

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING



Assessing Possible Ways of Reusing Ethiopian Old Railway Ballast
(Addis-Awash Section)

A Thesis in Civil and Environmental Engineering in Railway
Stream

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March, 2018

Assessing Possible Ways of Old Ethiopian Railway Ballast (Addis-Awash Section)

A Thesis Submitted to the School of Civil and Environmental
Engineering

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Presented In Fulfillment of the Requirements for the Degree of Masters
of Science (Civil and Environmental Engineering in Railway Stream)

Addis Ababa University

Addis Ababa, Ethiopia

March, 2018

Addis Ababa University
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This is to certify that the thesis prepared by “Yabibal Getaneh”, entitled “Assessing Possible Ways of Reusing Old Ethiopian Rail Track Ballast (Addis-Awash Section)” and submitted in partial fulfillment of the requirements for the degree of Masters of Sciences (Civil Engineering Railway Stream) compiles with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

Different studies show that production and installation of ballast had considerable cost during the construction of ballasted track. The main objective of this research was to find and identify effective techniques of recycling/processing Ethiopian old railway ballast to its valuable form. The capacity of the ballast to with stand traffic loads after thorough recycling process was studied.

During assessment, Physical and mechanical properties of the ballast were inspected and analyzed by using different site assessment and laboratory testing techniques related with different international standards. Result of most tests conducted on this ballast shows that the ballast produced from recycling is effectively reusable. Results of tests like density, abrasion and crushing resistance, absorption and impact value fulfills the requirements of good ballast while physical properties like elongation, flakiness and fouling content fails related with some standards. Depending on the site investigation considerable amount of ballast is available on the track line that can be reused. More than half of the ballast available on the track line is reusable by threating it with proper recycling method and blending material. Based on the results of the study conducted most portion of ballast of this track line is recyclable. The result of cost/benefit analysis also showed that reprocessing this ballast is economically feasible after blending with new ballast over the use of a totally new ballast.

Finally this study was resulted with ballast of Ethio–Djibouti old rail way line incorporates hugely recyclable economic asset that can be used for in situ maintenance and construction of new projects. It proved that processing and recycling this ballast can reduce cost of production of new ballast material for in situ track maintenance and new track projects by three fold. But the whole track system is currently deserving reservation, management and further study for rehabilitation and renewal.

Key words

Old Railway Ballast, Ballast Recycling, Ballast Characterization, Economic Evaluation

Acknowledgments

First, I would like to give the deepest gratitude for my God who gives and facilitates me all the path and passion before and during the development of this thesis. Secondly, I would like to thank my main Advisor, Dr. Ing. Henok Fikre for his invaluable guidance and supervision throughout the whole research. This thesis would not have been completed without his support. I would also like to express my sincere gratitude to the following people for their advice and help:

- Instructor Mequanint Mulugeta my co-supervisor and AAiT civil railway department coordinator.
- Mr. Solomon, the Chief Executive Officer of Ethio-Djibouti Old Railway Corporation for his legal and personal support during data collection.
- For all Workers of Ethio-Djibouti railway corporation, Addis Ababa, Adama and Awash station crews.
- All technicians and experimental officers in the School of Civil and environmental Engineering for their help during laboratory work, particularly AAiT high way and material lab workers and officers of railway center.
- Finally my greatest gratitude goes to my family, friends and my co-workers for their consistent support, initiation, collaboration and encouragement in every aspect of my life.

Yabibal Getaneh

March, 2018

Addis Ababa

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CHAPTER ONE

1. Introduction

1.1. Background of the study

Ethio-Djibouti old railway line was the longest and the only rail track in the history of east African transportation for a long time. This line is extended from Addis Ababa to port Djibouti with approximate length of 781km. The line gives continues service for more than a century. Due to a long-lasting service and ineffective maintenances major components of the track system are subjected to multiple malfunctioning. Studying condition of the track system component by component can create the opportunity to develop maintenance schedule and budgeting. It can also facilitate distinguishing reusable parts from non-reusable. Among the major track system components ballast is very noticeable part which plays significant role in supporting and distributing axle load to the formation. Studding the condition of ballast of Djibouti-Ethiopian old railway is particularly important to actuate economic value of reusing it in the construction of new projects and for in situ maintenance.

Ballast recycling is defined as the process of maintaining and replenishing ballast aggregates until it regains its original state to reuse in the construction and maintenance process of track system. The process of developing recycling and reusing technique needs understanding of the property and current condition of the ballast. Extending the service life of a ballast and proper renewal mechanism deserves thorough studding and modelling. Not much research has been conducted on the condition of Ethiopian old track sub structures, including the ballast to help track maintenance and safety concerns yet. Understanding how to optimize the complex geotechnical and mechanical properties of this track system ballast will likely lead to huge benefit.

This study is conducted to put techniques of understanding the condition of old track ballast material and finding ways to optimize reusability. To go through this basic investigation methods are supplemented. Field and laboratory testing techniques are applied as per different international standards. Available amount of reusable ballast on the considered track system is quantified and economic benefit of the process over new ballast production is estimated.

1.2. Problem Statement

For most developing countries including Ethiopia mass transit infrastructures like railways are insufficiently provided. Economic incapability, inadequate knowledge and lesser consideration by policy makers led those countries to have insignificant provision of these basic arterial infrastructures. Some track systems were established in some historic countries by some historic occasions which allows the people to have awareness about the benefit it provides. Historic track system of Ethio-Djibouti is among those systems constructed during the imperial era. This track system serves the people for more than a century and currently subjected for multiple deterioration. The reason behind for its ineffectiveness is the long-lasting use without proper consideration and maintenance.

This track system is a ballasted track type with metric gauge system installed on steel crosstie or steel sleeper and non-electrified traction system. Currently this line is subjected to ceasing its function due to different reasons such as incompatibility problem of gauge and traction system with the modern technology, improper track maintenance and rehabilitation and unsafe and warned out locomotives and wagons. Though the system is getting ceased most components are recyclable and reusable for the construction of new track systems and in-situ rehabilitation. Among those recyclable components ballast portion of the track system is considered in this research to be investigated and studied. Analyzing and finding possible ways of reusing this economic asset to use as a ballast or sub-ballast material by itself or by mixing it with fresh ballast aggregate needs detail investigation. The concern of this study is to assess the benefit of recycling and reusing this old track ballast as alternative option to produce new (fresh) ballast in the track maintenance work and construction of the new projects.

1.3. Objectives

1.3.1. General Objectives

Fundamentally this research emphasizes on analyzing economic advantage of recycling Ethiopian old railway track ballast by using different physical and mechanical characteristic classification and recycling methods.

1.3.2. Specific Objectives

The aims of this research can be stated as:

- Investigation of major defects and analyses of ballast characteristics
- Studying major causes of deterioration of this track component during its service life
- Studying ballast behavior and degradation under stresses induced by traffic loading
- Finding practicable methods applicable for refining, recycling and reusing purpose
- Analyzing economic benefit of properly recycled or upgraded railway track ballast

1.4. Scope of the Study

Depending on the condition of the ballast under consideration the scope of this research is limited to the site investigation, characterization and recycling process. Due to the complex nature of the track system and its condition this study is mainly emphasis on the ballast recycling and reusing process other than the rail, sleeper and other components. Due to resource and time constraints to cover the whole line extension from Addis to Djibouti it is estimated based on the result of the line section that extends from Addis Ababa to Awash. In this regard the study is made to develop recycling guideline and cost evaluation only for the oldest railway ballast rehabilitation work of Addis-Awash section.

The scope of the research is focused on assessment and optimization of Ethio-Djibouti old rail track ballast material on the selected section and depending on the provided time frame mainly emphasizing on;

- Site investigation, condition assessment and Sampling
- Characterizing by laboratory testing
- Economic evaluation of recycled ballast

1.5. Methodology

In developing this research the method and procedure had been established based on different standards, specifications, manuals and researches developed before. Basic and related literatures

had been reviewed supportive of studying the characteristics of old railway ballast. Assessment and analysis of the condition of the ballast had taken place in based on the following stages:

1. Field investigation
2. Understanding defects on Ethio-Djibouti old railway ballast
3. Ballast aggregate lab testing
4. Quantifying portion of the ballast that can be used as ballast and sub-grade material after proper rehabilitation and maintenance

During Field investigation, current condition of the whole track system components on the sample area or track segment had been assessed. Settlement of the track system, track geometric deformation, losing components, fouling condition, vegetation cover and drainage condition had been quantified on the sample segments. After site or field investigation samples are taken by using appropriate sampling techniques and procedures for further investigation in the laboratory. Representative samples had taken from several trenches with appropriate sample size based on the requirement. Finally, evaluation of the benefit of recycling legacy track ballast compared with new ballast production is conducted.

1.6. Organization of the Thesis

This thesis is divided into six chapters. The first chapter is the introduction part which clearly states the background of the research, statement of problem, and objective, scope and limitation of the study and benefits of the research.

A review of background knowledge and literature relevant to this work is presented in Chapter 2. It covers information on rail track environment, ballast, particle breakage, behavior of ballast aggregates under monotonic and cyclic loading, driving forces of ballast aggregate degradation and effect of ballast degradation on track function and laboratory tests on ballast.

Chapter 3 focuses on old Ethio -Djibouti old rail way track site investigation and the result and ballast laboratory testing and analysis results are covered concisely. Los Angeles abrasion, aggregate impact value, water absorption capacity, specific gravity, bulk density, aggregate crushing value, gradation, elongation and flakiness of the ballast aggregate are tested for three selected samples.

Following all the above chapters economic evaluation of recycling old track ballast and comparison with the cost of new ballast production had provided in chapter four. The volume and quantity of ballast available on the whole track section is estimated based on the quantity of the ballast available on the sample segments. Comparison of the cost of ballast recycling with new ballast production is also included in this chapter

Finally, depending on the results found in the above chapter's general discussion, conclusion and recommendations are provided while possible improvements that can be made were discussed in chapter five as part of future works. Collected data and laboratory results are also available in appendix after the reference.

CHAPTER TWO

2. Literature Review

2.1. Introduction

Different countries around the world uses different alternative solutions to handle the demand for transportation. Rail network is becoming an important part of transportation system in Ethiopia and many other countries of the world. Railway in Ethiopia is proposed and designed to play a vital role in Ethiopian future economic development through transporting freight and bulk commodities between major cities and ports, and mobilizing passengers, particularly in urban areas. Rail way system has carried around one third of import export goods by using Djibouti port as departure and Addis as processing center for more than a century. Improper consideration for rehabilitation and maintenance makes it incompetent with cross country road mobility and airline transportation on this corridor. Thousands of passengers and traders were using the Ethio- Djibouti track line each year before it becomes malfunctioned and currently ceased from of its normal mobility service.

There is more than 700km long old railway track that extends from Ethiopian capital Addis Ababa to the port of Djibouti. The cost of maintaining this old rail infrastructure (rail, sleeper, ballast signaling, communication etc.) on the main line alone is beyond judgment because of the nature of installation and its component characteristics. Instead of maintaining and upgrading the whole track system as it is, it may be preferable of adopting innovative technology and techniques to renew and reuse component by component to use for the construction of new projects.

2.2. Structure of Railway Track

Interactions between track components have been the major reason for several investigators to have begun their research on the track system by studying characteristics of each individual track components. Understanding the property and enter-contact relation leads researchers to formulate different design and modeling tools. Railway track structure is designed and constructed to provide safe and economical guide way for passenger and freight traffic. This requires a stable enough in both vertical and horizontal alignments under the various speeds and axle loadings of different trains. A track system usually consists of several components, each of which must perform its specific functions to maintain the rail system safely and satisfactorily.

There are two types of railway track systems

1. Ballasted track and
2. Ballast less (slab track) system

Ballasted track system is the major concern of this study. The structure of ballasted track is divided in to sub-structure and supper structure which is mainly comprised of the rail, fastening systems and sleepers or ties. This study has emphasized on mainly old track system sub-structural component called ballast. Component while the substructure mainly consist the three layers; ballast, sub-ballast and sub-grade. The sub structure is separated from the superstructure by the sleeper–ballast interface. Among those layers’ ballast is studied and characterized in detail to develop recycling and reusing techniques in the construction of new projects or on track itself.

Function and service life of a track system is dependent on many factors. The quality of each component, method of design and installation and through maintenance on each system component increases its reliability and reduce accidents tangibly. Track stiffness is an important track property tied up on the quality and loading duration of track components. It is constituted from the properties of the substructure and superstructure. Relatively high track stiffness is desired to provide adequate track resistance to the applied loads and to limit the track deflection. This will in turn, reduce the track deterioration. Too high track stiffness and especially variations in stiffness on a stiff track can cause increased dynamic forces on sleepers, ballast and in the wheel-rail interface. This can lead to wear and fatigue damage on track components. Low track stiffness leads to large rail displacements and high bending moments in the rails. On the other hand, low track stiffness leads to better load distribution between sleepers and lowers train/track interaction forces (Berggren, 2009).

2.3. Ballast

Ballast, being the largest component of the permanent way in terms of volume and cost, should ideally be a cheap material capable of being packed. It is a crushed granular material placed as the top layer of the sub-structure and between sleepers in a track and has many functions. It is the selected material placed on top of the track subgrade to support the track structure. Conventional ballast is a coarse-sized, non-cohesive, granular material of a uniform gradation. Traditionally, angular, crushed, hard stones and rocks have been considered good ballast materials. Granite, limestone, slag or other crushed stones have been used.

Availability and economic motives have often been prime factors considered in the selection of ballast material. The sleepers, to which the rails are fastened, are embedded in the ballast, which

is tightly compacted or tamped around the sleepers to keep the track precisely levelled and aligned. The standard depth of ballast is 0.3 meters, but it is packed to 0.5 meters around the sleeper ends to ensure lateral stability.

The main functions of ballast are to secure track stability in all directions, prevent excessive sleeper movement, absorb static and dynamic loads and provide good drainage of water (Andersson and Berg, 2007). To secure these functions, high quality ballast in terms of good vertical and horizontal load bearing capacity is required (Banverket, 2002).

Different countries around the world use ballast with a particle size of 32 – 64 mm to meet these requirements while more finely grained ballast, 11 – 32 mm, is used in railway yards and sometimes at switches and crossings to get a more level surface. Harder stone material is generally preferable as ballast in for many different reasons e.g. granite.

2.4. Purpose of Ballast

The primary purpose of ballast is providing support for the load from the sleeper in the lateral and vertical direction. It also drains water away from track super structure. In addition to supporting the load from the tie it also serves in spreading out the load from the train passed through the superstructure such that the underling layer can handle it without failing. Based on the observations by Selig and Waters (1994), ballast rock's importance includes:

- Maintain the track position by supporting the vertical, lateral, and longitudinal forces applied to the rail and into the ties.
- Adequately distribute stress from the superstructure materials into the underlying sub-ballast and subgrade.
- Enable track maintenance through resurfacing of ballast and adjustment of track geometry through tamping of ballast particles.
- Impart rapid drainage of water that enters the track system.
- Provide an elastic base that can withstand the dynamic loading applied by locomotives.
- Have sufficient void space to store and allow for the movement of fouling materials through the ballast.
- It limits sleeper movement by resisting vertical, transverse and longitudinal forces from the trains.
- It distributes the load from the sleepers to protect the subgrade from high stresses, thereby limiting permanent settlement of the track.

- It provides necessary resilience to absorb shock from dynamic loading.
- It facilitates maintenance surfacing and lining operations.
- It provides immediate water drainage from the track structure.
- It helps alleviate frost problems, and
- It retards the growth of vegetation and resists the effects of fouling from surface-deposited materials.

With all the above functions ballast needs to perform, sourcing high quality to resist rapid degradation, withstand dynamic forces, and prevent fouling are an important component in choosing ballast material. Different ballast specifications outlined important role of reducing maintenance requirements of the track embankment.

The ballast layer should be at least 300 mm thick below a sleeper and the layer on bridges should be at least 400 mm (Banverket, 2002). The ballast layer should not cover the sleeper surface to minimize the risk of ballast spray and fling. It is also important for the sleeper ends to be surrounded with a enough ballast to secure the sleeper's lateral stability.

2.5. Railway Ballast Aggregate Requirements

Railway track ballast must can withstand the loading from the train traffic, many loading cycles, vibrations of varying frequencies and intensities, repeated weathering and other factors that cause deterioration. The top width of the ballast bed influences the restraint of horizontal displacements of the sleepers. The higher width of the ballast bed shoulder the larger this restraint. The ballast bed shoulder shall be 35–45 cm wide on average. According to different standards the crushed rock used for the ballast shall comply with the following requirements:

- Resistance to environmental factors;
- High compressive strength and high impact resistance;
- The ballast shall contain no admixtures which prevent air circulation and water filtration e.g. loam or other soil admixtures;
- The ballast shall contain no crushed rock elements with sharp ends (sides).
- It must be tough enough to resist breakdown through fracturing, and it must be hard enough to resist attrition through wear with neighboring ballast particles,
- It must be dense enough so that it will have sufficient mass to withstand lateral forces to anchor the sleepers,

- It must be resistant to weathering so that weakening of the ballast due to crystallization or acidity do not occur, and

For good mechanical stability in track, ballast particles should be angular and equi dimensional in shape with rough surfaces to provide maximum friction. Under cycling loading from repeatedly passing wheel loads, ballast undergoes irrecoverable plastic deformation and particle degradation, in addition to recoverable elastic strains. Accumulated plastic deformation may become excessively high after millions of load cycles.

Continuous degradation process makes originally sharp angular particles in to relatively less angular and semi-rounded grains, thereby reducing inter-particle friction interlock. Thus, the frictional resistance is decreased, which leads to a further increase in plastic strains. Ballast degradation and associated plastic deformation have been ignored in conventional design and analysis of track substructure. Traditionally, when the plastic deformation exceeds a tolerance level, or ballast becomes excessively fouled by mechanical degradation or other process, these shortcomings in design and analysis are covered by frequent costly maintenance operations, which also disrupts the flow of trains traffic. Effect of ballast degradation and deterioration must be studied and analyzed by most appropriate and rationalized analysis and modelling techniques.

2.6. Factors Governing Ballast Characteristics

The primary geotechnical component of a rail track foundation is the ballast section. Ballast performance depends on four major geotechnical properties. Characteristics of aggregate mass that govern ballast behavior includes particle size distribution (PSD), void ratio (or density) and degree of saturation. These characteristics are discussed in the following section (Park, C. B., Miller, R. D., 1999).

The mechanical response of ballast is governed by four basic factors:

- a) Characteristics of constituting particles (e.g. size, shape, surface, roughness, particle crushing strength, resistance to attrition etc.)
- b) Bulk aggregate characteristics including particle size distribution, void ratio, or density and degree of saturation
- c) Loading characteristics including current state of stress, previous state of stress path, and
- d) Particle degradation which is the combined effect of grain properties, aggregate characteristics and loading.

2.6.1. Particle Characteristics

Physical and chemical properties of individual constituent ballast particles significantly influence the behavior of ballast under both static and cyclic loading.

2.6.1.1. Particle Size

Typically, size of ballast particles varies in the range of 10-65mm. With the increase in the number of train passages, the ballast particles are further degraded and gradually decrease in size. However, even after these changes in size, more than 90% of ballast grains remain in the original range of 10-60mm. Experimental evidence showed that the angle of internal friction decreases with an increase in maximum particle size. Indraratna et al. (2002) observed similar findings in their study and indicated that the peak friction angle decreased slightly with an increase in grain size at low confining pressure (<300kpa). They concluded that at high stress level (>400kpa), the effect of particle size friction angle becomes negligible.

Raymond and Dyaljee (1979) observed that larger ballast of uniform grading provided higher plastic strain compared to small-sized uniform ballast. Considering the advantage and disadvantage of varying particle size, Selig (1984) recommended that the ideal ballast should be of 10-50mm size with some particles beyond this range. The larger particle stabilizes the track and the smaller particles reduce the contact forces between particles and minimize breakage.

2.6.1.2. Particle Shape

Different findings evidenced that the angle of internal friction is remarkably higher for angular aggregates compared with sub-rounded aggregates. Generally, angularity increases frictional interlock between grains of aggregate, which increases its shear strength Indraratna et al (1998). He concluded that shear strength of highly angular quarried materials is higher than that of relatively sub-angular, or sub-rounded river gravels. However other researchers concluded that the angle of friction depends on grain angularity that demonstrate angular aggregates give less settlement than round aggregates. As dictated by Jeff's and Tew (1991) shape of ballast grains depends on the production process, natural sources rock and the intensity of cyclic and static loading. Raymond (1985) indicated that most specifications restricted the percentage of flaky particles whose ratio of the longest to smallest dimension exceeds 3, and excluded particles exceeding the ratio 10. Because these long but very thin particles can align and form planes of weakness in both vertical and lateral directions, they cannot be used as ballast. The disadvantage of increased flakiness appears to be increased abrasion, increased breaking, increased permanent

strain accumulation under repeated load and decreased stiffness (Selig and Water, 1994). Different studies stated that cubic shape aggregate is best shape for high quality ballast.

2.6.1.3. Surface Roughness

Surface texture is the key factor that govern the angle of internal friction and hence, the strength and stability of ballast. Each grain has roughness on its surface. Friction and frictional force is based on the roughness of the loaded surface, and the shear resistance of ballast and other aggregate depends on this frictional force. Particle shape and surface roughness have chief importance and long been recognized as the major factors influencing track stability. An increase in resilient modulus with increasing surface friction of grains that the resistance plastic strain accumulation increases with increasing visible surface roughness (Thom, 1989).

Almost all specifications of ballast demand crushed or fractured particles, which are defined as grains having a minimum of three crushed faces (i.e. freshly exposed surface with a minimum of one third of the maximum particle dimension (Selig and Water, 1994). These specifications ensure minimum surface roughness of ballast particles, and assume that freshly exposed surface have a higher roughness compared to old surfaces, which have been smoothed by mechanical abrasion and weathering.

Due to internal attrition of grains under cyclic loading surface roughness of ballast deteriorates with time (i.e. increasing number of ballast fouling). Internal attrition also produces powder like fines and is a cause of most ballast fouling. This reduction in surface roughness by internal attrition and breakage of sharp corners (as mentioned earlier) after millions of load cycles, causes the angle of internal friction and the shear strength of recycled ballast to decrease considerably. Therefore, it is conceivable that the surface roughness of individual particles significantly affects the mechanical behavior of ballast and ultimately, track stability.

