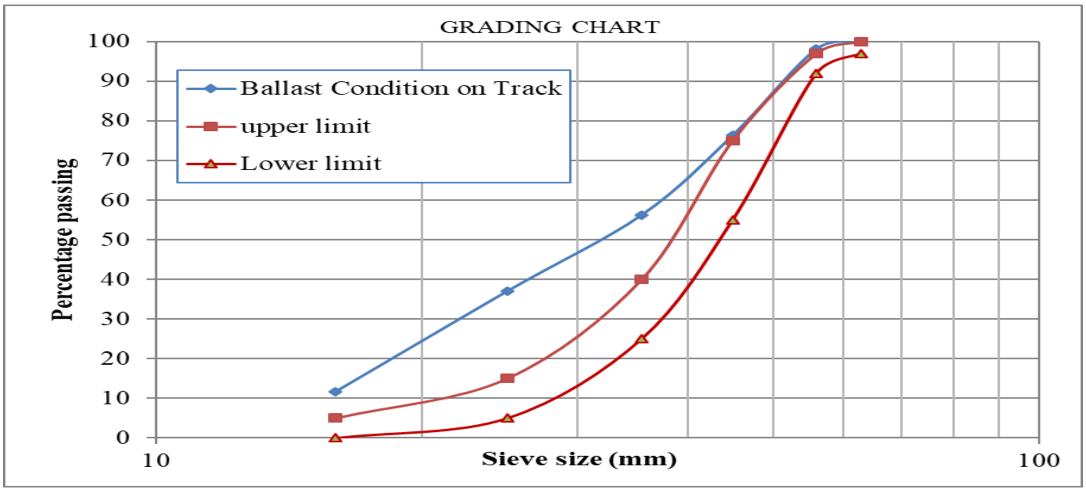

Figure A.0.9 On Track Ballast Grading Chart for DK 129+150-800

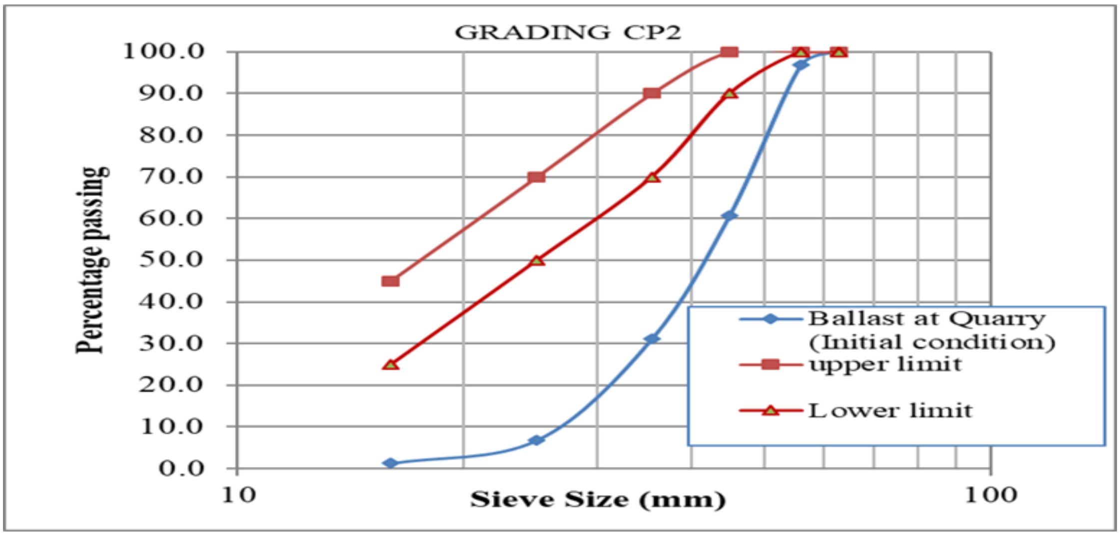

Figure A.0.10 Average of Cumulative Mass Passing Plotted on CP2

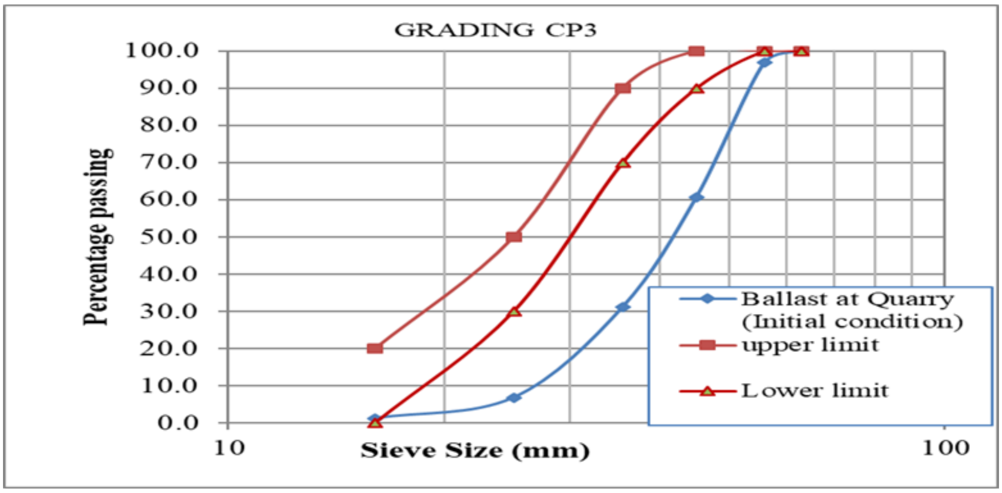

Figure A.0.11 Average of Cumulative Mass Passing Plotted on CP3

Table A.0.26 Show the Ballast Grading Standards for Chinese and Canadian Pacific Rail

GRADATION STANDARDS FOR CHINES AND CP RAIL BALLAST													
Chines Std. Sieve Size (mm)	Standard Requirement (%) Passing		CP Rail Std.Sieve Size (mm)	Standard Requiurement (%) Passing for Canadainan Pacific Rail Ballast Gradings									
				CP1		CP2		CP3		CP4		CP5	
	lower	upper		lower	upper	lower	upper	lower	upper	lower	upper	lower	upper
63	97	100	63.5	100	100	100	100	100	100	100	100	100	100
56	92	97	50.8	100	100	100	100	100	100	100	100	90	100
45	55	75	38.1	100	100	90	100	90	100	90	100	35	70
35.5	25	40	25.4	90	100	70	90	70	90	20	55	0	5
25	5	15	19.1	70	90	50	70	30	50	0	5	0	0
16	0	5	12.7	40	60	25	45	0	20	0	0	0	0
			9.5	20	40	10	25	0	5	0	0	0	0
			4.75	0.0	3	0	3	0	3	0	3	0	3
			0.075	0	2	0	2	0	2	0	2	0	2

Table A.0.27 Annual Freight Train Summary of Ethiopia-Djibouti Railway, 2018

<table>