2.6.1.4. Parent Rock Strength

The strength of the parent rock is probably the most important factor directly governing ballast degradation and indirectly the settlement and lateral deformation of the track. Parent rock stiffness includes both compressive and tensile strength. Under the same loading and boundary conditions, weak particles will result in more grain breakage and more plastic settlement than strong particles. Although the strength of the parent rock is not usually examined by most ballast specifications higher parent rock strength is ensured by the selection criteria, which includes petro-logical make

up examination. However, in order to enhance the control on the quality of ballast during selection, parent rock strength values may be in the specification.

High rock strength is indirectly reflected in other tests such as ‘Aggregate crushing value’ Los Angeles abrasion value’ and ‘Wet attrition value’. These test results collectively indicates the durability of ballast and the strength of the parent rock is an important factor governing particle degradation, which includes grain splitting and breakage of sharp corners under loading. Particle fracture plays a vital role in the behavior of crushable aggregates. Particle crushing strength depends primarily on the strength parent rock, the geometry of the grain, the loading point and loading direction. Fracture in rock, grains initiates by tensile failure, and the fracture strength can be measured indirectly by diametrical compression between flat and plates.

Festag and Katzenbach (2001) categorized grain crushing in to particle breakage (fracture) and grain abrasion. Particle breakage is the division of grains into parts with nearly the same dimension and generally occurs in high stress domain. On the other hand, abrasion is independent of the stress level. Abrasion of ballast surface takes place in granular materials when the particles slip or roll over each other during shear deformation and may occur even at low stress level. Grain breakage may be absent if the stress level is low compared to particle strength, however, grain abrasion will continue at any stress level. The crushing strength of particles is also not required by many ballast specifications. However, it is reflected in the ‘Aggregate crushing value’ and other standards durability tests required by many ballast specifications.

2.6.1.5. Resistance to Attrition and Weathering

These properties individual grains also govern ballast degradation under traffic loading and environmental changes. Usually, ballast particles are not individually assessed for their capacity to resist attrition and weathering, rather, their resistance is collectively assessed for the aggregate mass. Several standards and test methods for quantifying the resistance of ballast against attrition and weathering are available and used by different railway organizations. These tests include Los Angeles Abrasion (LAA), test Mill Abrasion (MA), the Deval test and sulfate soundness test etc. (Selig and Water, 1994). The sulfate soundness test is primarily used to assess resistance to the chemical action of sodium sulfate and magnesium sulfate. High resistance to attrition and weathering is usually ensured by specifying certain values required for the above mentioned durability tests in the ballast standards and specifications.

2.6.2. Characteristics of the Constituting Particles

2.6.2.1. Particle Size Distribution

Ballast gradation is a primary factor affecting the stability, safety and drainage of tracks. A specified ballast gradation must provide the following two key objectives (Park, C. B., Miller, R. D., 1999)

1. Ballast must have high shear strength to provide increased stability and minimum track deformation. This can be achieved by specifying broadly-graded (well graded) ballast and
2. Ballast must have high permeability to provide adequate drainage; this readily dissipates excess pore water pressures and increases the effective stress. This can be ensured by specifying uniformly graded ballast.

These two objectives are different and require optimized particle distribution in addition to quality. The optimum ballast gradation needs balance between uniform and broad gradations.

The distribution of ballast particle size (i.e. gradation) has a remarkable influence on the track deformation. (Jeff's and Tew, 1991) conducted a series of repeated load tri-axial tests on crushed aggregates with similar maximum particle size varying the particle size distribution from wide to uniform gradation.

According to Thom and Brown (1988) as the uniformity increases the shear stiffness (modulus) and permeability also increase while density and friction angle decreases. They indicated that optimum dry density was achieved at about uniformity coefficient approaches 0.3 for all types of compaction efforts (i.e. heavily compacted, slightly compacted and uncompacted) and noted that particle size distribution has no significant effect on the angle of internal friction for uncompacted specimens. One significant finding of their research is that uniform gradation provides a higher stiffness compared to well grade aggregate. In contrast, in the past researchers demonstrated that well-graded ballast gives lower settlement compared to single sized ballast. Single sized (uniform) ballast has larger void volume than broadly graded ballast. Well graded (broadly graded) ballast is stronger due to its ratio being less compared to uniformly graded ballast (Jeff's and Tew, 1991). However, ballast specifications generally demand uniformly graded aggregate to fulfill its drainage requirement. Since ballast must be a free draining coarse medium, the optimum gradation would be between uniformly graded large aggregate that give almost instantaneous drainage and broadly graded (well-graded) aggregates that provide higher strength and less settlement.

Optimum gradation should provide sufficient drainage capacity along with density, strength, and resilience.

2.6.2.2. Void Ratio

The volume of voids in a porous medium (e.g. soil and rock aggregates) compared to its volume of solids (i.e. void ratio) significantly affect its mechanical behavior. It has been well established that an aggregate having a lower initial void ratio (i.e. higher initial density) is stronger and gives a smaller settlement compared to an aggregate with higher initial void ratio (i.e. lower initial density).

A ballast is porous granular material, its strength and deformation behavior is also governed by its void ratio (or degree of compaction) (Selig and Waters, 1994) different researchers who investigate track stability concluded that an increase in ballast density (i.e. lower void ratio) enhances its strength and stability (Indraratna et al., 2000) while low density ballast leads to high strains.

2.6.2.3. Degree of Saturation

Ballast response to mechanical forces is affected by water and the degree of saturation. Water influences track settlement and particle breakage, and leads to other serious problems. In saturated conditions, subgrade soils soften and mix with water to form a slurry which under cyclic traffic loading, can be pumped up to the ballast layer, as mentioned earlier. Clay pumping is one of the major causes of ballast contamination (Selig and Waters, 1994) indicated that water entering micro fissures at the points between particles increases local stress and leads to increased particle breakage.

(Indraratna et al., 2000) conducted one dimensional compression tests to determine the effects of saturation on the deformation and degradation of ballast. They observed a sudden increase in ballast settlement by about 2.6mm due to sudden flooding. Moreover, reported a further increase in settlement with time creep) under saturated conditions. They finally concluded that saturation increased settlement by about 40% of that of dry ballast.

2.6.2.4. Loading Characteristics

The deformation and degradation of a ballast is profoundly dependent on its loading characteristics. The confining pressure, previous load history, current state of stress, number of load cycles, frequency and load amplitude are among the key loading parameters that govern track deformation.

2.6.2.5. Confining Pressure

The significant pressure on the strength and deformation behavior of soils and granular materials from the earliest days of soil mechanics (Terzaghi and Peck, 1948) was one of the pioneers who closely studied the effect of confining pressure on the deformation behavior and particle breakage of aggregates. They stated that different aggregates under high confining pressure (500-2500kpa) and observed that the shear strength is not a linear function of the acting normal pressure. Charles and Watts (1980) reported a pronounced non-linearity of failure envelope for coarse granular aggregate at low confining pressure. A breakdown stress represents the stress level at which all dilatancy effects disappear and beyond which particle breakage becomes the only mechanism, in addition to simple slip, by which shear deformation takes place.

As different laboratory experiment results of railway ballast which revealed that as confining pressure increase from 1kpa to 240kpa, drained friction angle of ballast decreases from about 67° to about 46° . High values of apparent friction angle at low confining pressure are related to low contact forces well below the grain crushing strength and the ability of aggregates to dilate a low stress levels. Shearing of rock fill causes a significant amount of particle breakage

Based on different researchers it is concluded that as the mean normal stress increases, the crushing becomes more pronounced and the dilatancy effects gradually disappear. Indraratna et al (1993) indicated that the large reduction of friction angle at high confining pressure is probably associated with significant crushing of angular particles.

2.6.2.6. Load History

Diyaljee (1987) conducted a series of laboratory cyclic tests to investigate effects of stress history on ballast behavior. In each test, he applied various cyclic diatonic stresses (70-315kpa) in several stages (10000 cycles each) on identical ballast specimens (same gradation, density and confinement). Based on his own investigation he concluded that a previous stress history more than 50% of the currently applied cyclic deviator stress significantly decrease the plastic strain accumulation in ballast. However, a previous stress history less than 50% of the currently applied cyclic deviator stress does not contribute to plastic strain accumulation.

2.6.2.7. Current Stress State

Current state of stress also influence the deformation and degradation behavior of ballast. In soil mechanics, the state of stress and the failure criteria are usually defined by two stress invariants: the mean effective normal stress p' , and the deviator stress q (Roscoe et al 1958; 1963).

Plastic strain increment is mainly dependent on the state stress and other factors. As the state of the stress and another state variables (void ratio) of a soil element moves towards the critical state, the rate of plastic shear strain corresponding to any load increment becomes higher at a critical state the shear and strain continuous to increase at a constant stress and constant volume.

2.6.2.8. Number of Load Cycles

Recognizing the influence of number of load cycles on the accumulation of plastic deformation of ballast and granular media is a prior area of researchers and engineers. Increase in the number of load cycles generally increases settlement and lateral deformation of granular aggregate including ballast. Track settlement immediately after tamping increased at a decreasing rate with the number of axles. It may also be approximated by a linear relationship with the logarithm of load cycles. However, Raymond and Dyaljee (1979) showed evidences on the accumulated plastic strains of ballast may not be linearly related to the logarithm of load cycles for all ballast types, grading and load magnitudes.

Shanton (1984) examined a wide range of track settlement data and concluded that the linear relationship of track settlement with the logarithm of load cycles or total tonnage might be a reasonable approximation over a short period. Jeff's and Marich (1987) attributed re-compaction to the failure of particle contact points within the bed causing a sudden increase in settlement rate by conducting a series of cyclic load tests. By conducting series of true tri-axial tests on ballast aggregate one can decide that, the behavior of ballast is highly non-linear under cyclic loading. A rapid increase in the initial settlement during the first 20000 load cycles, followed by a consolidation stage up to about 100000 loading cycles Ionesco, D. (2004).

2.6.2.9. Loading Frequency

Since the speed of the train on the track varies each time, it is important studying influence of loading repetition on the ballast characteristics. Shanton (1984) carried out a series of cycle loading tests, by varying the frequency from 0.1 to 30 Hz, while maintaining other variables (e.g. confining pressure, load amplitude etc.) constant. Then he concluded that the loading frequency does not significantly influence the settlement and deformation behavior instead he adopts that increased train speed increases the dynamic forces and impart greater stresses on the ballast

2.6.2.10. Amplitude of Loading

The magnitude of cyclic loading also plays major role in ballast deformation. When a series of cycling tri-axial tests by varying the load amplitudes at every 1000 cycles conducted one can study

the influence of load amplitude on ballast deformation and settlement. Then he adopted that as load amplitude or magnitude increases in the first cycle, permanent strain, settlement and final (long term cumulative strain also increases significantly. The effect of cyclic loading amplitude on the ballast behavior calculated by the formula developed by Suinkur (2002).

Load amplitude = cyclic load ratio/ maximum static stress ratio

$$[n = (q/p)_{cyc} / (q/p)_{stat. max}] \dots\dots\dots 1$$

At low cyclic stress level the rate of plastic deformation of ballast is negligible.

2.6.3. Degradation of Ballast

Ballast may break and become pulverized by repeated cycle of loading that causes deterioration and deformation of track geometry, and will affect ballast mechanics. Broken bond was used to distinguish breakage. Degradation or deterioration is the reduction of the original quality due to various influences. The dynamic load is directly related to the axle load and track geometry. The main processes of track deterioration are Wear, Fatigue and Settlement. Three main groups of factors may be distinguished that contribute to the degradation of railway track ballast:

- Use: wear by physical contact and dynamic load
- Environment: climatic influence, water
- Failures: faulty components, bad construction.

Most important mechanical behavior of granular materials are strain stress and strength behavior, volume change and pore pressure developments and variation in permeability, depend on the integrity of the particles or number of particles crushing that occurs from stress change. Deterioration of ballast and sleepers is caused by external factors, such as vegetation and trainloads but also by maintenance actions and self-contamination. The main factors influencing the normal operation of ballast bed is thickness of the ballast layer and the draining properties of subgrade (of them, the cross fall of subgrade). Stability of the ballast bed is strongly influenced by its resistance to transverse displacements, which decreases when the contamination increases.

2.6.3.1. Ballast degradation – Effects on particle size distribution

Sieve analysis results and the determined degradation patterns in terms of change in particle size distributions during LAA test which clearly shows how the ballast gradation changed from a one form of gradation to the other e.g. from uniform to a well-graded gradation in time. Additionally, Fouling Index (FI) values associated with degradation also considered significantly. Non-fresh ballast is not much susceptible to for abrasion. Most sharp corners and edges of crushed particles

breakage of the large sized particles mostly happened in the early stages of track service. (P. Tolppanen, 2001)

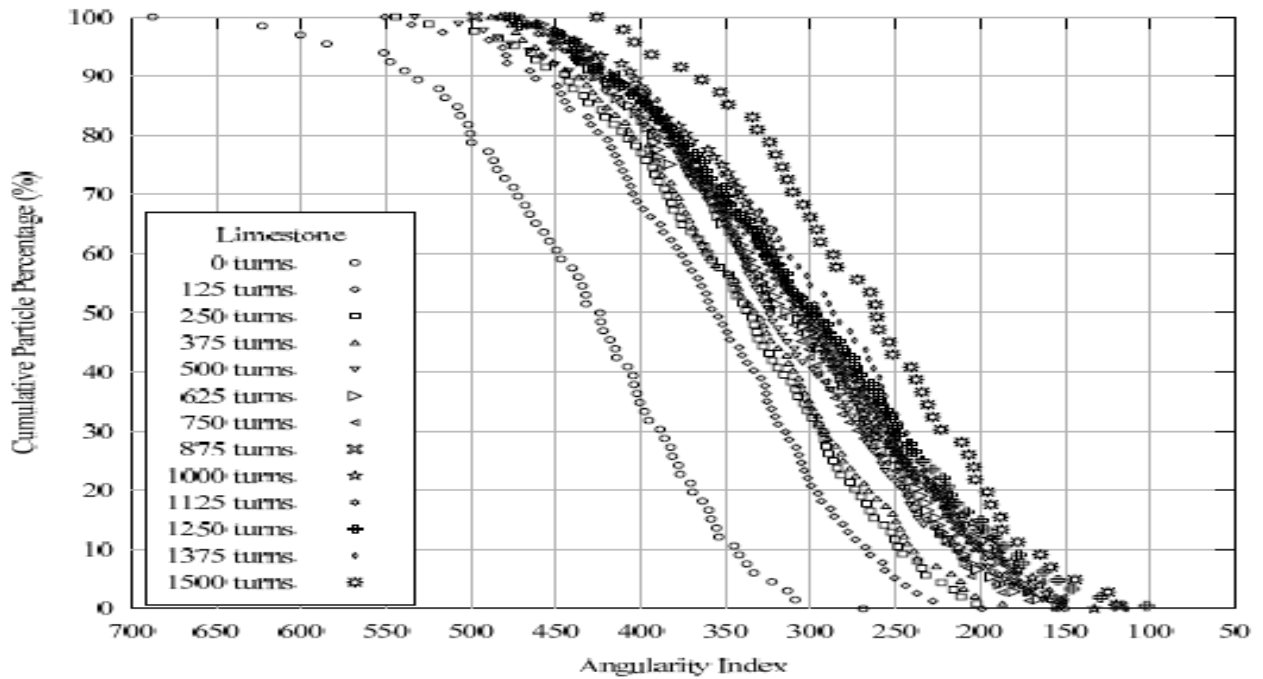


Fig.2.1. ballast Angularity Index (AI) values determined during LAA test (P. Tolppanen, 2001)
 Ballast degradation not only changes the particle size distributions but also influences the shapes of individual aggregate particles. Like the grain size distribution concept, the overall degradation trends of AI changes in time with the increasing number cyclic loading.

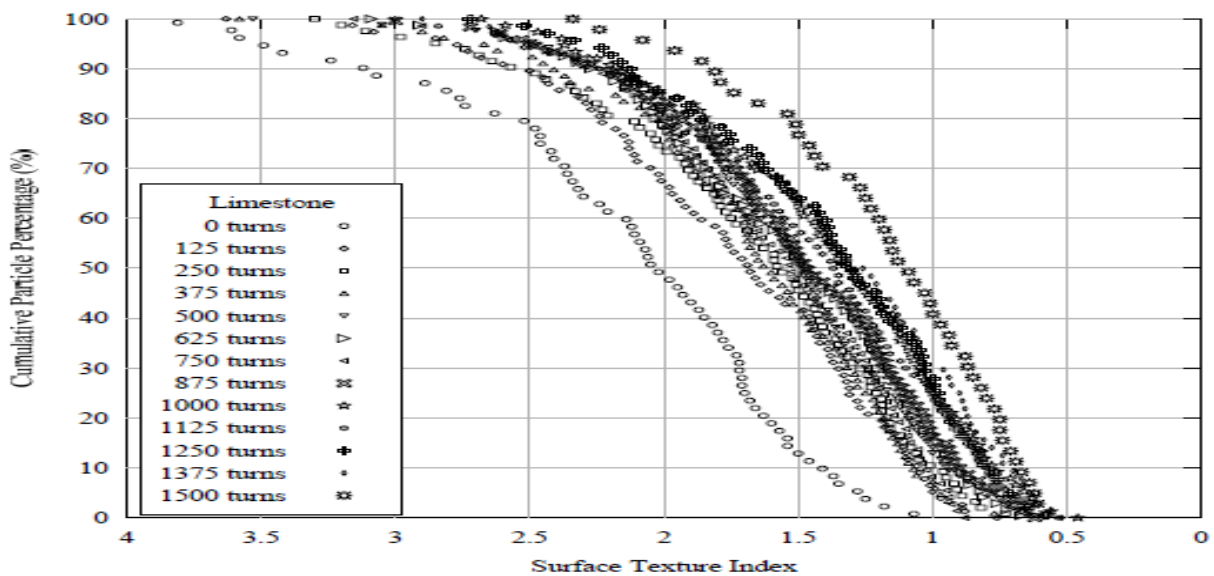


Fig. 2.2. Limestone Surface Texture Indices (STI) determined during LAA test (P. Tolppanen, 2001)

2.6.3.2. Driving Forces of Degradation

Railway track can be degraded without any traffic action. Even though it is the main cause of track deterioration there are many other reasons, e.g. soil may settle due to weight of the embankment, especially in the early years after construction. In most cases running trains is the driving force of deterioration. A railway track is designed to distribute the load from trains down to the soil/ground. This distribution through super- and substructure depends on original tracks design and current track condition. Stiffness of different components in the track structure, as well as the resulting (global) track stiffness will partly determine how the loads are distributed.

There are three main group of factors that drive degradation of track system specially the ballast. These factors are grouped in two dynamic, quasi-static and static forces.

Table 2.1. Driving forces of ballast degradation

Sources	Characteristics	Influence of the source
Traffic loads	Speed	Static Quasi-static and Dynamic forces
	Axle load	
	Unsprang mass	
	Suspension	
	Wheel profile	
	Axle spacing	
	Wheel current condition	
	Track design geometry	Static and Quasi-static
	Geometric quality	
	Rail and sleeper condition	Dynamic forces High-frequency forces Impact forces
	Rail misbehaves	

Ballast and sub-layers are influenced by the stiffness above and under themselves. A ballast layer resting on bedrock will experience large internal compression/expansion during a train-passage as compared to a ballast layer resting on a soft clay layer. Differential settlements in the ballast layer is more loosely connected with stiffness and more with compaction and variations in sleeper support which yet may be detected by stiffness measurement. Settlements of lower layers and soil are also more loosely connected with stiffness

2.6.3.3. Particle Breakdown

All granular materials subjected to stresses above normal geotechnical ranges exhibit considerable particle breakage. Some researchers try to approve that particle breakage can even occur at low confining pressure. Influence of particle breakage is on the mechanical property of granular materials is significant. Different particle breakage indices are developed based on;

- change in particle size after loading
- change in single particle size and
- Overall grain size distribution.

Miura and O-hara (1979) used the change in grain surface area (ΔS) as an indicator of particle breakage. They imagined that new surface will be generated as the particles are broken and therefore the changes in surface area can be used as a measure of particle breakage. In their method of the specific surface area of each particle size (i.e. sieve size) is computed assuming that all grains are perfectly spherical.

2.6.3.4. Factors Affecting Particle Breakage

Ballast breakage depends on several factors, including load amplitude, frequency, number of cycles, aggregate density, particle angularity, confining pressure and degree of saturation. But the most significant factor governing ballast breakage is the fracture strength of constituting particles (Inderanta and Salim, 2003) indicated that particle size, angularity, particle size distribution and magnitude of confining pressure affect particle degradation. They conclude that larger particle size, higher grain angularity and uniformity in gradation increases particle crushing. Additional key factors include average value of contact forces (stresses), strength of particle at contact points, and the number of crushed rocks from blasting and crushing processes is another reason of particle breakage.

2.6.4. Ballast Fouling

After long term service, ballast becomes damaged and contaminated and its gradation changes. Thus, its performance reduces. Damage on the ballast bed is mostly caused by infiltration of smaller particles in-between ballast grains. These particles contaminate the ballast, which reduces the capacity of the ballast. This process is mostly known as “ballast fouling” (Sundvall, 2005).

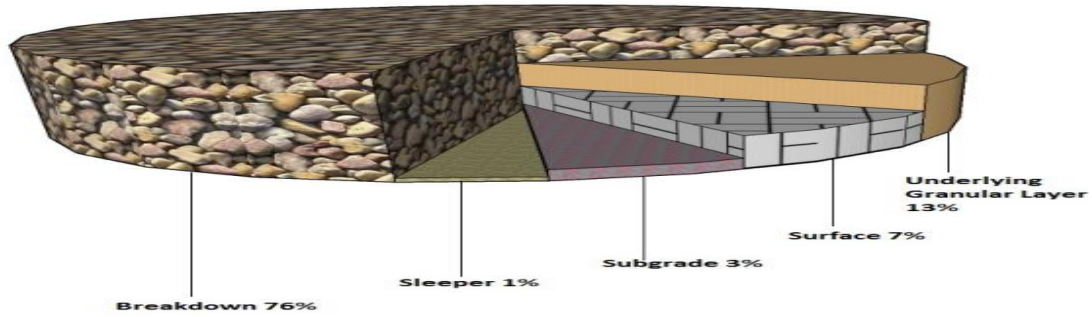


Fig.2.3. Ballast fouling (Aursudkij, 2007)

Selig and Waters (1994) described railway ballast fouling as generated by particles smaller than 4.76 mm diameter that are situated within the void spaces of the ballast particles. When the ballast is made up of greater than 20% of fouled material by weight, the ballast layer can be considered highly fouled because the ballast to ballast contact is compromised by the fine-grained materials (Indraratna et al, 2011a).

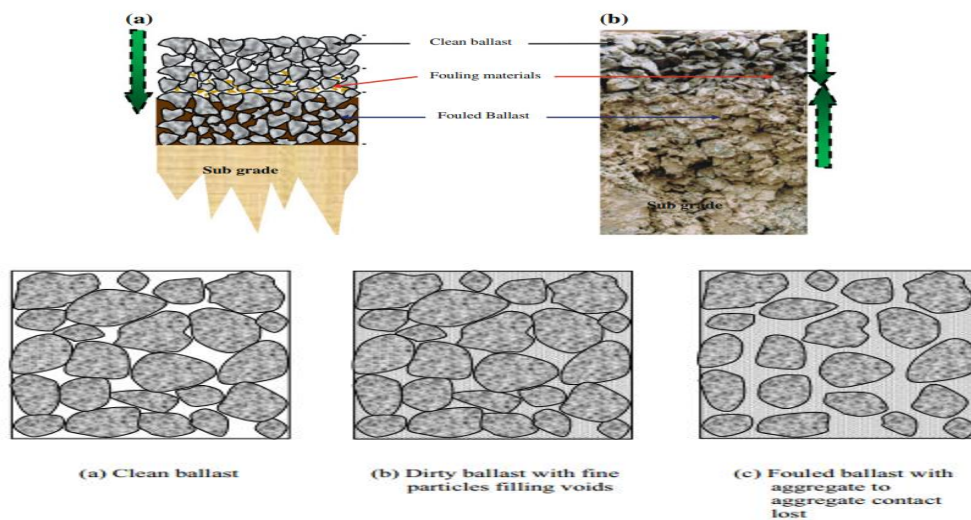
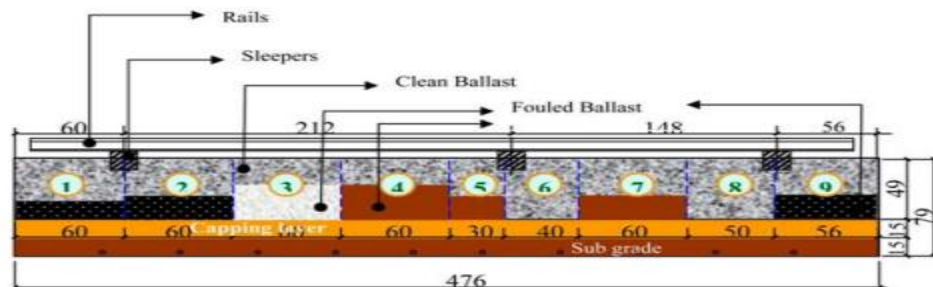


Fig. 2.4. Ballast fouling condition (Indraratna et al, 2011a).

2.6.4.1. Mechanisms of Ballast Fouling

Based on an extensive literature review and observations, Selig and Waters (1994) found that ballast fouling was caused through five primary modes which is illustrated in figure 2.5.:



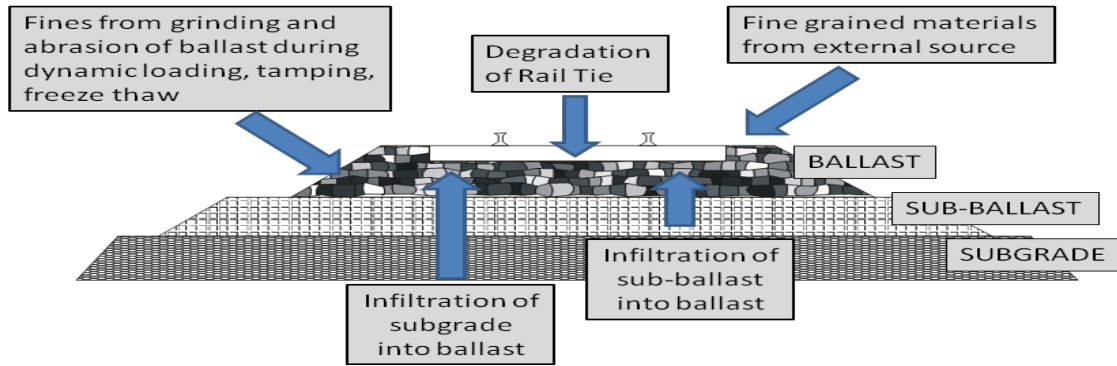


Fig. 2.5. Track structure and Ballast fouling mechanisms

2.7. Ballast Renewal and Recycling Techniques

The process of ballast recycling starts by putting working guidelines and frameworks which can direct how to collect and remove materials from the natural position it installed before and how to rehabilitate and renew collected material. The first step in ballast rehabilitation and renewal work is investigation of the site where it is located and understanding the characteristics of its constituent particles. Its interaction with environment and the load bearing capacity are also another major character to be studied. There are a lot of advanced technologies helpful in removing defective and used up ballast and cleaning and recycling it for further use. Understanding mineralogical and petro logical make up of a ballast and studying the level of deterioration, better ways of mitigation and the benefit it will provide on farther national and local development should be examined in detail.

There are plenty of field investigation and laboratory assessment techniques to determine the level of deterioration. Characterizing it based on detail study on the field, in the laboratory and by using computational modelling techniques that can help in developing appropriate renewal mechanism and specifying or assigning future functional capacity.

2.7.1. Ballast Field Investigation Methods

Field investigation of old track system is an important part of geo-mechanical track condition assessment which helps in the examination of engineering properties of structural materials and prediction of the performance of the structure. There have been many of ballast studies with the advancement of track investigation that track has explored an assortment of field investigation methods `and practices. Various types of field investigation efforts have been conducted over the years to study many aspects of ballast and track sub-structures. Principal parameters required during a geotechnical investigation can be strength, in-situ stress, permeability, deformation and

defects like fouling and ballast breakage by using field laboratory. These parameters can be obtained by in-situ (field) investigation and laboratory testing approaches. Among the in-situ investigation techniques in-situ investigation test pits and trenching are the most appropriate techniques selected for this research work. While lab mechanical and geotechnical testing includes LAA, ACV, gradation, density and so on.

2.7.1.1. In-Situ Testing

This testing technique can provide estimates of soil properties rapidly and relatively inexpensively for each test location. Potential advantage of in-situ testing

- 1) Can be take place on difficult sites for sampling
- 2) Difficulties of sample handling can be avoided
- 3) Significant reduction in time of investigation
- 4) Larger total volume of sample for testing
- 5) Potential for large cost saving in testing, etc.

There are a lot of in-situ testing for use on a variety of problems and materials. Field Van shear Test (FVT), Cone Penetration Test (CPT), Standard Penetration Test (SPT), Piezocone, Flat Dilator-Meter (DMT), and Full- Displacement pressure-meter Test are mostly used techniques for in-situ geo-mechanical testing. SPT and CPT are the most popular field investigation techniques for railway track sub-structure condition investigation. The limitation of these two approaches is that they are more appropriate in sub-grade and soil testing and hardly applicable for coarser aggregate ballast.

2.7.1.2. Test Pits and Trenching

A common method for any geotechnical field investigation is the implementation of test pits and trenching for the characterization of earth structures. This has been especially true in the study of railway substructure to investigate ballast, sub-ballast, and subgrade components.

Sampling from trenching is preferable due to the control an investigator has on the sample region and resulting sample sizes. Samples can be taken of sufficient size to conduct proper ASTM qualified sieve testing, stress testing, and any other required geotechnical tests. If the trench is of sufficient depth, the entire column of the track substructure can be investigated and sampled from the ballast to the subgrade. Direct access to the ballast layers allows for a greater quantity of material to be sampled, allowing for a wide array of laboratory testing to be conducted (Brough et al, 2003).

2.7.2. Ballast Laboratory Testing Techniques

Investigation of condition of track ballast can be made by analyzing results obtained from laboratory tests leading to the development of models.

The most fundamental properties of ballast and sub-grade materials that should be investigated using laboratory tests includes;

- 1) Resilient or elastic behavior
- 2) Plastic or permanent strain and
- 3) Failure stress level.

The tri-axial test is the most common method for the investigation of ballast material properties.

2.7.2.1. Tri-Axial Compression Testing

It is the most versatile and useful laboratory test for sub-structure components strain-stress and strength analysis for both granular materials (ballast) and fine grained soils (sub-grade). To more realistically develop stress condition of that exist in the field a confined sample should be subjected to a repeated axial loading by using cyclic tri-axial load test. The dynamic tri-axial test has the following advantages over the static tri-axial tests.

- 1) Both elastic and plastic property of material, such as resilient modulus and plastic deformation
- 2) Relatively the same duration of dynamic loading as occurred in the field
- 3) Stress condition under the sleeper at the desired point can be developed by dynamic tri-axial test and
- 4) Effect of frequency and number of repetitive loadings can be studied

Triaxial apparatus is used to investigate the behavior of ballast under static loading and repeated loading under different stress conditions. It was designed for a sample of 300-mm diameter and 450-mm height.

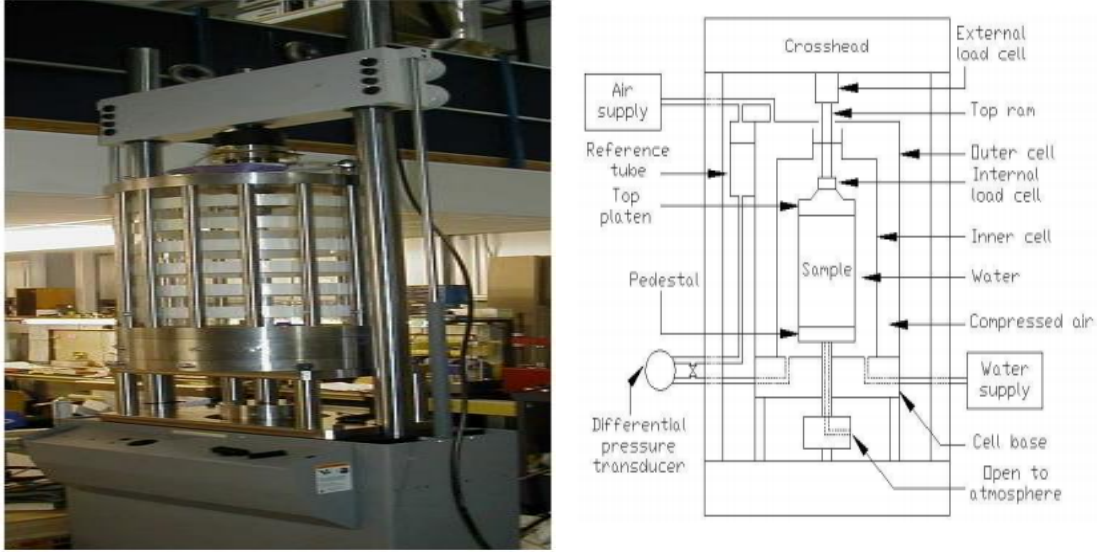


Fig. 2.6. Different Laboratory tri-axial testing apparatus and its Schematic diagram

2.7.2.2. Ballast Grain Size Distribution

The grain size distribution of Ballast is a primary indicator of its mechanical suitability as a rail substructure component. A grain size distribution plot is essential in the study of ballast fouling because of its ability to represent the proportion of fouling agents found within a ballast sample (Craig, 2004).

Table 2.2. Ballast grain size distribution standards

Large rectangular sieves(86cmx50.8cm)		CN SPECIFICATION
Sieve No.	Sieve opening(mm)	% passing
3inch (tested separately)	76.8	100
2inch	50.8	75
1.5inch	38	45
1inch	25.8	0
3/4inch	19.35	0
1/2inch	12.7	0
No.4	4.76	0
pan		

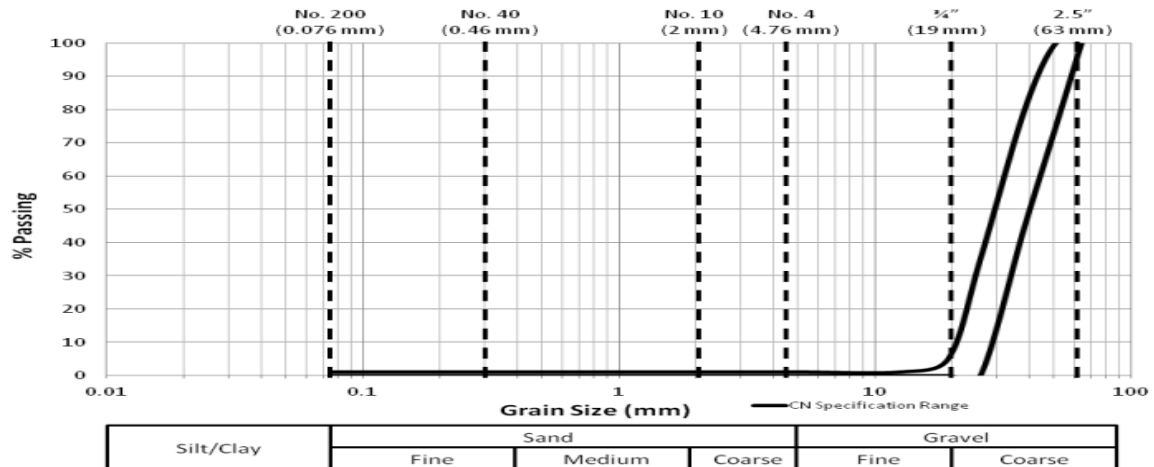


Fig. 2.7. Classification of aggregate based on particle size distribution

The figure shows the size range for silt/clay, sand, and gravel along with their respective fine, medium, coarse sized specification according to ASTM naming standards.



Fig. 2.8. Different sieve size (ASTM 2011)

2.7.2.3. LA Abrasion Testing

The LA Abrasion test has been a popular tool for the testing of aggregate durability in both industry and research contexts. The test gives an adequate indication of the relative quality and competence of an aggregate with similar mineral composition. However, as concluded by many studies related to the use of LA Abrasion testing of aggregate, the results of the LA abrasion are unsuitable for comparison between aggregate sources of distinctly different origin, composition, and geological structure (ASTM, 2011). Lim (2004) concluded that LA Abrasion testing was adequate to identify specifically ballast field performance, which directly relates to the research presented in this thesis.



Fig. 2.9. LA abrasion testing instrument (ASTM, 2011)

2.7.2.4. Ballast Quality Standards and Specifications

Based on the standard developed by, Italferr-sis. t.a.v.s.p.a., ballast material shall comply with the following requirements:

- It shall consist of crushed stone, and be free from clay, debris, and organic or other deleterious matter. Weathered rock shall not be accepted.
- It shall be angular in shape with all dimensions approximately equal,
- It shall be free from dust.

Table.2.3. Consta JV's suggested ballast requirements

Parameter	Permissible vale
Density	Minimum 1400kg/m ³
Abrasion	22%
Crushing resistance	120/140n/mm ²
Aggregate impact value	<22%
Water absorption value	<0.5%
Elongation index	<25%
Flakiness index	<25%
Contamination with fine material	<1%

ASTM Ballast Specifications

According to ASTM soil and rock material standard the property of aggregate appropriate for railway ballast should confirm with the following standard values.

Rejection of Proposed Ballast Material

Igneous or other rock, displaying minerals considered to be harmful to the overall performance of the ballast may be rejected following petrographic analysis or durability testing, even though the rock complies with other sections of the specification.

Bulk Density

When determined in accordance with AS 1141.4 the compacted bulk density of ballast material shall not be less than 1200 kg/m³.

Particle Density

When determined in accordance with AS 1141.6 the particle density of ballast material shall not be less than 2500 kg/m³.

Particle Size Distribution

The particle size distribution (grading) of ballast aggregates, when determined in accordance with AS 1141.11 and AS 1141.12, shall conform to the requirements set out in Table2.4 below.

Table.2.4. particle size distribution standard by ASTM

Sieve (mm)			63.0	53.0	37.5	26.5	19.0	13.2	9.50	4.75	1.18	0.075
Nominal Size (mm)	60	%age passing	100	85-100	20-65	0-20	0-5	0-1	-	0-1	-	0-1

Different countries around the world use ballast with a particle size of 32 – 64 mm to meet these requirements while more finely grained ballast, 11 – 32 mm, is used in railway yards and sometimes at switches and crossings to get a more level surface. Harder stone material is generally preferable as ballast in for many different reasons e.g. granite.

Particle Shape

When tested as described in AS1141.14 the proportion of misshapen particles in the fraction of the ballast material retained on the 9.50 mm test sieve shall not exceed 30% using a ratio of 2:1.

Flakiness Index

When determined in accordance with AS 1141.15 the proportion of flaky particles in the ballast material retained on the 6.70 mm test sieve shall not exceed 30%.

Crushed Particles of Coarse Aggregate

When determined in accordance with AS 1141.18, ballast that is derived from river gravel shall consist of at least 75% by mass of crushed particles. The proportion of uncrushed particles shall not exceed 5%.

Durability

Aggregate Crushing Value

The aggregate crushing value of particle when determined in accordance with AS1141.21, for the fraction of material passing the 26.5 mm test sieve and retained on 19.0 mm test sieve shall be 25% maximum.

Note: The aggregate crushing value of the ballast material when determined in accordance with AS1141.21, for the fraction of material passing the 53.0mm test sieve and retained on 37.5mm test sieve shall have a result no greater than 30%.

Los Angeles Values

The Los Angeles Values of the ballast, as determined in accordance with AS1141.23 shall be 25% maximum.

AREMA ballast standard

The AREMA No. 4A gradation for ballast, which is recommended for main track line, is adopted. Depending on ASTM(Americans) and BS(British) test procedure and AREMA's limiting value; test for specific gravity, % absorption, loose unit wt. Comp. unit wt., elongation index, flakiness index, % finer than 75- μ m, ACV and LAA has been done. Though, the result for all tests not fall within the standard limiting value; solution have been made by blending the material with Beru sample which is more fresh and strong. Blending the sample done on trial mixing of 20%-80% mix and 40%-60% mix by mass. Finally, better mix sample is done by 40%-60% mix by mass of the sample which falls within the standard limiting value which is listed on AREMA.

Acceptable results shall fall within recommended limiting values given in AREMA below.

Table.2.5. AREMA standard limiting value for ballast material

Bulk specific gravity	≥ 2.60
unit weight (kg/m ³)	≥ 1400
Absorption %	$\leq 1.0 \%$
Degradation	$\leq 25\%$
flakiness /elongation Index	$\leq 25\%$
Aggregate crushing value	$\leq 25\%$
SSS (5 cycles)	$\leq 5.0 \%$
flat/elongated particles	$\leq 5.0 \%$

Limiting values not found in AREMA but used in study in accordance to other standards and practices in Europe are given below.

Table.2.6. limiting value of sub-ballast material

Tests	Result(org sample)	Result	Result (20%-80%)	Result (20%-80%)
-------	--------------------	--------	------------------	------------------

	A(1)	B(1)	blending material	A	B	A(3)	B(4)
Specific Gravity	2.1	2.22	2.92	2.32	2.38	2.59	2.74
%Absorption	1.47	1.44	0.83	1.25	1.21	1.08	0.94
Loose Unit Weight	1145.14	1225.9	1407			1309.87	1316.8
Comp. Unit Weight	1290.1	1316.8	1501			1407	1424.87
Elongation Index	26	23	24				
Flakiness Index	24	19.22	22				
%Finer Than 75m	0.96	0.91	0.32				
Acv	26.4	25	19			23	21
LAA(For Small Size)	29.4	27.4	22			24.3	24
LAA(For Large Size)	28.2	27.7	21			24.6	23.9

Railroad ballast is usually considered as uniformly graded. There are, however different gradations of ballast commonly used around the world such as AREMA ballast gradations (see Table 2.6). Grading of crushed stone truck ballast shall be compatible with the following specification.

Table 2.7. Typical gradation value of railway ballast

Sieve (mm)	70	64	45	32	1
%age passing	100	93-100	25-55	0-7	0-1

No.	Nominal size square openings	Percentage Passing								
		76.2 mm	63.5 mm	50.8 mm	38.1 mm	25.4 mm	19.1 mm	12.7 mm	9.5 mm	4.75 mm
24	63.5-19.1 mm	100	90-100		25-60		0-10	0-5		
25	63.5-12.7 mm	100	80-100	60-85	50-70	25-50		5-20	0-10	0-3
3	50.8-25.4 mm		100	95-100	35-70	0-15		0-5		
4A	50.8-19.1 mm		100	90-100	60-90	10-355	0-10		0-3	

The following parameters have to be satisfied along with the gradation:

- Coefficient of Uniformity, $C_u > 14$.
- Coefficient of Curvature, $1 < C_c < 3$.
- Sand equivalent shall be greater than 45% for the material passing through sieve size 2 mm.

- For cases where sub-ballast material is in contact with the sub grade (embankment) material in which the percentage passing of fine materials (passing sieve size 0.063 mm is greater than 15% of the weight of material passing through Sieve 63; one should make sure that the following conditions are satisfied for the sub-ballast.
 - ✓ Percentage of Sand material (2 to 0.063 mm) must be more than 30% of the total weight of the sub-ballast sample.
 - ✓ Percentage fraction passing sieve size 0.2 mm must be in the range from 20 to 25% of the total weight of the sub-ballast sample.

Fresh ballast; part of a ballast newly delivered to the track site with its particle size, gradation and other index properties are relatively well defined sharp angular coarse aggregates of crushed from source rocks. Most fresh ballast aggregate looks fine-grained, dense-looking black rock, with essential minerals

Recycled ballast; used up and rehabilitated ballast which is removed from the original track during renewal and demolishing operation. It is the process of Recycling old track ballast after proper treatment to use in road construction and other rail track projects. Recycled ballast shall be tested for contamination. Contaminated ballast may require cleaning and remediation to meet the contamination threshold levels that make it suitable for reuse and recycling. Based on different researches physical examination of recycled ballast indicates that most part of recycled ballast is semi-angular crushed rock fragments, while the remaining part consisted of semi-rounded river gravel and other impurities. (Cemented materials, sleeper fragments, nuts, bolts, fine particles etc.) (Inderanta et al., 2002a). Most of the semi-angular rock particles were less angular and had less clean appearance. Fine particles are visible on recycled ballast grains even after it passes through screening operation. Its strength, bearing capacity and resiliency will be less due to less angularity, more heterogeneity and more impurities than fresh ballast.

CHAPTER THREE

3. Old Track Ballast Investigation Techniques

3.1. Ethiopian Old Rail Way Track

Djibouti-Ethiopian old railway line was the longest and the only one rail track in east Africa for a long time. It is more than 750km that extends from the port of Djibouti to the capital of Ethiopia ‘Addis Ababa’ that connects land locked country’ Ethiopia to the red sea for more a century. It is metric gauge line that stretch 780km of which 681km is within Ethiopia while the rest approximately 100km is within Djibouti. It was constructed at the beginning of 20th century which becomes deteriorated due to the lack of maintenance, poor management and lack of commercial focus.