<tr><td rowspan="2">Period</td><td colspan="2">Number of trains operated</td><td colspan="2">Load transported (tonne)</td><td>Remark</td></tr>
<tr><td>Full</td><td>Empty</td><td>Full</td><td>Empty</td><td rowspan="8">Transported goods: Container, steel, steel bar, wheat, fertilizer and maintenance vehicles</td></tr>
<tr><td rowspan="7">Annual</td><td>383</td><td>387</td><td>858,958.25</td><td>23,024.96</td></tr>
<tr><td colspan="2">770</td><td colspan="2">881,983.21</td></tr>
<tr><td colspan="2">to-km</td><td colspan="2">Average tonnes/year 571,255,853.08</td></tr>
<tr><td>Negad-Modjo</td><td>Negad-Dire Dawa</td><td colspan="2" rowspan="4">Negad-Modjo=652 km, Negad-Dire Dawa=282 km, Negad-Adama=630km & Negad-Indode=709km</td></tr>
<tr><td>527,592,425.00</td><td>1,897,747.20</td></tr>
<tr><td>Negad-Adama</td><td>Negad-Indode</td></tr>
<tr><td>40,454,158.50</td><td>1,311,522.38</td></tr>
</table>

Table A.0.28 Tests and Specifications for Characterization of Ballast Material

Test	Procedure	AREMA	CPR
Los Angeles Abrasion	ASTM C535	35 % max.	45 % max
Mill Abrasion	Selig and waters	--	9 % max
Bulk specific gravity	ASTM C127	2.6 min	2.6 min
Absorption	ASTM C127	1.0 % max	0.5 % max
Sulfate soundness	ASTM C88	5.0 % max	1.0 % max. mainline