Since Ethiopia is a land locked country the corridor this track line extended is the main gate in which the center Addis connects to the rest of the world by land transportation. The oldest track system was the key import export route and it was a reason for the establishment of different centers along the route. These are not the only gift that the line provides, but also it was strategically preferable for international shipping through Red Sea in east Africa with potential to be a regional transport hub. Due to its strategic location, it is the most preferable route even today to handle the demand for efficient and modern marketing in the country. At present Ethio-Djibouti track is subjected to multiple malfunctioning with a noticeable deficiency of basic components. Due to improper protection from surface water caused by inadequate embankments and crossing structures and by the presence of inadequate maintenance almost all the component of the track system is subjected for massive deterioration. Track geometric deformation, misalignment and many other defects are observed on Addis-Awash section. The ballast of the track is reduced significantly by the surface water action and inadequate maintenance for long time. Currently the line incorporates the following characteristic:

Table 3.1. Basic characteristics of old Ethio-Djibouti railway

Total length	781Km
Study area length	235Km
Study spots	18 with min length in between 10km
Minimum curve radius	100m
Stations	34
Max height above sea level	2400m
Gauge	1000mm

Maximum speed for ordinary train		50km/h100m
Minimum distance between stations		7.5km
Maximum distance between stations		46.2km
Telecommunication		overhead tel. lines
Signaling		fixed boards
Bridge span >12m		101
Permanent way	Sleepers	Steel
	Rails	20/25/26/30/36kg/m
Traction		diesel electric and call
Hauled load		450-800 tones
Axel load		14 tones

The track section that extends from Addis Ababa to Awash is characterized by the following soil and geologic condition.

1. **Eluvial, alluvial silty sand and sandy gravel and rock debris**, with excellent bearing capacity and good capacity of withstanding effect of presence of water. CBR value 25%
2. **Sand and sandy silts**, with fair bearing capacity and presence of water can not affect significantly with CBR value 15-25%
3. **Silty and silty clayey residual eluvial or alluvial soils of low to medium plasticity**, having medium to poor bearing capacity that can be affected by the presence of water with CBR value 5-15%
4. **Silt and silty clayey residual soils of high plasticity**, which have poor bearing capacity while presence of water and increased air humidity leads to the rise of lateral flow of materials. CBR value below 5%
5. **Rock outcrops and quarry-sites**, the rock that can be used as ballast or sub-ballast are merely volcanic rocks that erupts in different period in the history of the region. The main source of the rock for these section of the line is located at Wolenchiti located between Awash and Adama. The bearing capacity of this outcrop is unlimited with very good rock surface condition (surface texture) or roughness and good porosity for surface water infiltration.

Regarding geotechnical characteristics, the line extension from Addis Ababa to Awash is divided in to the following three homogeneous sections.

- **Addis Ababa–Debre–Zeit (km 0-51)**, this section is characterized by the presence of 2-3m thick residual clayey and peaty deposits which implies the supper-structure laid directly on

this soil is liable to frequent instability and maybe it was subjected to frequent maintenance and realignment. The section is merely characterized by the soil type described on No. 5 above.

- **Debre-Zeit Nazareth (km 51-99)**, the soil underlying this section consists of alternation of rocky outcrops and sand or sandy silt deposits. On the other hand, there also be parts with heavily eroded steep slope catchment basins which needs considerable flood protections.
- **Nazrate-Awash (km 99 – 232)** the line runs along wide and extensive plains and characterized by very long straight sections. Up to approximately length of 130km. length the embankment mostly consists of rocky materials taken from the surrounding area. (Italferr-sis., 1997).

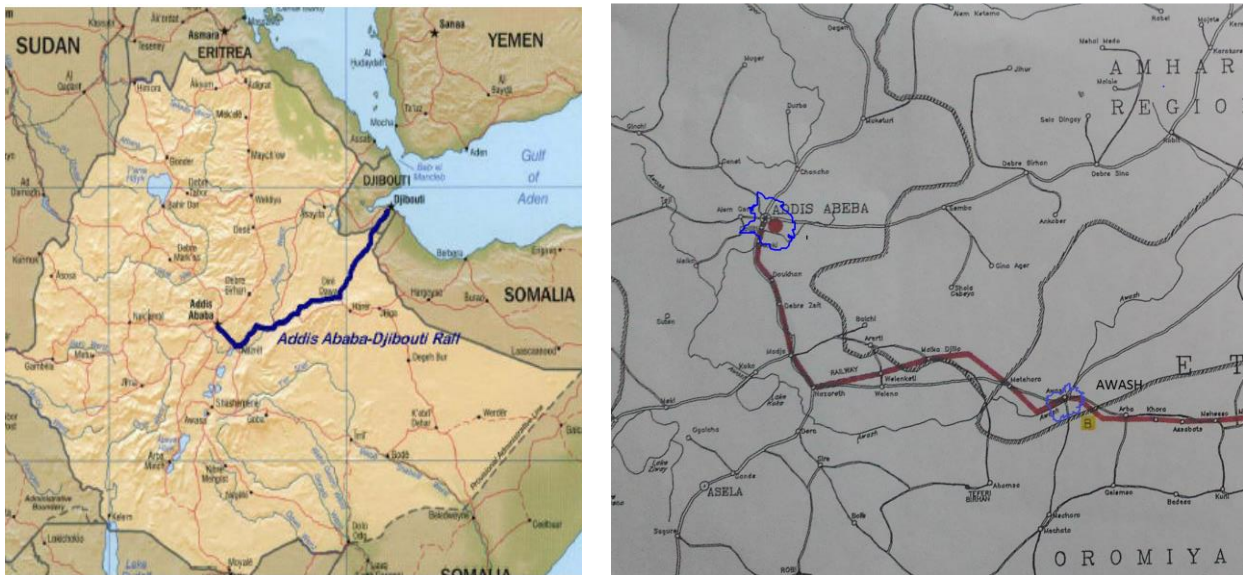


Fig. 3.1. Route of Ethiopian old railway line

3.2. Current Condition of the Ballast

Currently this historic track line is getting out of consideration due to the construction of new projects along the corridor and the nature of its traction system and components. Legacy rail track system is supposed to be demolish due to its nature of the track gauge system which is metric or narrow gauge because of its compatibility problem with the modern trains and locomotives. Even though different international companies were tried to rehabilitate the system no one is gone through the action due to economic constraints. As it was tried to explain above components of the track are devastated. Since it was extensively used up with a minimum maintenance and operational care components of the system are severely deteriorated. This study is merely

emphasized on the characteristic evaluation and renewal measures to be taken to rehabilitate the ballast.

Ballast of this track line is subjected to different defects due to its much longer time service. As it is observed physically the whole track fails due to settlement, fouling and deposition of sand and soil by the wind and flooding in vicinity of the line. Ballast breaking, differential settlement, fouling and sedimentation are the most causes of the track failure while lack of proper maintenance and rehabilitation also the main problems to be considered. There also seen a removal of track components like the rail and the sleeper by the local community and different firms for the construction of roads and flood ditches.

During site inspection, a significant ballast insufficiency was noted on the whole section under consideration. From the section considered special account should be given for the section that extends from Lagahar to Debre Zeit. Either the whole system or the ballast is not available on some parts of the line. But some extension especially on rural sections it is possible to find satisfactory geometrical configuration of the track and ballast which can assure safe run of trains.



Fig. 3.2. Condition of Ethiopian old railway track

3.3. Old Ethiopian Railway Ballast Failure

During the site investigation, it is observed that from the total length of the track (781Km) Addis-Awash section covers almost 235Km. On this section alignment of the line is mostly flat and stretches long distances with a small number of curves. From multiple investigation, it is recorded that marked scarcity of ballast throughout the section. On some parts of the section the whole portion of the sleeper is completely embedded by the track formation while on other parts the whole track ballast and the sleepers are covered by grass and weeds. And on some portion the

whole ballast is eroded or removed and only the rail and sleeper are remained on the alignment while on some portion the thickness of the ballast is reduced to a few centimeters.

Based on site investigation Addis Ababa- Djibouti old railway line crosses different geologic and geographic origins. The region where this line extended comprises a top soil having technical characteristics and parallel intrinsic stability with highly variable natural condition. The study conducted by Italferr-sis t.a.v.s.p.a. in 1997 underlines the following natural condition along the line that extends from Addis Ababa to Dire Dawa. Due to the following major factors speed limit or total cease of traffic is imposed on the section.

- Lack or lose of track ballast
- Lack of super elevation and lose of normal track alignment
- Lack of thorough maintenance due to lack of spare part and machineries
- Aging of permanent way components

Main causes of these problems are;

1. Absence of protective side and interception ditches
2. Absence of side gutters
3. Absence of side protection of embankments
4. Absence of regular and frequent maintenance
5. Absence of human protection like fence and guard



Fig.3.3. Unfouled and fouled ballast of old Ethiopian railway

3.3.1. Cycle of Deterioration

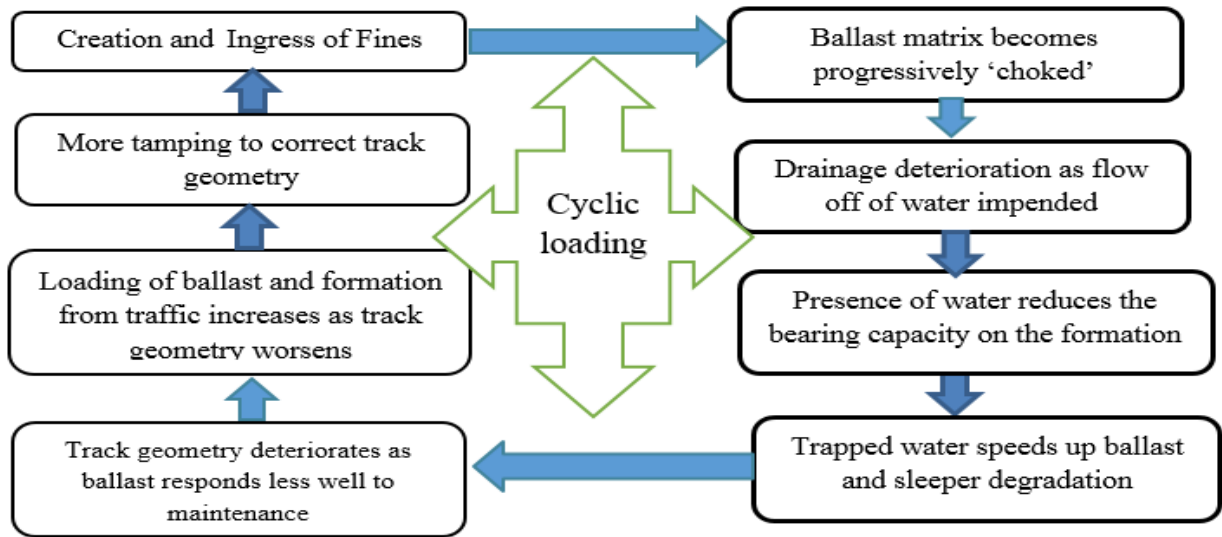


Fig. 3.4. Ethiopian old railway ballast failure mechanism

3.3.2. Implications of the Failures

Due to the above listed reasons and many other driving agents the whole track system is subjected for the following and many other deterioration and malfunctioning,

- Deteriorating track quality – poor ride quality
- Discreet track geometry faults (e.g. twist & cyclic top) risk of derailment
- Loss of lateral stability - increased risk of track buckling
- Ponding' of water - damage to the formation
- Formation of wet beds - damage to the sleepers and bearers
- Excessive Settlement of superstructure
- Excessive Deformation in geometry



Fig. 3.5. Ballast and sleeper contact lose condition at Lagahar-Akaki section

3.4. Track Site Assessment and Investigation

3.4.1. Old Railway Track Ballast Fouling

Ballast fouling is the presence of more fines in the ballast material from crushed aggregate, sleeper wear, fine particles from sub-grade or external (“surface spillage”) fines from freight and coal fouling, which causes soft and deformable ballast structure.

As described in the literature review part railway ballast fouling is generated by particles smaller than 4.76 mm diameter that are situated within the void spaces of the ballast particles. When the ballast is made up of greater than 20% of fouled material by weight, the ballast layer can be considered highly fouled because the ballast to ballast contact is compromised by the fine-grained materials. The ballast considered under this study is observed to have fouling intensity difference on different locations.



Fig. 3.6. Fouling condition of old rail track ballast Lagahar-Akaki section

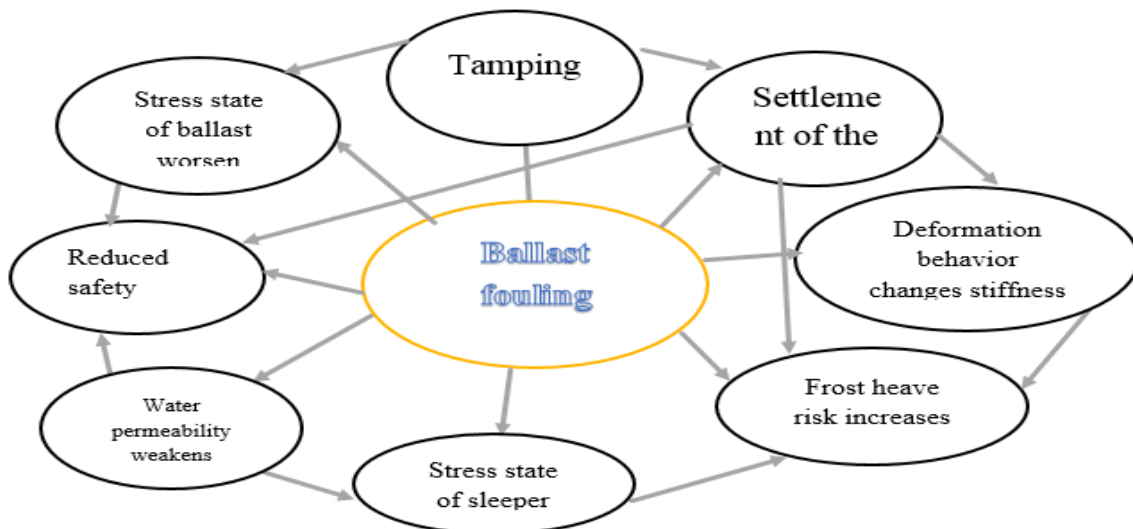


Fig 3.7. Causes of Ethiopian old track ballast fouling

3.4.2. Sources of Ballast Fouling on Ethiopian Old Rail Track

Fouling of Ethiopian old railway track ballast is due to many reasons. Even though it needs detail investigation the proportion of the source of ballast fouling on Ethiopian old railway track is estimated as follows. The method of estimation mainly related with different international investigation undertaken on different old tracks around the world. The result of site investigation on different sections indicates that the major sources of fine materials can be categorized as external and internal. Major causes of ballast fouling include:

- Wind born fine material accumulation
- Water born fine and external flood deposition of sediments
- Abrasion and breakdown of ballast due to rail loading
- Migration of sub-ballast or subgrade material into the ballast layer
- Migration of environmental material onto the surface of the ballast

3.4.3. Effect of Ballast Fouling

Fouling Index

There are several ways to describe ballast fouling, but the most accepted methods are the so called “Selig Indices”:

- 1) fouling content
- 2) fouling Index

Table 3.2. Ballast classification based on fouling index (AREMA)

Ballast classification	Fouling index
Clean	<1
Moderately clean	1 - 10
Moderately fouled	10 - 20
Fouled	20 - 40
Highly fouled	≥40

Fouling index FI is expressed as:

$$FI = P_4 + P_{200} \dots\dots\dots (2)$$

Where P_4 is the cumulative % passing the No. 4(0.19 in or 4.75mm) sieve and P_{200} is the cumulative % passing the No. 200 sieve (0.003 in or 0.0075mm).

Fouling Content, FC, is expressed as

$$FC = \frac{P_{3/8}^3}{W_r} \dots\dots\dots (3)$$

Where $P_{3/8}$ " is the cumulative percent passing the $3/8$ " Sieve (9.5mm) and W_r is the dry weight of the total sample.

3.4.4. Review of Selected Section Area of the Track Line

Different investigations have been made in the past with the aim of developing major roads passing through the vicinity of the project area. More importantly, a recent study has been made for the rehabilitation of the exiting Ethiopia – Djibouti railway line.

One of the studies conducted by, (Italferr-sis. t.a.v.s.p.a., 1997) deals on the rehabilitation of the old Ethiopia-Djibouti railway line. However, it does not have relevant information with regard the condition for ballast and sub-ballast because material investigation was out of the scope of the this study.

Another study was developed by (Consta JV and Addis Environmental, 2002) It is the most recent study on the rehabilitation of the old railway line and contains the most relevant information on material investigation for ballast and sub-ballast. The study was conducted to find quarry sites for ballast and sub ballast material for the rehabilitation work of Ethio-Djibouti old railway track. It was not directly investigated the condition of the existed ballast.

3.4.5. Data collection

Secondary Data Collection

Prior to the field survey all information or data relevant to the study have been gathered, reviewed and analyzed. The main sources of data and information are:

- Research conducted by Ethio – Djibouti railway corporation
- Previous studies related international documents and
- Other Reports from governmental and nongovernmental organizations.

Field Survey

During the field survey, preliminary site visit, taking measurements and locating/selecting sampling area is taken place consequently. The old track ballast exploration has been carried out with the help of Ethiopian railway corporation right of way personnel.

3.4.6. Preliminary Site Visit

The main objectives of the preliminary site visit were:

- Getting insight and overall picture of the line.
- Assessing the geologic nature and acquire information on the nature of track components.
- Getting insight on the accessibility of the route.
- Acquiring information regarding the level of damage/deterioration of the track
- Visiting previously identified quarry sites.

Field survey had conducted From April 1, 2017 to April 8, 2017, with the guidance of Addis-Awash section from Ethio – Djibouti Railway Corporation right of way personnel and federal police of Ethiopia personnel. During the field visit, it has been toughly considered representative sections for ballast material at different locations.



Fig.3.8. Preliminary Site Visit (within Addis, Awash station)

3.4.6.1. Field Survey for Ballast Site Identification

At this stage a thorough exploration of track ballast condition on the considered section were conducted. Factors considered during field survey for old railway ballast assessment and identification includes:

- Ballast aggregate quality and availability
- Depth and width of ballast section
- Ballast and sleeper interaction
- Fouling condition
- Settlement condition





Fig.3.9. Ballast condition (Kaliti, Adama and Awash Park)

Ballast samples were taken to be tested in the laboratory from different location of the line in order to undertake different tests to evaluate Reusability of the ballast considered.



Fig.3.10. Field investigation and sampling (awash park area, Lagahar station, Wolenchiti quarry site, Metehara area respectively)

As it is shown in the figure above the ballast distributed on the whole section under study is a porous volcanic rock taken from a Wolenchiti quarry site. Previous Studies conducted on line shows that strength of ballast and the track system is not merely affected by its porous nature. Eighteen main samples are taken arbitrarily from different sections which extends from Addis to Awash. Each sample have a minimum gross weight of 30kg. The collected ballast samples were first taken according to different international standards and specified requirements for the laboratory testing.

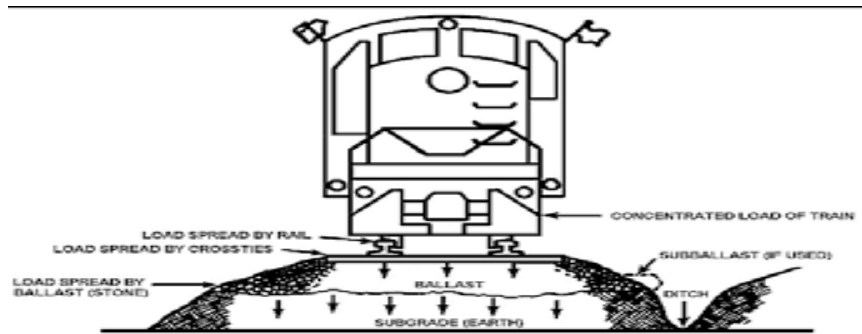


Fig.3.11. function of track structures

3.4.6.2. Track Ballast Condition Assessment

During site investigation, current condition of the line was assessed by using different measuring techniques. Parameters related with Track settlement, geometric deformation, grass and debris cover, removal of track components and loss of ballast were investigated in each extension. For the simplicity of analysis considered extensions are represented by letters A, B and C where A represents the section that extends from Lagahar to Akaki Kaliti B represents the section that extends from Akaki Kaliti to Adama C represents the section that extends from Adama to Awash

3.4.6.3. Major Track and Ballast Defects

Track Settlement;

The settlement of the track was measured by referencing stable track segments which have a minimum length of 100m constant alignment. The stable segment was selected along the side of settled track segment. It is expressed in %age with respect to the length of the whole section. Sample track segments were taken in different extensions along the section and averaged as follow. In each section a minimum of three sample track segments were taken

$$\text{Average \%age} = \frac{\text{sample 1} + \text{sample 2} + \text{sample 3} + \dots}{\text{length of the section considered}} \dots \dots \dots (4)$$

The minimum length of the track segment investigated for track settlement in each sample extension is 145m.

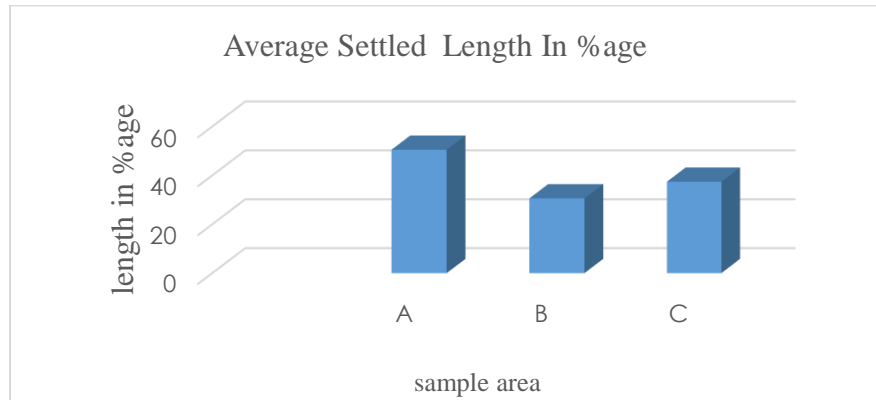


Fig.3.12. Representative Value of track settlement

Ballast fouling with grass and debris;

This is a track defect where grass, soil and debris deposition covers the ballast and sleeper or the whole track system. Grass and debris accumulation on the track system is worst in urban areas exacerbated by the action of inhabitants and urban west.

During the site investigation measurement of those defects is taken by assigning sample track segments as it is designed for track settlement investigation provided above. Special consideration is taken for track blocks in urban areas. All the data is available in Appendix I.

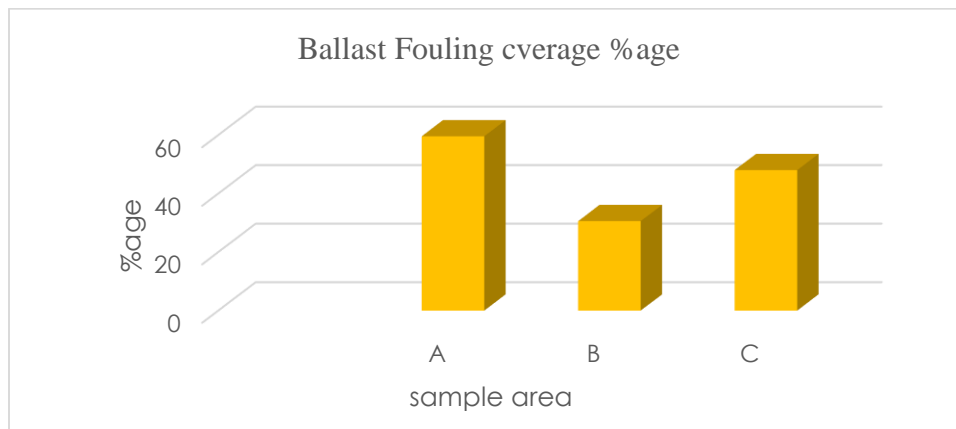


Fig. 3.13. Representative value of track section covered by grass

Track Component Removal;

Due to the demolition and removal of components or the whole track system the service of the system is halted in some sections. Since most components of the system are steel in some parts it is taken by local inhabitants while on other parts it is removed by the action the government. As the case for Grass and debris accumulation demolition and removal is also worsen in urban areas

like Addis Ababa Debre Zeit, Adama and Awash. It also observed around stations and unprotected section in the rural area. During the site investigation sample track segments are selected and averaged to get representative value based on the length of the defect observed is presented in Appendix I.

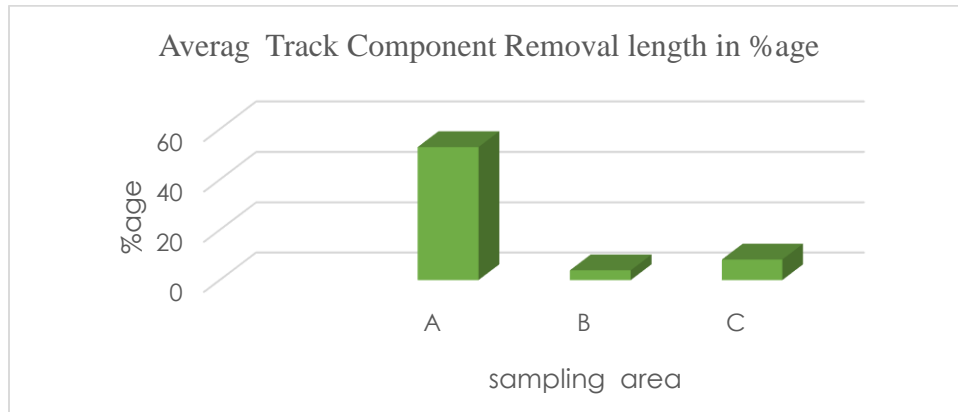


Fig.3.14. Representative Value track component removal

Loss of Ballast;

This is the fundamental defect considered in this study. Since this study is designed to develop thorough investigation on the ballast component of Ethio- Djibouti old rail track ballast, investigation of in situ ballast condition is prior work to be considered.

Removal of the ballast from the track due to human action, erosion due to the absence of proper drainage system and ballast fouling by fine particles are major causes of defects on the ballast and the whole track system. Considerable amount of ballast removal is observed throughout the line while in some track segments it becomes worsen. Especially in urban areas action of the people and urbanization exacerbates this defect while lesser maintenance and water action also have significant effect on it.

The quantity of ballast lost from the track is calculated in terms of volume estimated by referencing the quantity originally available or by considering standard dimensions of metric gauge track ballast.

Total quantity of ballast within the section = volume of shoulder ballast + ballast volume under the sleeper..... (5)

Shoulder ballast volume = $0.5 \times \text{depth of ballast} \times 1 + 0.7 \times \text{depth of the ballast} \times 1 + \text{depth of ballast} \times \text{length of the sleeper} \times 1 - 0.5 \times \text{volume of the sleeper (steel sleeper)}$ (6)

- $0.5 \times \text{depth of ballast} \times 1$ is volume under side slope
- $0.7 \times \text{depth of the ballast} \times 1$ is volume between side slope and the sleeper

- Depth of ballast*length of the sleeper*1 is volume under the sleeper
- 0.5*volume of the sleeper half of the volume of the sleeper which is submerged in the ballast

All volume calculations conducted for metric length of the section

Fouling condition of the ballast is analyzed after appropriate sieve analysis is under taken Appendix I.

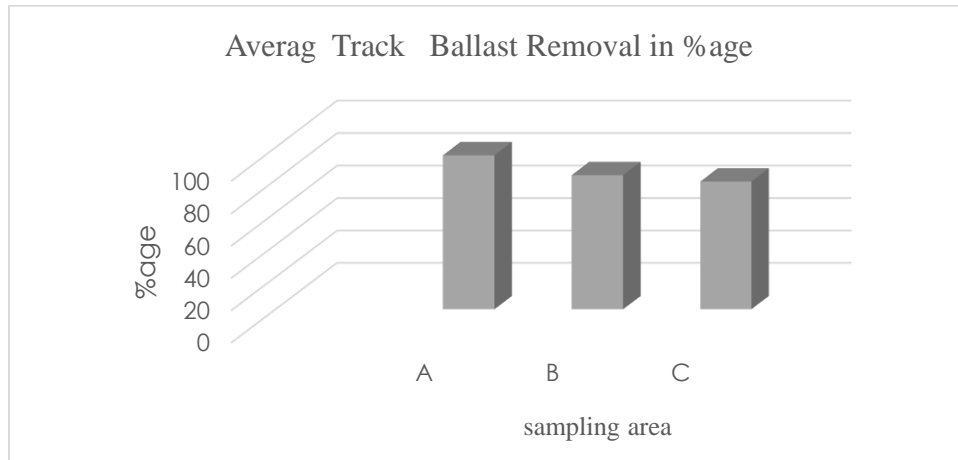


Fig.3.15. Representative Value of track ballast removal

Some stands for the section that extends from Lagahar to Akaki Kaliti

B stands for the section that from extends Akaki Kaliti to Adama

C stands for the section that extends from Adama to Awash

3.4.6.4. Estimated Volume of Ballast before Refinement

Estimation of volume of ballast for this narrow-gauge track system is totally single track except the stations located on different centers. This study specifically underlines and covers the railway section between Lagahar and Awash stations. So only the corresponding volume of ballast available on this section of the line is summarized as bellow:

Average depth under the soffit of sleepers is taken to be 281 mm and the total ballast depth up to top of sleepers is 313mm, which is average value of measured data from different sections.

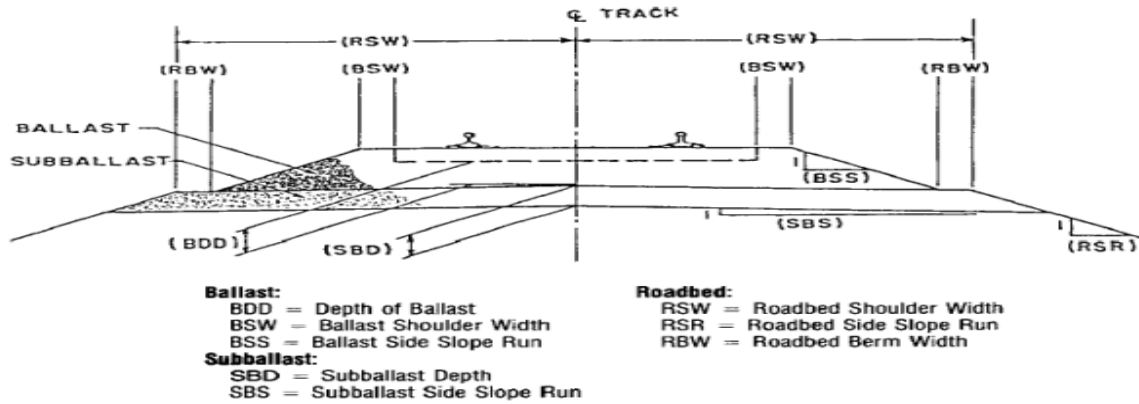


Fig.3.16. typical single rail track substructure AREMA (2009)

During the process of investigation, the line part under consideration is divided in to the following three sections. The division of the line segment is done based on the major stations available on the track line.

- A-----Lagahar to Akaki Kaliti -----32km
- B-----Akaki to Adama -----97km
- C-----Adama to Awash -----128km

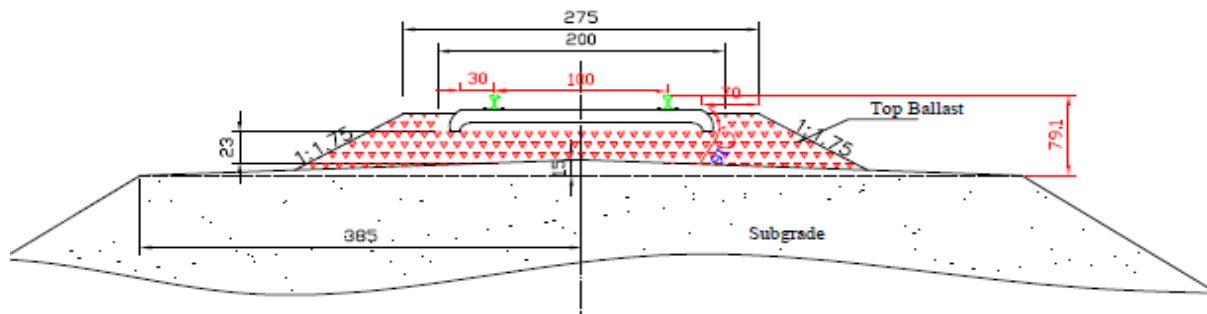


Fig.3.17. Standard cross sectional view of metric gauge railway track

All the dimensions on the above figure are average value on considered sections

Estimated Volume on Each Section;

In addition to the typical section shown above the following results have been developed to estimate volume of ballast.

Table 3.3. Detail of volume analysis

No.	criteria	Section Location					Average
		Awash - Adama		Adama - Akaki		Akaki - Lagahar	
		urban	rural	urban	rural	urban	
1	track gauge	1.00m					
2	sleeper length	1.75m					
3	ballast shoulder width	0.65	0.78	0.53	0.75	0.55	0.652
4	ballast side slope	1:1.25	1:1.75	1:1.25	1:1.75	1:1	0
5	ballast top width	3.35	3.61	3.11	3.55	3.15	3.354
6	ballast bottom width	6.47	7.33	6.83	7.27	6.87	6.954
7	depth of ballast	0.26	0.36	0.27	0.38	0.13	0.28
8	volume of sleeper	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216
9	volume of ballast per meter	1.23	1.93	1.30	2.01	0.61	1.42

- The track gage is taken to be 1.00m (metric gage (AREMA, 2009))
- The measured sleeper length is approximated to 1.75 m.
- Volume occupied by the sleepers per meter of track is calculated by using length of sleeper *thickness*width of the sleeper
- Volume of ballast per meter of track by using all parameters including top ballast width, bottom ballast width and the volume of the sleeper
- All the value listed in the table are taken by averaging three sample trenches or pits taken from each section





Fig.3.18. Depth of ballast on awash, Adama and Lagahar respectively

Considering additional 10% from passing loop, depots and station ballast available, the total volume of ballast becomes

$$\text{Awash – Adama section Rural} = 120,000\text{m} \times 1.23\text{m}^3/\text{m} = 2.31 \times 10^5 \text{ m}^3$$

$$\text{Urban} = 8021\text{m} \times 1.93\text{m}^3/\text{m} = 9.89 \times 10^3 \text{ m}^3$$

$$\text{Adama – Addis section Rural} = 91000\text{m} \times 1.29 \text{ m}^3/\text{m} = 1.83 \times 10^5 \text{ m}^3$$

$$\text{Urban} = 6000\text{m} \times 2.01 \text{ m}^3/\text{m} = 7.79 \times 10^3 \text{ m}^3$$

$$\text{Akaki - Lagahar section Rural} = 0 \text{ m}^3$$

$$\text{Urban} = 32000\text{m} \times 0.61\text{m}^3/\text{m} = 1.95 \times 10^4 \text{ m}^3$$

Estimated available volume of recyclable ballast in each section

$$\text{Lagahar to Akaki Kaliti} = 19459.2 = 1.95 \times 10^4 \text{ m}^3$$

$$\text{Akaki to Adama} = 190938.8 = 1.91 \times 10^5 \text{ m}^3$$

$$\text{Adama to Awash} = 241013.1 = 2.41 \times 10^5 \text{ m}^3$$

Based on the result of above analysis gross volume that can be recycled and reused is calculated as:

$$\text{Total estimated recyclable ballast} = 19459.2 \text{ m}^3 + 190938.8 \text{ m}^3 + 241013.1 \text{ m}^3 = 451,411.1 \text{ m}^3 = 4.51 \times 10^5 \text{ m}^3$$

$$\text{Volume of ballast for 1m track} = 2.75\text{m} \times 0.791\text{m} \times 1\text{m} + 2 \times 0.791\text{m} \times 0.5 \times 1.384\text{m} = \mathbf{3.2699\text{m}^3}$$

Therefore, from considered section of Ethio –Djibouti old railway track (Addis (Lagahar) to awash stations) a gross volume of about $4.51 \times 10^5 \text{ m}^3$ is available. Estimated volume to be reduced from the above value includes, sleeper volume, bridge sections, level crossings and passing loops, signaling and light systems including contingency is estimated to be 20%. So, the total volume of ballast required for the total length of the section from Addis to Awassh is estimated to be;

Total volume needed = $257,000\text{m} * 3.27\text{m}^3/\text{m} = 840,390\text{m}^3$

The gross amount of ballast after reducing 20% of discontinuities on the track system becomes $672,312\text{ m}^3 = 6.72 * 10^5\text{ m}^3$

$451,411.1\text{ m}^3 / 672,312\text{ m}^3 * 100 = 67.14\%$

So, from this analysis available reusable amount of ballast on the track system from the total amount required is **67.14%**.

$100\% - 67.14\% = -32.86\%$

The deficiency or lose of ballast from the total requirement for the maintenance action of this line segment **32.89%** of more ballast is needed. The amount of ballast required for the whole track section is estimated by calculating the volume of ballast needed for a metric gauge track system.

Estimated volume of refined and usable ballast

Based on the simple inspection during site assessment the following amount of pure ballast is produced. During the process of refining the manual techniques were supplemented with manpower and non-mechanical equipment.

Table 3.4. Volume estimation of usable ballast

Sample area	Site location	Sample collected (m ³)	Length for sampling (m)	Sample after washing and screening (m ³)	Estimated Total quantity (m ³)	Refined quantity (m ³)	%age value
A	Rural	3	0	0	0	0	0
	Urban	3	4.93	1.46	19459.2	9470.14	48.67
B	Rural	3	1.49	2.58	183146.6	157506.08	86.00
	Urban	3	2.31	2.12	7792.2	5506.488	70.67
C	Rural	3	1.56	2.83	231120	218023.2	94.33
	Urban	3	2.43	1.94	9893.1	6397.54	64.67
Total		18	12.72	10.93	451411.10	396903.45	87.92

Estimated Total volume of ballast that can be produced from **Addis to Awash** is **396,903.45m³ = 4.00*10⁵m³**.

%age of refined ballast with respect to total required ballast for the considered track section $396903.45 / 672,312 = 59.03\%$

%age of refined ballast with respect to the available ballast on the considered track $396903.45 / 451411.10 * 100 = 87.92\%$

3.4.7. Ballast Quality Test and characterization

3.4.7.1. Sample Collection and Laboratory Test Procedures

Data Collection;

During the data collection stage, available and valuable data had been assessed and gathered by using appropriate methods and techniques. Supporting materials and assessment results had been incorporated during site investigation and laboratory work. Samples are collected from totally different three segment of the line. Representative sample with appropriate size and quality had been gathered manually by using hand tools for trenching and pit digging. Condition and geometric measurements had been taken during site assessment numerically by using different measurement techniques. Depth and width of the segment or area and track geometry had been measured and quantified by using different measurement techniques. Collected data had been tabulated in appropriate format for further analysis and to be used as input for lab and DEM analysis. All the sample collected for laboratory test is conducted by using trenches and pits from specific sites selected on the track.

Sample Size;

Based on different specification and standards the size of the sample to be collected for laboratory work to characterize the ballast had been done based on the requirement each testing techniques consume. More than seven lab tests had been conducted to put appropriate characterizing parameters for this ballast. Basically, the selection of lab testing had been done based on availability of testing facility in AAiT. Size of the sample collected is as per different countries standard and specifications like AREMA, ASTM, and Italferr code of standards.

Based on the specified techniques, procedure and sample size detail site investigation and sampling have been take place. Desk study, secondary data collection, field survey, preliminary site visit, track condition assessment identification and Sample collection were taken place. Representative sample was taken to their respected laboratories from the specified track site. All the graphs provided below are developed based on the analyses result tabulated in Appendix II.

Gradation Result;

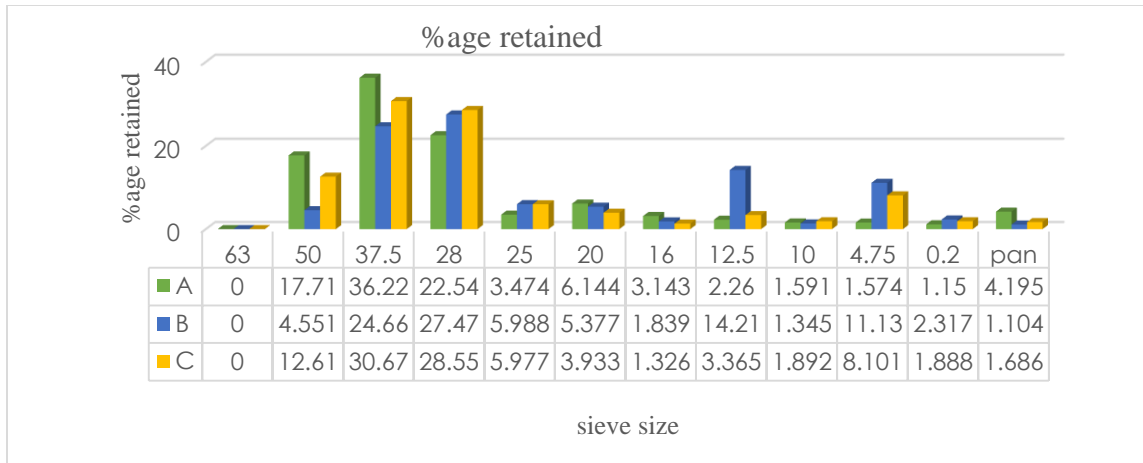


Fig. 3.19. Graph of ballast gradation %age retained

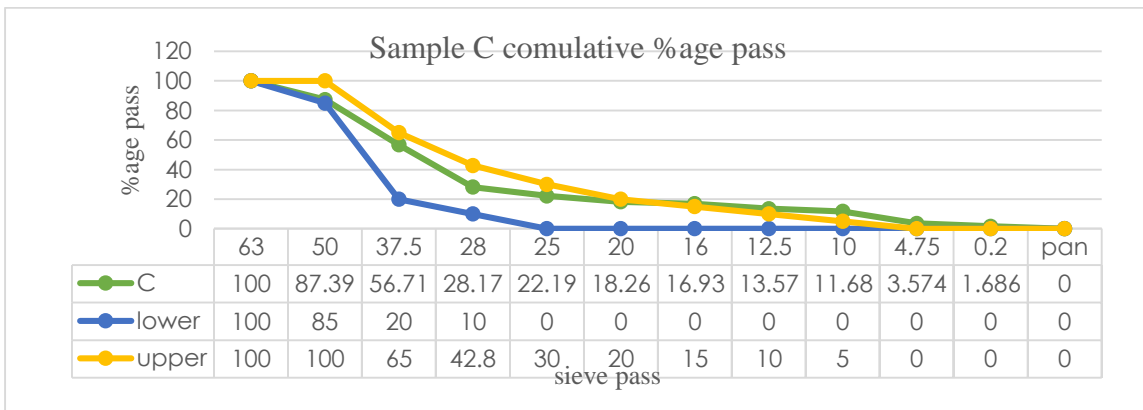


Fig. 3.20. Graph of sample C ballast gradation commutative %age passed

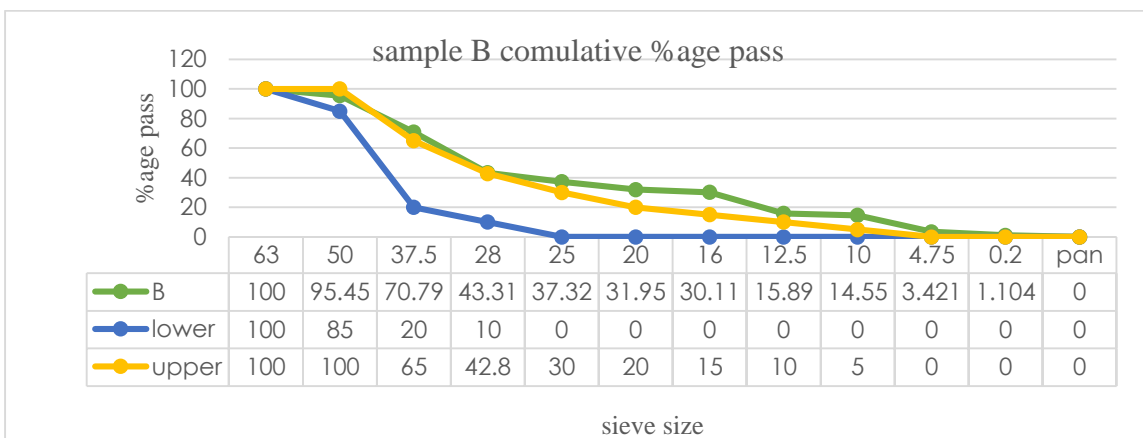


Fig. 3.21. Graph of sample B ballast gradation commutative %age passed

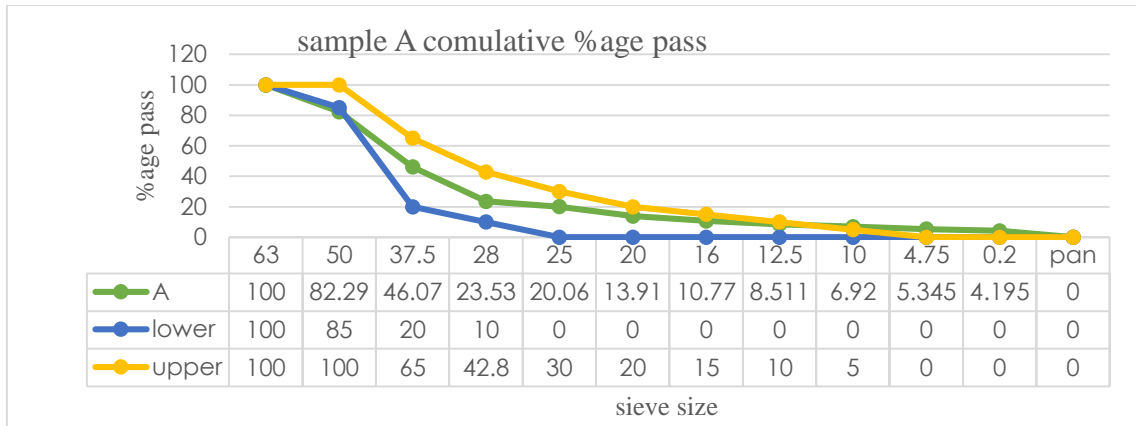


Fig. 3.22. Graph of sample A ballast gradation commutative %age passed

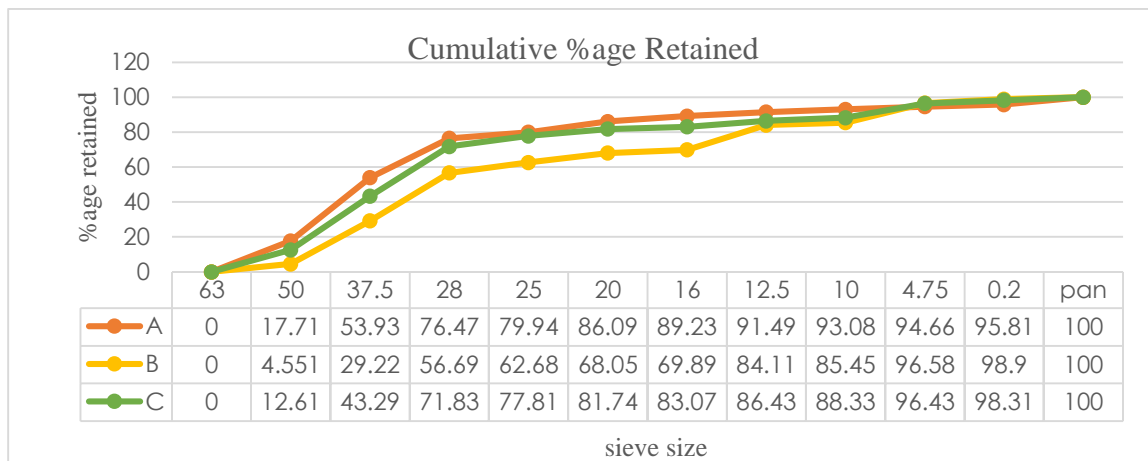


Fig. 3.23. Graph of Sample A, B and C ballast gradation commutative %age retained

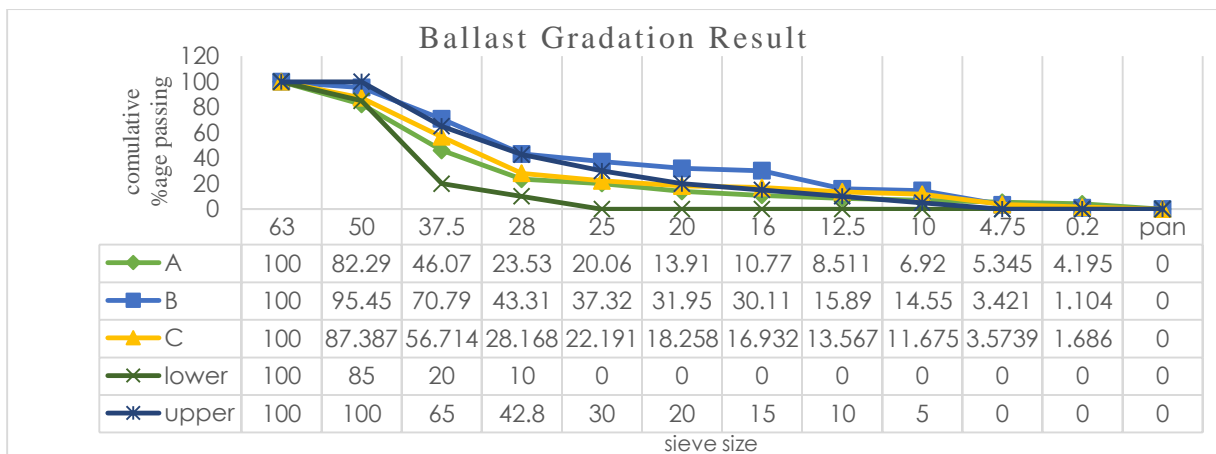


Fig. 3.24. Graph of sample A, B and C ballast gradation commutative %age passed

All the above charts are resulted from the gradation conducted on the sample taken from three selected sampling sites as explained above. Depending on this chart available amount of recyclable ballast from Ethio-Djibouti old rail track within the aggregate gradation standards (10-65mm) is evaluated. Fouling content of the ballast also deduced based on the value of this analysis. Based on the cumulative percentage passing chart provided above these ballast uniformity coefficients indicates that mostly uniformly graded which fulfills the requirement of the three international standards. All charts developed above are by considering upper and lower gradation limiting values from different standards provided above. Depending on these values all the results fall within the limits which indicates that most parts of this ballast is reusable.

Flakiness and Elongation of the Ballast;

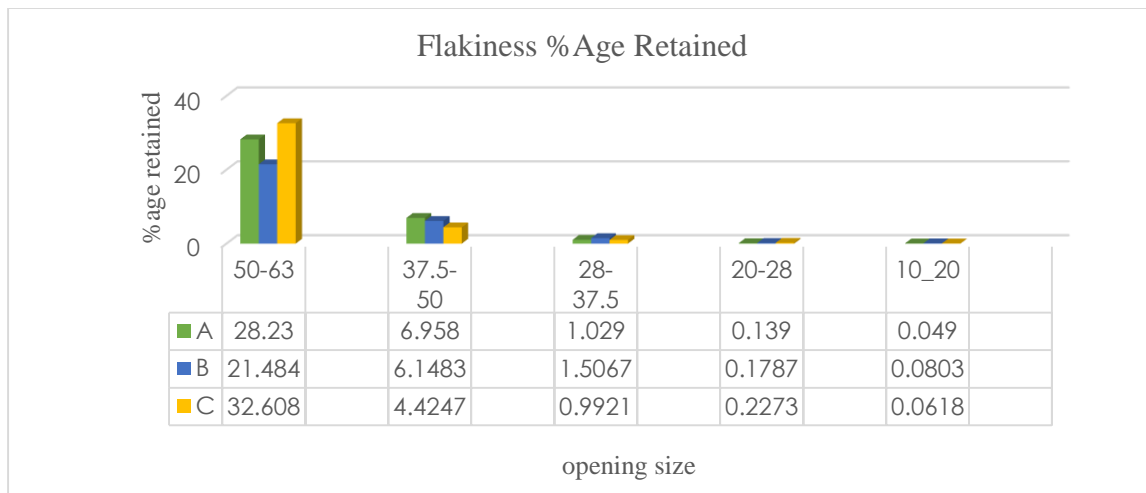


Fig. 3.25. Graph of sample A, B and C ballast flakiness %age retained

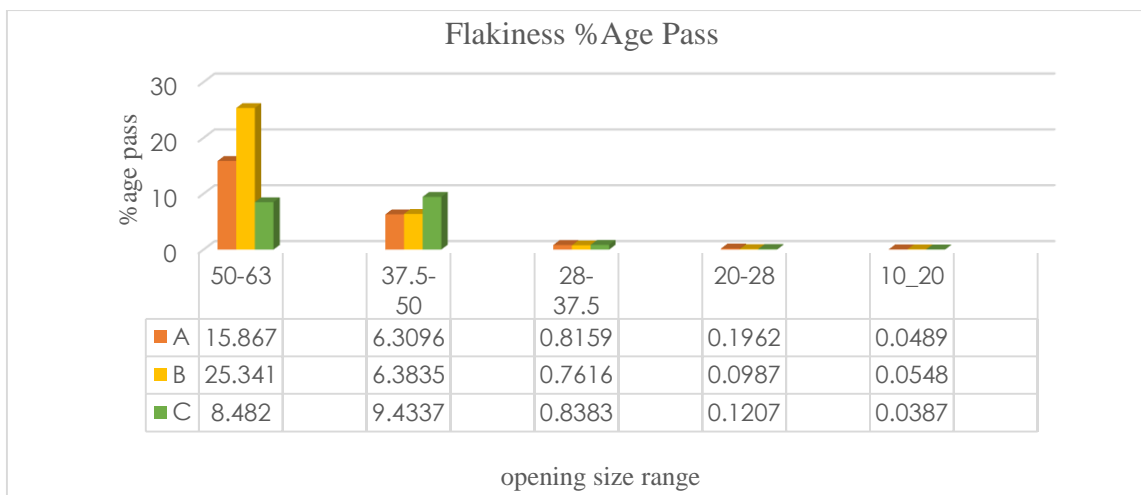


Fig. 3.26. Graph of sample A, B and C ballast flakiness %age passed

Elongation

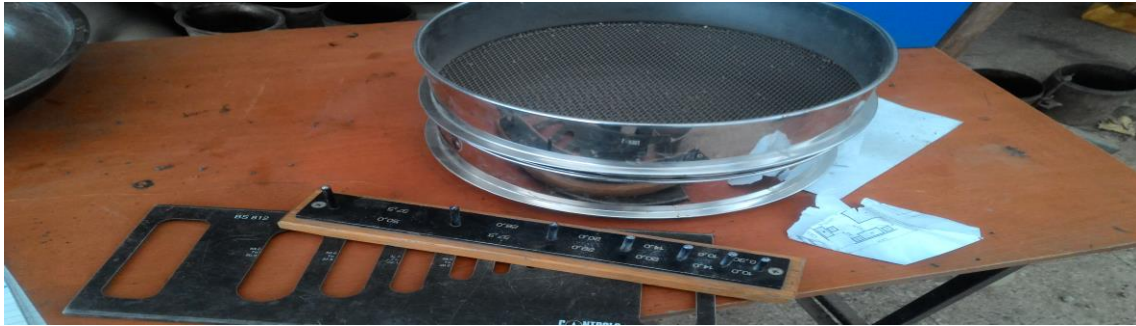


Fig. 3.27. AAiT laboratory materials (sieve, elongation and flakiness measuring tools)

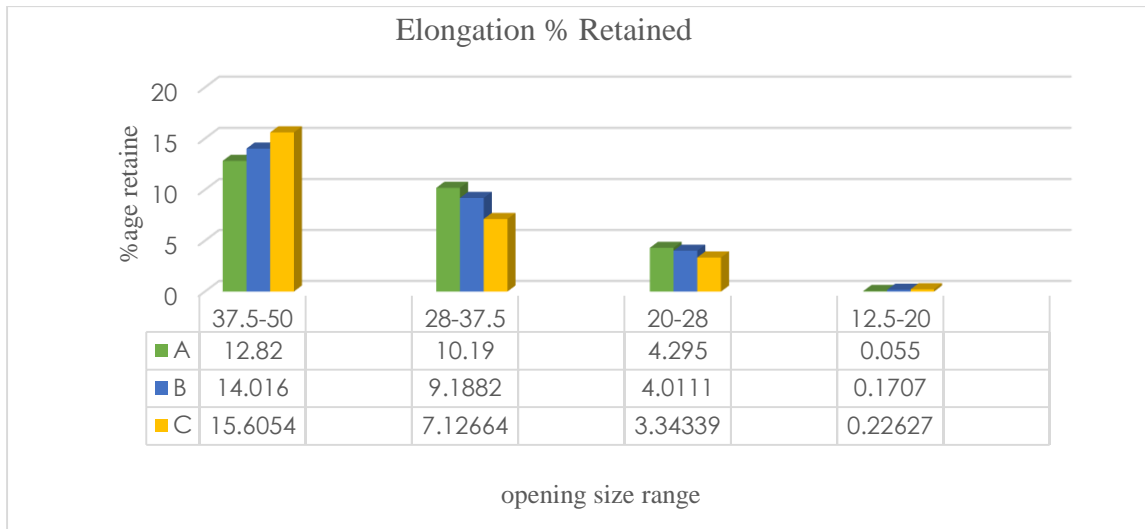


Fig. 3.28. Graph of sample A, B and C ballast elongation %age retained

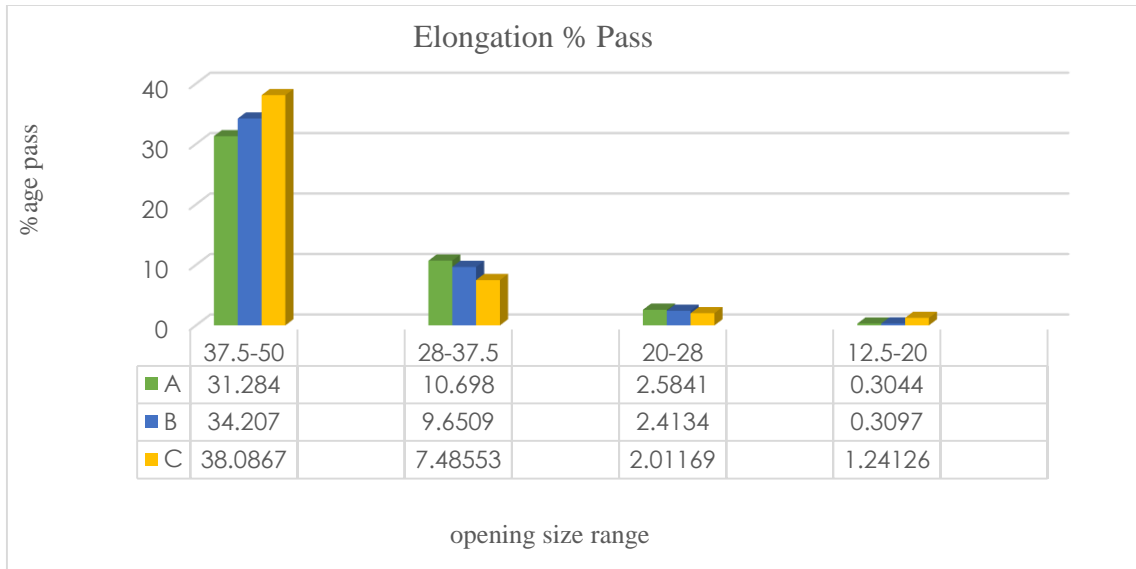


Fig. 3.29. Graph of sample A, B and C ballast elongation %age passed

Flakiness and elongation values of Ethio-Djibouti railway track ballast from the sample taken shows that it falls out of the limiting values of the standards provided above. The reason behind this result is that the source of this ballast is mostly natural volcanic gravel. It is not mechanically crushed aggregate.

Ballast aggregate crushing value (ACV);

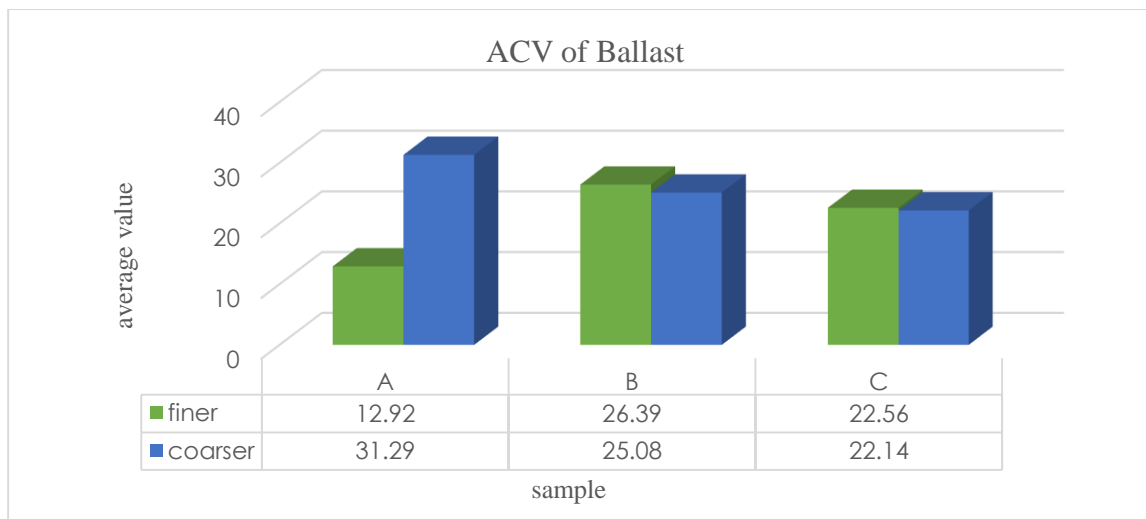


Fig. 3.30. Graph of sample A, B and C ballast ACV average %age value

Ballast aggregate LAA value;

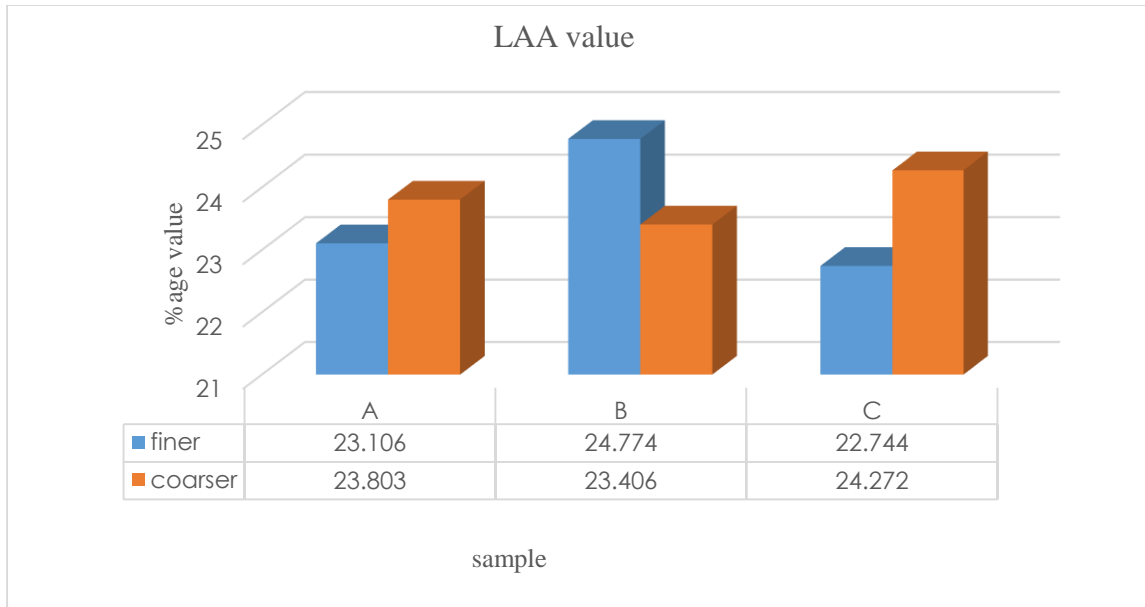


Fig. 3.31. Graph of sample A, B and C ballast LAA average %age value

The chart developed above for the two lab tests (ACV and LAA) are based on the principle of aggregate durability evaluation. Depending on the result of these tests the quality of the ballast aggregate considered fulfills the limiting value of the three standards shown above. As it is clearly shown from the chart finer samples are 10-12.5mm and coarser materials taken are 24-37.5mm gradation value. Both test results conducted on finer and coarser fall on the standard limiting value which shows that durability of this ballast is well for further recycling.



Fig. 3.32. AAiT crushing value and impact value testing machines for aggregate durability test



Fig. 3.33. Old track ballast during crushing and sieving

Impact value;

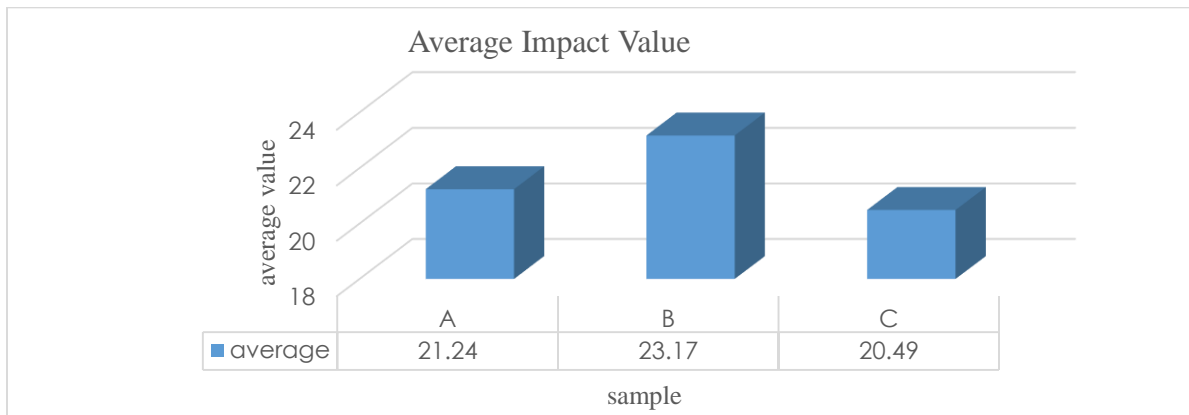


Fig. 3.34. Graph of sample A, B and C ballast aggregate impact value average in %age

This test is also conducted in order to check its durability. Based on the result of this test the durability of this ballast is within the limit of the three standards shown above.

Fouling content;

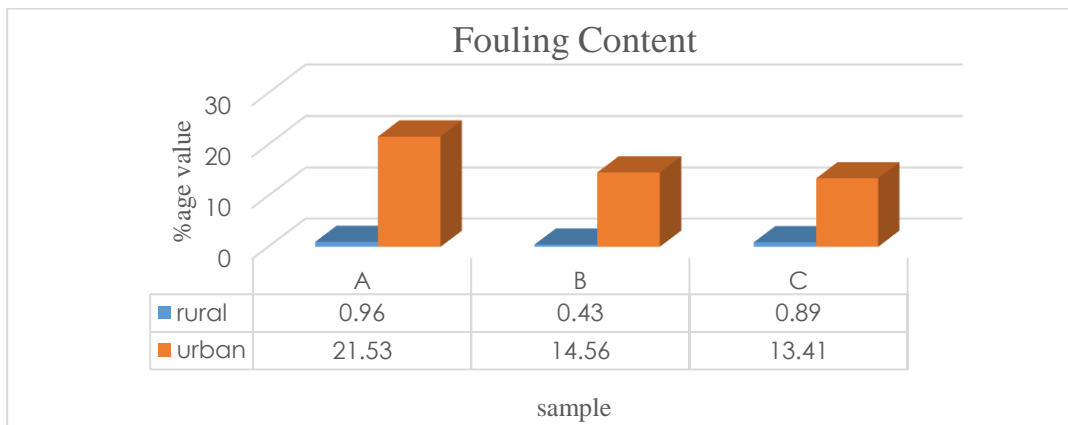


Fig. 3.35. Graph of sample A, B and C ballast fouling content

As it is shown from the chart above fouling content of the ballast is hugely dependent on the physical location of the track section. The ballast on the track of most urban centers is seriously fouled while fouling content of rural area track section ballast is minimum. Depending on this test result it is concluded that most reusable portion of the track ballast is found on rural sections. Considerable amount of ballast in urban areas along this track line is fouled due to the action of urban community and problem on system of drainage. The length of the track that passes through urban area is far shorter than the rural track length. So effect of fouling on urban track ballast insignificant on the characterization of the whole track ballast.

Specific gravity and water absorption;

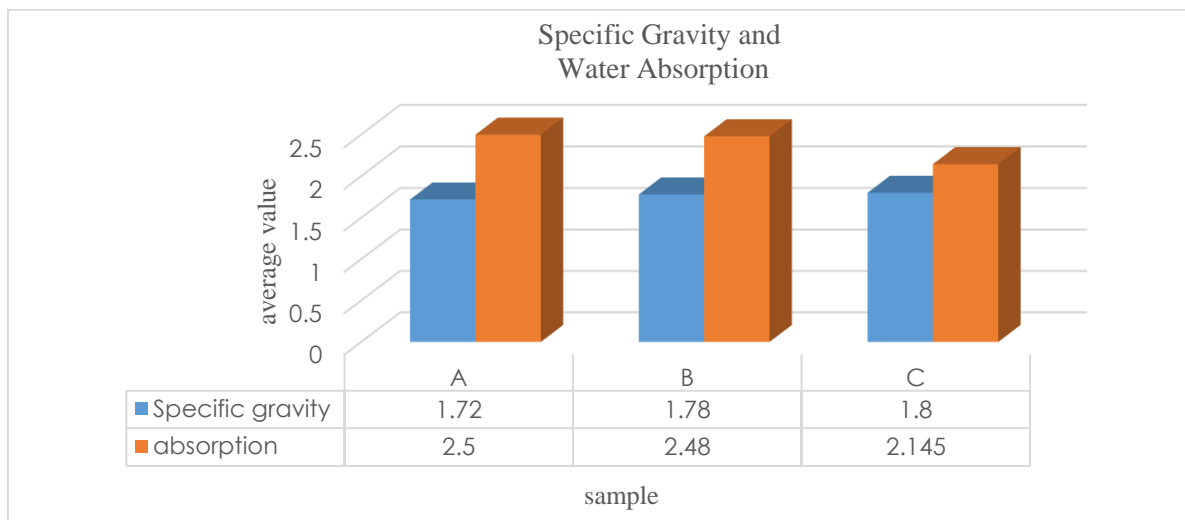


Fig. 3.36. Graph of sample A, B and C ballast specific gravity and water absorption value

Unit weight;

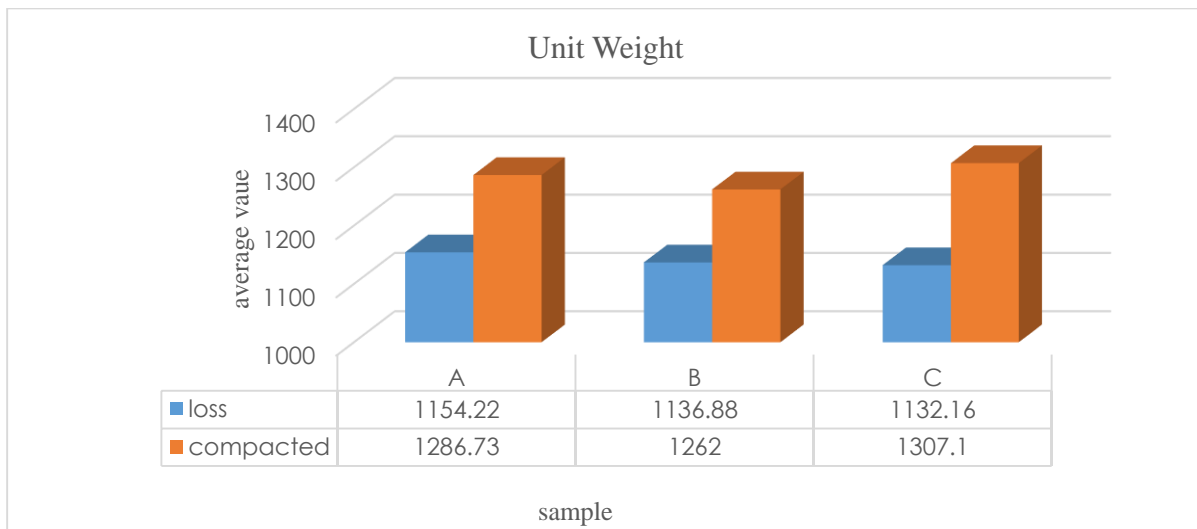


Fig. 3.37. Graph of sample A, B and C ballast unit weight value

3.4.7.2. Summary of Laboratory test Result

In order to reach a solid deduction on the geo-mechanical property of Ethio-Djibouti old track ballast a figurative and significant lab tests are conducted. Based on those lab tests on the selected sample ballast material realistic results are obtained which can be taken as input for further investigation and to work on the recycling process. Based on the result of laboratory tests conducted above, evaluation of characteristics of these track ballast with respect to the above listed three standards is provided in the following table.

Table 3.5. Summary of lab test result w.r.t. the three standards

Parameter	Test Result			Permissible value								
				ASTM			AREMA			ETALFER		
Sample type	A	B	C	A	B	C	A	B	C	A	B	C
Density	1788.55	1799	1685.6	√	√	√	√	√	√	√	√	√
LA Abrasion	23.80%	23.41%	24.27%	√	√	√	√	√	√	√	√	√
	23.11%	24.77%	22.74%	√	√	√	√	√	√	√	√	√
Crushing resistance	12.92%	26.39%	22.56%	√	X	√	√	√	√	√	√	√
	31.29%	25.08%	22.14%	X	√	√	√	√	√	√	√	√
Aggregate impact value	21.24%	23.17%	20.49%	√	√	√	√	√	√	√	√	√
Water absorption value	2.5%	2.48%	2.15%	√	√	√	√	√	X	√	√	√
bulk Sg	1.72	1.78	1.8	√	√	√						

As shown in the above table lab test results conducted on Ethio-Djibouti old rail track from selected sites confirms that; gradation of most samples is on the required range the three standards. The type of rock used as a ballast is mostly a natural gravel created by volcanic eruption in Afar region. It is capable of withstanding compression and impact loads as impact and crushing value test results affirmed. Failed results like porosity (water absorption and density), elongation and flakiness are due to this reason that can be mitigated by blending with freshly produced. Most of its density and water absorption result also in the range all listed standards are acquired. Due to unavailability of basic testing facilities tests related with roughness are not included in these result. But from the result of the research conducted by Italferr the porous nature of the volcanic rock is

pronounced as an advantage which provides a potential of shear capacity and lateral stability for the whole track system.

Based on the site investigation and laboratory test conducted above most parts of old rail track of Ethiopia fails mainly due to the following ballast failure mechanisms while other factors also have their own contribution.

- ✓ Fouling
 - Crushing
 - Overloading
 - Windborne and societies action
- ✓ mechanical maintenance (Machine and manual tamping) and longtime use
- ✓ Abrasion
 - dynamic track and static movement under train traffic

Degradation due to: creation of fines ingress of fines from above (Spillage from trains, windborne material) ingress of vegetable matter ingress of material from the formation and absence of proper ballast and track structures maintenance.

CHAPTER FOUR

4. Cost-Benefit Evaluation of Recycled Ballast

4.1. Cost Evaluation and Comparisons

Fundamental objective of this study is to evaluate economic advantage of recycling Ethio- Djibouti old railway ballast. By assessing the track structural composition and ballast material geo-mechanical properties. Its economic feasibility analysis and general comment on the selected sections and developing estimation of the track condition for the remaining sections of the line is assessed. Mainly the process of recycling is dependent on the following criteria and factors;

- Particle size and level of deterioration
- Machine and Human power requirement
- Volume of valuable quantity
- Accessibility
- Comparative economic out put
- Economic factors

Basic economic evaluation of cost breakdown is studied for a recycling process and production of new ballast from quarry sites. In order to prefer better of the two, basic comparison parameters are selected in terms of cost and benefit. Basically selected comparison parameters used in this economic evaluation are;

1. Availability of the resource
2. Cost of production
3. Time of production
4. Availability of machineries like crushing plants, cleaning machineries and hauling requirement
5. Operational costs like man power and fuel

In developing this economic analysis cost estimation is conducted based on the cost of old railway track rehabilitation instead of considering construction of new track project. The comparison is estimated based on different international experiences and feasibility studies of track rehabilitation costs.

4.2. Alternative 1, Economic Evaluation of Recycling Old Rail Track Ballast

To reduce the cost of transportation and mobilization there is variety of machineries that can refine fouled ballast in situ. These machineries are much advanced and cost effective as they are practiced by many countries and proved their efficiency. In order to increase their efficiency manufactures are always adding different values and assembling more advanced parts. Single machine with 1-10 operators can recycle and rehabilitate more than 50 tone of ballast aggregate within a day. This self-propelled machineries are assembled with

- Sleeper and rail lifting and correcting structures,
- Ballast hopper to store and carry up to 15m³ ballast,
- Power full ballast management system,
- Shoulder profiling and surplus ballast draw up machine
- high ballast saving and wastage reduction devices,
- Surface cleaning and dust removing equipment's,
- Ballast distributing device,
- Ballast screening sieve,
- Washing and drying accessories and
- Mixing or blending equipment's

Machines provided by Plasser and Theurer are characterized by

- ✓ The RM 80 ballast cleaning machine, which is features a single screening unit with a screen surface of 30m², that offers a cleaning output of 550-500m³/h
- ✓ Ballast cleaning machines with double screening units such as the RM801, RM900 and RM2002 have a screen surface of 2x23m and offer a cleaning output of 1000m³/h
- ✓ RM860 ballast cleaning machine, which features a double screening unit with a screen surface of 2x25m² offers a cleaning output of 1000-1200m³/h



Fig. 4.1. Ballast cleaning machine, together with material conveyor and hopper (MFS)

Based on the specification provided by different manufactures, it is possible to rehabilitate 50-150km single track ballast within a year which depends on the accessibility, duration of work per day, fouling condition and level of deterioration of the track and the ballast. The only problem

related with such advanced technologies is initial cost acquired by the producer. It is skilled manpower and capital dependent to own and lease.



Fig. 4.2 Self-propelled ballast recycling machine

Total volume of recycled and reusable quantity of ballast can be estimated in two or more ways. For example;

- Calculating refined quantity of ballast that can be used as fresh ballast by itself without blending with other fresh ballast
- Calculating refined ballast quantity that can be used by blending with fresh ballast
- Calculating refined ballast quantity that can be used as sub-ballast material which can fulfill sub-ballast material requirements

Amount of track ballast available is estimated in chapter three that is $4.51 \cdot 10^5 \text{ m}^3$ on the track which can be cleaned recycled and produce $4.00 \cdot 10^5 \text{ m}^3$.

By considering this quantity analysis of the cost of recycling and redistributing is calculated as follow in terms of the above basic evaluation parameters. Economic evaluation is basically featured and analyzed based on the requirement of machineries and accessibility for the track with the following characteristics:

- Cost for fuel (call and petroleum) consumption of the mobile cleaning train per km per $\text{m}^3 = 1250 \text{ Birr}$
- Rental and adaptation Cost for of mobile cleaner (refiner) machine per machine (birr) = 175million Birr
- Cost of manpower (birr) = 10 million Birr
- 235 km single track line and more than 75km station tracks (passing points on different centers)
- Metric track gauge

- Continuously welded rail
- Line speed max 60km/h
- Axle load 20-25t
- General cost of time and mobilization = 105.5million Birr

Ballast cleaning off the entire 235 track line and 35km station track should be completed within 3 years period thus requiring an annual cleaning output of 100km of plain track and 12km of station track. The spoil should be removed simultaneously from the track corridor.

Due to the climatic condition (rainy season) work can only be performed for ten months in a year. 2.273km of plain track needs to be cleaned in a week. Since seven working days are available per a week, a daily output of at least 325m plain track and 500m station track should be cleaned in a week. For the cleaned track sections the track geometry corrections spread over a two year cycle (Plasser and Theurer report 2015).

Table 4.1. Three different ballast cleaning technologies cleaning capacity

Ballast cleaning technologies		1	2	3
Output		Average	High	Very high
Ballast cleaning machine without consolidation unit		RM 76 (195 m/h)	RM 80 (230 m/h)	RM 2002 (350 m/h)
MFS units continuously transport the spoil for disposal		MFS 100 (68m ³ , approx. 100t)		
Supply of new ballast using self-discharging ballast wagons		Ballast wagon (54m ³ , approx. 80t)		
1 st mechanized maintenance train (MDZ 1)	Tamping machine	09-32	09-32	09-3X
	Ballast regulating machine	SSP 203	SSP 203	SSSP 110
	Dynamic track stabilizer	DTS 62N		
2 nd mechanized maintenance train (MDZ 2)	Tamping machine	09-32	09-3X	09-3X
	Ballast regulating machine	SSP 203	SSP 110	SSSP 110
	Dynamic track stabilizer	DTS 62N		

Each technologies are assembled with ballast cleaning machine, MFS units to spoil removal, self-discharging ballast wagons for new ballast supply, mechanized maintenance train (MDZ), tamping machine, ballast profiling machine and dynamic track stabilizer to correct the track geometry with simultaneous consolidation and stabilization of track (URM 700. 2015).

Cost of ballast cleaning depends on;

- The possession of the site with respect to the two end stations for spoil hauling
- The track condition
- Condition of the cleaning machine

- No of material conveyer and hopper on the machine (MFS units)
- Length of track section under cleaning
- The travel time required which includes the time required reach to the work site, setting up of working units, the work itself, departure time from working site and checking up of working units condition.
- Availability of fresh or new ballast for blending

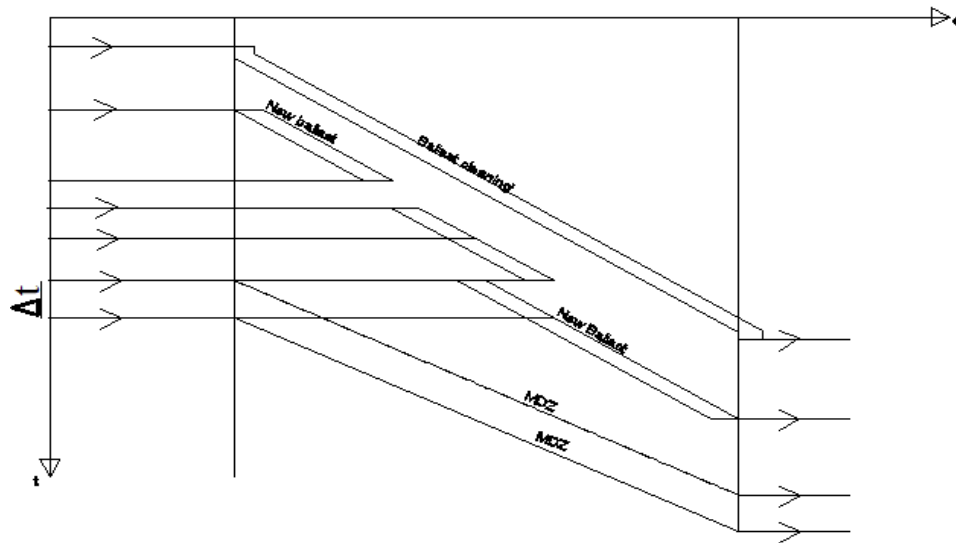


Fig.4.3. Influence of the No. of ballast wagons during ballast cleaning,

Ballast transport on the starting time of subsequent working process

Estimated total cost of recycling Ethio-Djibouti legacy railway track ballast is calculated as follows;

Cost For Integrated Cleaning Mobile Machine and Accessories (Birr)

Leasing cost of refining and recycling plant by choosing the first machine from the three Plasser & Theurer machines explained above; assuming a capacity of $15\text{m}^3/\text{minute}$ - $25\text{ m}^3/\text{minute}$ main machine: ballast aggregate feeder, mixer, washer, loader and tamper, vibrating screen, belt conveyor, motor, control panel etc. and spare parts for common wearing parts for 1 year with consulting one mechanical engineer excluding transportation cost is 802,233 USD (17,589,200Birr/year) (from Plasser and Theurer manufacturing specification). **Cost for Fuel**

Consumption of the Integrated Cleaning Mobile Machine per Km per m^3

The amount of liters a mobile refiner train consumes is calculated per unit of energy the train engine operates; 1 liter per 3.15 units of energy operated. On other hand it also depends on the

speed of the train pulling the rolling stock; 60 liters per km for 100 km/hr. and to 45 liters per km for 15km/hr.

Generally speaking, in field experience the amount of liters the diesel engine consumes ranges between 0.3km/hr-5 km/hr.

The volume of ballast that can be cleaned by average size mobile refiner is 15m³ per minute as per the specification of Pleaser & Theurer. So the time required in order for refining the total volume of ballast available on Addis – Awash section of Ethio-Djibouti old railway track estimated above is calculated as follow.

Max speed of average mobile refiner = $(325+500)/8\text{m/h} = 103.125\text{m/h} = \mathbf{0.103\text{km/h}}$.

Daily working hour is taken 8h

So the total amount of fuel required for single cleaning machine to finish the total 235km plain track and 35 station track = $(235+35) \text{ km} * 1000\text{m/km} = 270000\text{m}$

0.0618 liters of fuel per km for 0.103km/h is required. From the total fuel required is estimated to be;

$270\text{km} * 61.8\text{litters/km} = 16,686\text{litters}$

Cost of fuel = $16,686\text{litters} * 20.1\text{birr/litter} = \mathbf{335,388.6\text{birr}}$

For estimation error, fuel wastage during operation and machine maintenance and time dependent cost fluctuation 15% contingency additional money is recommended

Total fuel cost including contingency = $0.15 * 335,388.6 + 335388.6 = \mathbf{385,696.89 \text{ birr}}$

For spoil transportation

- ✓ The production plant site shares equal range of work of spreading volume within the railroad section; 270 km.
- ✓ The diesel train used to transport the ballast material is assumed to have twenty haulage rolling stock; with each of 20 m³ capacity.
- ✓ The train consumes 10 liters/ km as considered above.
- ✓ 2.62 m³/m volumes of ballast and sub ballast is required for the track section as calculated in the volume calculation.

Train capacity = $20 \text{ m}^3 * 20 \text{ rolling stock} = 400 \text{ m}^3$

One trip coverage = $400 \text{ m}^3 / 2.62 \text{ m}^3/\text{m} = 152.67 \text{ m}$

Trip = $30000\text{m} / 152.67 \text{ m} = 19.65\text{trips}$

Km coverage = $(152.67)^1 \sum_{k=1}^{20} (1 + 2 + 3 + \dots + n) = 78,920.299\text{m}$

In order to execute 270km long track it needs 9 spoil pilling sites. Assuming the trip coverage is the same for all spoil pilling site the total track trip covers

$$9 * 78,920.299m = 710282.691m$$

So, since fuel cost for 1km is 1250birr, it is **887,853.394birr** is required for the total trip

$$\text{Total fuel cost} = 887,853.394\text{birr} + 385,696.89 \text{ birr} = \mathbf{1,273,550.25\text{birr}}$$

Cost for blending ballast production

$$\text{Required fresh ballast is } 672,312 \text{ m}^3 - 396,903.45\text{m}^3 = 273,408.55 \text{ m}^3$$

It is 49% of the total ballast required for the whole 257km track line.

$$\text{Hauling Distance; single trip in Km (G)} = 4.3 \text{ Km}$$

$$\text{Production; Time for one trip in Hr. /trip (L)} = ((2 * G / K) + D) = 0.42$$

$$\text{Fuel Cost; Fuel consumption in Lit/trip (H)} = 2 * G / B = 5.73$$

$$\text{Fuel consumption in Lit/m}^3 \text{ (I)} = H / E = 0.41$$

$$\text{Fuel consumption rate in Birr/m}^3 \text{ (J)} = I * C = 8.12$$

$$\text{No. of trip per hour in Trip/hr. (M)} = 1 / L = 2.38$$

$$\text{Volume per hour in m}^3 \text{ /hr. (N)} = E * M = 33.36$$

$$\text{Birr per Volume in Birr/m}^3 \text{ (O)} = A / N = 10.49$$

$$\text{Total rate with fuel; Total rate per volume in Birr/m}^3 \text{ (P)} = O + J = 20.45$$

$$\text{Total rate per kilometer per volume in Birr/Km/m}^3 \text{ (Q)} = P / G = 4.76$$

Basic assumptions are provided in Table 4.2. Below.

$$\text{Available Volume for the whole stretch} = 3.27 \text{ m}^3/\text{m} * 257000 \text{ m} - 0.2 * 3.27 \text{ m}^3/\text{m} * 257000 \text{ m} = \mathbf{672,312 \text{ m}^3}$$

$$\text{Total required Volume for the blending material} = 40\% * 672,312 \text{ m}^3 + (304435\text{m}^3 - 120,819\text{m}^3) = 268,924.8 \text{ m}^3 + 183,606 \text{ m}^3 = \mathbf{452,530.8 \text{ m}^3}$$
 of blending material.

$$\text{Cost for transporting blending material for 4.3km} = 4.76\text{birr/km/m}^3 * 4.3\text{km} * 452,530.8\text{m}^3 = \mathbf{9,262,400.4\text{birr}}$$

Transportation cost for deficiency of ballast from the total requirement for the maintenance work of this line segment which is **41% or (275,647.92m³)** of the total requirement.

$$4.22\text{birr/km} * 4.3\text{km} * 275647.92\text{m}^3 / 3.27 \text{ m}^3/\text{m} = \mathbf{1,529,635.216\text{Birr}}$$

$$\text{Total new ballast production including blending material} = 1,529,635.216\text{Birr} + 8,211,609.38\text{birr} = \mathbf{9,741,244.596\text{Birr}}$$

Production is under taken simultaneously with the process of old ballast cleaning.

Blending material

The production of fresh ballast in order to improve the performance of this recycled ballast and in order to substitute the ballast wasted during screening and refining adds huge cost. The capital to be invested for the production of this substituent ballast is dependent on the availability of quarry sites along the corridor of the track line and also it depends on the efficiency of production plants, technological advancement of construction firms and the quantity of ballast aggregate required. In this case the adapted quarry site available in this area is Wolenchiti which is 4.3km from the track line.

Cost of man power

In addition to the above major sources of track ballast rehabilitation work cost, the expense incurred by the man power is unforgettable. For this economic analysis average monthly salary including any allowances for each individual worker is assumed to be an average value of 11500birr/month. And the cost is done assuming screening plant will be utilized for three years projected time. The maximum field work crew for this rehabilitation work should be 30 skilled technicians. The management and other department personnel should be minimum of 25 professionals. Labor force required is estimated 50 with a daily wedge of 90 ETB and monthly wedge pre person 2700ETB which is deducted from (European Academic Research - Vol. III, 2016).

So the total monthly cost incurred by man power is calculated as;

Management and skilled technical man power = $25+30 = 55$ professionals

$55\text{persons} * 11500\text{ETB/person/month} * 12\text{month/year} * 3\text{years} = 22,770,000\text{ETB}$

Labor force = $50\text{persons/month} * 2700\text{ETB/month} * 12\text{month/year} * 3\text{year} = 4,860,000 \text{ ETB}$

Three year cost for man power = $22,770,000\text{ETB} + 4,860,000 \text{ ETB} = 27,630,000 \text{ ETB}$

10% additional money for contingency should be saved. So the total amount of money including contingency is **30,393,000ETB**.

Most pronounced advantage of ballast in situ recycling with mobile refiner machine is its lesser man power requirement.

4.3. Alternative 2, Cost of Production of New Ballast

The source of data for the new ballast production in this evaluation is from a research by (Biruk Gebremedhin Mesfin, 2015)'. Time dependent cost and values are corrected based on the current situation.

Total amount of ballast required in order to rehabilitate 235km plain track and more than 20km station track if the whole old ballast is removed is estimated above which is $6.72 \times 10^5 \text{ m}^3$. So analysis of economic cost should be developed considering the production, transportation and distribution of this much amount of ballast for the whole section rehabilitation.

Cost for plantation of crushing plant and machineries (birr)

The cost for crushing plant from Zenith machinery company, China; capacity of 120 tone/h -150 tone/h, main machine: feeder, jaw crusher, impact crusher, vibrating screen, belt conveyor, and spare parts for common wearing parts for 1 year with consulting one mechanical engineer motor, control panel etc. and spare parts for common wearing parts for 1 year with consulting one mechanical engineer excluding transportation cost for two containers (200,000 Birr) is 256,259 USD.

Three ballast aggregate production plants are recommended in order to cover the whole length of the track section. So cost of ballast production plants including 10% time dependent cost fluctuation;

$$3 \times 256,256 \text{ USD} \times 22.9 \text{ Birr/USD} + 0.1(3 \times 256,256 \text{ USD} \times 22.9 \text{ Birr/USD}) = \mathbf{19,365,492.6 \text{ Birr.}}$$

Section A: Addis-Debre Zeit Ballast Rehabilitation Site

When the project uses center site for this section the following projection were made to calculate the cost for fuel consumption from (Biruk G/Medhin 2015) study.

- ✓ The production plant site shares equal range of work of spreading volume within the railroad section; 51 km.
- ✓ The diesel train used to transport the ballast material is assumed to have twenty haulage rolling stock; with each of 20 m^3 capacity.
- ✓ The train consumes 10 liters/ km as described above.
- ✓ $2.62 \text{ m}^3/\text{m}$ volumes of ballast and sub ballast is required for the track section as calculated in the volume calculation.

$$\text{Train capacity} = 20 \text{ m}^3 \times 20 \text{ rolling stock} = 400 \text{ m}^3$$

$$\text{One trip coverage} = 400 \text{ m}^3 / 2.62 \text{ m}^3/\text{m} = 152.67 \text{ m}$$

$$\text{Km coverage} = (152.67)^1 \sum_{k=1}^{334} (1 + 2 + 3 + \dots + n) = 13,179,696 \text{ m} = 13,179.696 \text{ km}$$

$$\text{Job executed from both two sides of the plant sites} = 2 \times 13,179.696 \text{ km} = 26,359.392 \text{ km}$$

$$\text{Overall liters consumed by to execute the job} = 10 \text{ liters/km} \times 26,359.392 \text{ km} = 263,593.92 \text{ liters}$$

$$\text{Trip} = 51000 \text{ m} / 152.67 \text{ m} = 334 \text{ trips}$$

Fuel cost = 263,593.92liters*20.1birr/litter = 5,298,237.792 birr

Section B: Debre-Zeit-Adama site, selected by this study

When the project uses center site for this section the following assumptions were made to calculate the cost for fuel consumption

- ✓ The screening plant site shares equal range of work of spreading volume within the railroad section; 48 km.
- ✓ The diesel train used to transport the ballast material is assumed to have twenty haulage rolling stock; with each of 20 m³ capacity.
- ✓ The train consumes 10 liters/ km as listed above.
- ✓ 2.62 m³/m volumes of ballast and sub ballast is required for the track section as calculated in the volume calculation.

Train capacity= 20 m³ *20 rolling stock= 400 m³

One trip coverage = 400 m³ / 2.62 m³/m =152.67 m

Trip = 48,000 m/ 152.67 m= 314.4036 = 315trips

Km coverage = (152.67)¹ $\sum_{k=1}^{315} (1 + 2 + 3 + \dots + n) = 12,696,037\text{m}=12,696.037\text{km}$

Job executed from both two sides of the plant sites = 2* 12,696.04km = 25,392.07km

Overall liters consumed by the diesel train to execute the job = 10 liters/km *25,392.07km = 253,920.7liters

Fuel cost = 253,920.7liters * 20.1 birr/liter = 5,103,807 birr

Section C: Adama-Awash site, selected by this study

When the project uses center site for this section the following assumptions were made to calculate the cost for fuel consumption

The screening plant site shares equal range of work of spreading volume within the railroad section; 1km.

- ✓ The diesel train used to transport the ballast material is assumed to have twenty haulage rolling stock; with each of 20 m³ capacity.
- ✓ The train consumes 10 liters/ km as listed above.
- ✓ 2.62 m³/m volumes of ballast and sub ballast is required for the track section as calculated in the volume calculation.

Train capacity= 20 m³ *20 rolling stock= 400 m³

One trip coverage = 400 m³ / 2.62 m³/m =152.67 m

Trip = 67,000 m/ 152.67 m= 438.855= 439trips

Km coverage = (152.67)¹ $\sum_{k=1}^{439} (1 + 2 + 3 + \dots + n) = 17,693,843m=17,693.843km$

Job executed from both two sides of the plant sites = 2* 17,693.843km = 35,387.69km

Overall liters consumed by the diesel train to execute the job = 10 liters/km *35387.69km = 353,876.9liters

Fuel cost = 353876.9liters * 20.1 Birr/liter = 7,112,925Birr

Total cost of fuel estimated to be = 7112925Birr + 5,103,807 Birr + 5,298,238 Birr=
17,514,970Birr

Cost of manpower (birr)

In addition to the above major sources of track ballast rehabilitation work cost, the expense incurred by the man power is unforgettable. For this economic analysis average monthly salary including any allowances for each individual worker is assumed to be 11,500birr. And the cost is done assuming production plant will be utilized for next four years project time.

Assuming the requirement of man power for the production and distribution of new ballast extensively man power intensive. Labor, technical and management personnel for the three production plant sites and distribution on the track line minimum of 150 persons will be included. So the cost of new ballast is mainly dependent on the management man power.

Total cost estimated for man power is;

150persons*6500birr/person/month*12*4 = **82,800,000Birr**

Cost for transportation of blending material from 4.3 km(birr)

Table 4.2. Assumption of different items current unit cost:

1. Hourly rental rate, (A)	450.00	Birr/Hr.
2. Fuel Consumption,(B)	1.50	Km/lit
3.Fuel cost, (C)	20.10	Birr/lit.
4. Loading and Unloading time, (D)	0.13	Hr.
5. One trip, (E)	14.00	m ³
6. Min working hour per day, (F)	8.00	Hr./Day
7.Average assumed speed (k)	30.00	Km/Hr.

Calculation:

Hauling Distance; single trip in Km (G) = 4.3 Km

Fuel Cost; Fuel consumption in Lit/trip (H) = 2*G/B = 5.73

Fuel consumption in Lit/m³ (I) = H/E =0.41

Fuel consumption rate in Birr/m³ (J) = I*C =8.12

Production; Time for one trip in Hr. /trip (L) = ((2*G/K) +D) = 0.42

No. of trip per hour in Trip. /hr. (M) = 1/L = 2.38

Volume per hour in m³ /hr. (N) = E*M =33.36

Birr per Volume in Birr/m³ (O) = A/N =10.49

Total rate with fuel; Total rate per volume in Birr/m³ (P) = O+J = 20.45

Total rate per kilometer per volume in Birr/Km/m³ (Q) = P/G= 4.62

Available Volume for the whole stretch = 4.44 m³/m * 257000 m = 1,141.080m³ total

Required Volume for the blending material= 40% * 1,141.080m³ + (304435m³ - 120,819m³) = 456,432 m³+183,606 m³ = 640,038 m³ of blending material.

Cost for transporting blending material for 4.3km = 4.22birr/km/m³*4.3km*519,772m³ = **11,614,129.5birr**

4.4. Comparison of Cost Evaluation

Table 4.3. Comparison result of new ballast production vs old track ballast recycling

Alternatives	Cost (birr)					total
	Fuel consumption	Machinery cost	Cost for blending material	Man power	Producti on time	
Recycled ballast	1,273,550.25	17,589,200	9,741,244.6	30,393,000	3yrs	58,996,994.85
New ballast production	17,514,970	19,365,492.6	11,614,129.5	82,800,000	4yrs	131,294,592.1

Based on the estimation result shown in the table above cost of new ballast production is almost two folds compared with recycling old track ballast. The cost of recycling old Ethiopian track ballast may even better more over new ballast production due to

- Absence of ballast transportation cost
- Reduced man power requirement
- Reduced time of ballast laying
- Reduced cost of quarry site and machinery leasing

CHAPTER FIVE

5. Conclusion and Recommendation

5.1. Conclusion

Rehabilitation and recycling process starts by investigating real condition of the material considered to be studied. During studying Ethio-Djibouti old railway track ballast the first step thoroughly under gone is understanding in situ condition of the site where the ballast is located and distinguishing the level of deterioration this material is subjected. Furthermore effect of the defective ballast on the desired function of the whole track system is tried to be assessed and analyzed. After proper site investigation and sample data collection, appropriate ballast aggregate characterization process by using different laboratory tests were conducted Investigating the physical, mechanical and geometric properties of identified ballast of selected track sections by using standard laboratory tests and finally economic evaluation using clear economic break down are developed as practically applicable solution.

Referring to the results and discussions part of the thesis; it is concentrated on single track section of Addis-Awash old railway track which covers 235 km. And this section is selected as a case study due to economic constraint to cover the whole track length. Based on the result of this study ballast of Ethio-Djibouti is subjected serious deterioration on urban areas than on rural sections. Depending on the gradation, crushing value and impact test result, samples taken from rural track section fulfills the requirement of track ballast as dictated by different standards like AREMA and ASTM while the samples taken from urban centers like Addis and Adama found seriously fouled and deteriorated. The following are concluded depending on the result of this study:

- Based on the result from site investigation sufficient amount of ballast is available which can be recycled and reused for in situ and new track projects
- As it is indicated on the site assessment part the whole track section considered is subjected to different track defects which should be maintained and managed thoroughly
- In some parts of the track line quality of the ballast is seriously affected by fouling and degradation which deserves a total replacement or blending with newly produced ballast
- Based on the result from different lab tests it is realized that huge amount of ballast can be produced with good durability and quality

- As it is shown on the cost evaluation part, economic output of recycling oldest track ballast is more than two fold over the production of new or (fresh) ballast

5.2. Recommendation and Future Work

Naturally obtained and crushed, angular, rock material satisfying all the physical and mechanical property is good for ballast construction. Ballast particles breakdown and deteriorate progressively under heavy train cyclic loading. Breakage of ballast is always associated with railway track deformation, which requires costly regular track maintenance in the form of replacing or mixing the degraded ballast with fresh aggregates and subsequent re-compaction (tamping). Depending on the reality observed during the development of this research, multiple positive and negative conditions have been observed which deserves collaborative effort of handling and correcting.

There is no universal specification for ballast material property because of the difference in property of the subsoil condition of the structure and its index characteristics such as size, shape, hardness, friction, texture, abrasion resistance and mineral composition. Based on the result of this study relating with different international track standards, sufficient amount of ballast with proper quality can be produced by cleaning and recycling with appropriate technology. Recycled ballast from Ethio-Djibouti old railway track can be supplied for new projects or it can be used for in-situ maintenance. Furthermore, the whole track system components are very recyclable and reusable with a minimum maintenance and rehabilitation work. Basically this research is designed to create basic awareness on the process of rehabilitation and reusing components of old railway track structural components for in situ maintenance and for the construction of new project. During the development of this study the following points were encountered that should be considered and addressed in the near future:

- ✓ Development of effective old track management and regular track structure maintenance
- ✓ Developing fully packaged railway track inspection and testing laboratories
- ✓ Provision of international and national research institute linkage
- ✓ Provision of national railway track standards and specification
- ✓ Researching on rehabilitation and recycling of the whole old track line
- ✓ Further researches can be developed on investigating the condition of oldest rail track ballast and other track components like the rail and the sleeper
- ✓ Researchers can work on ways of changing oldest track line and adding different values to develop compatible track structures with latest and advanced track lines

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Appendixes

Appendix I: Site Investigation Result

Table 1. Akaki Kaliti – Adama section site investigation result

	Defects investigated	Location		Sample Area	Measured quantity		Measured Defect		Average	
		X	Y		length(m)	volume(m ³)	length(m)	volume(m ³)	length(m)	volume(m ³)
Akaki Kaliti - Adama Section	Track settlement	530517	944823	1	152	675.61	56	248.9	47	208.91
		530227	944942	2	149	662.275	38	168.9		
		529943	945053	3	160	711.168	47	208.9		
	Grass, soil and debris cover	530517	944823	1	153	680.054	29	128.9	45.33	201.5
		530227	944942	2	147	653.386	43	191.1		
		529943	945053	3	147	653.386	64	284.5		
	Track component removal	530517	944823	1	154	684.499	18	80.0	6	26.67
		530227	944942	2	150	666.72	0	0		
		529943	945053	3	155	688.944	0	0		
	Track ballast removal	530517	944823	1	146	648.941	112	497.8	123.3	548.19
		530227	944942	2	150	666.72	131	582.3		
		529943	945053	3	150	666.72	127	564.5		

Assessing Possible ways of Reusing Old Ethiopian Railway Ballast (Addis- Awash section)

Sectional Quantity		Projected Defect		Projected Defect Averaged		Projected %Age		Projected Average %Age	
length(km)	volume(m ³)	length(km)	volume(m ³)	length(km)	volume(m ³)	length(km)	volume(m ³)	length(km)	volume(m ³)
97	431146	36213	160961	30393	135092	37.33	37.3	31.33	31.3
		24573	109224			25.33	25.3		
		30393	135092			31.33	31.3		
		18753	83354.8	29316	130302	19.33	19.3	30.22	30.2
		27807	123595			28.67	28.7		
		41387	183955			42.67	42.7		
		11640	51737.5	3880	17246	12	12	4	4
		0	0			0	0		
		0	0			0	0		
		72427	321922	79756	354497	74.67	74.7	82.22	82.2
		84713	376534			87.33	87.3		
		82127	365037			84.67	84.7		

Table 2. Awash Adama section site investigation result

	Defects investigated	Location		Sample Area	Measured Quantity		Measured Defect		Average	
		X	Y		length(m)	volume(m3)	length(m)	volume(m3)	length(m)	volume(m3)
Awash - Adama Section	Track settlement	625679	991747	1	150	666.75	36.1	160.5	56.37	250.5
		627381	992798	2	152	675.64	86	382.3		
		628873	994191	3	149	662.305	47	208.9		
	Grass, soil and debris cover	625679	991747	1	153	680.085	114	506.73	72	320.0
		627381	992798	2	145	644.525	65	288.9		
		628873	994191	3	150	666.75	37	164.5		
	Track component removal	625679	991747	1	150	666.75	23	102.5	12.33	54.8
		627381	992798	2	151	671.195	14	62.5		
		628873	994191	3	146	648.97	0	0		
	Track ballast removal	625679	991747	1	174	773.43	112	497.8	123.3	548.2
		627381	992798	2	150	666.75	131	582.23		
		628873	994191	3	149	662.305	127	564.5		

Assessing Possible ways of Reusing Old Ethiopian Railway Ballast (Addis- Awash section)

Sectional Quantity		Projected Defect		Projected Defect Averaged		Projected %age	Projected Average %age Quantity		
length(km)	volume(m3)	Length (km)	Volume (m3)	length(km)	volume(m3)	Length (km)	volume(m3)	length(km)	volume(m3)
128	568934	30805	136930	48100	213803	24.07	24.1	37.58	37.67
		73387	326204			57.33	57.3		
		40107	178274			31.33	31.3		
		97280	432410	61440	273101	76	76.0	48	48.00
		55467	246549			43.33	43.3		
		31573	140343			24.67	24.7		
		19627	87240.5	10524	46781	15.33	15.3	8.222	8.22
		11947	53102.9			9.33	9.3		
		0	0			0	0		
		95573	424823	105244	467812	74.67	74.7	82.22	82.23
		111787	496892			87.33	87.3		
		108373	481719			84.67	84.7		

Table 3. Lagahar-Akaki Kaliti section site investigation result

	Defects investigated	Location		Sample Area	Measured Quantity		Measured Defect		Average	
		X	Y		length(m)	volume(m3)	length(m)	volume(m3)	length(m)	volume(m3)
Lagahar - Akaki Kaliti Section	Track settlement	472867	995680	1	156	693.389	82	364.5	77	342.27
		472854	995682	2	152	675.61	56	248.9		
		472845	995676	3	150	666.72	93	413.4		
	Grass, soil and debris cover	472867	995680	1	146	648.941	86	382.3	90.33	401.53
		472854	995682	2	150	666.72	67	297.8		
		472845	995676	3	157	697.834	118	524.5		
	Track component removal	472867	995680	1	148	657.83	150	666.8	78.67	349.67
		472854	995682	2	150	666.72	73	324.5		
		472845	995676	3	150	666.72	13	57.8		
	Track ballast removal	472867	995680	1	152	675.61	150	666.8	143.7	638.6
		472854	995682	2	151	671.165	138	613.4		
		472845	995676	3	150	666.72	143	635.6		

Assessing Possible ways of Reusing Old Ethiopian Railway Ballast (Addis- Awash section)

Sectional Quantity		Projected Defect		Projected Defect Averaged		Projected %Age		Projected Average %Age	
length(km)	volume(m ³)	Length (km)	Volume (m ³)	length(km)	volume(m ³)	length(km)	volume(m ³)	length(km)	Volume (m ³)
32	142234	17493.3	77757.9	16427	73017	54.67	54.7	51.33	51.34
		11946.7	53102.9			37.33	37.3		
		19840	88188.8			62	62.0		
		18346.7	81550.9	19271	85660	57.33	57.3	60.22	60.23
		14293.3	63533.9			44.67	44.6		
		25173.3	111895			78.67	78.7		
		32000	142240	16782	74597	100	100.0	52.44	52.45
		15573.3	69223.5			48.67	48.7		
		2773.33	12327.5			8.67	8.7		
		32000	142240	30649	136234	100	100.0	95.78	95.78
		29440	130861			92	92.0		
		30506.7	135602			95.33	95.3		

$$\text{Projected Defect} = \frac{\text{total length of the section} * \text{measured defect}}{\text{Measured Quantity}}$$

$$\text{Projected Defect Quantity Averaged} = \frac{\text{sum of Projected Defect Quantity} * 100}{3}$$

$$\text{Projected \% age} = \frac{\text{Projected Defect} * 100}{\text{volume of ballast in the section}}$$

During the site inspection and investigation for the above data collection the following track defects were also observed and quantified in simple format.

In each table volume of each line segment is estimated by using common factor developed by considering the volume of 1m line segment developed as follow.

$$5*0.4*0.82*1*2+0.4*0.7*1*2+ (1.75+0.05)*0.4*1-(1.75+0.05)*0.032*2 = 4.448m^3$$

This value considers all ballast available on the shoulder, below the sleeper and side slope of the line.

Average Track Settlement in %age

Table 4. Data of track settlement

Representative Sections	Approximate Location		Section Length (Km)	Average Settled Length in %age	Severity		
	X	Y			Fair	Moderate	Sever
A	472854	995682	32	51.3	15	24.1	12.3
B	530227	944942	97	31.3	10	14.7	7.5
C	627381	992798	128	37.58	11	17.7	9.12

Average %age Grass and Debris Cover

Table 5. Data of grass and debris cover of the track

Representative Section	Approximate Location		Section Length (Km)	Average Grass and Debris Cover in %Age	Severity		
	X	Y			Fair	Moderate	Sever
A	472854	995682	32	60.5	8	17	35.5
B	530227	944942	97	30.2	4	8.4	17.8
C	627381	992798	128	48.2	6.5	13.4	28.3

Average %age Track Component Removal

Table 6. Data of track component removal

Representative Section	Approximate Location		Section Length (Km)	Average Track Component Removal %Age	Severity		
	X	Y			Fair	Moderate	Sever
A	472854	995682	32	52.444	8	16.3	28.3
B	530227	944942	97	4	0.6	1.24	2.16
C	627381	992798	128	8.2222	1.2	2.549	4.44

Loss of track Ballast

Table 7. Data of loss of track ballast

All the data provided above are analyzed based on the general data provided in table 1, 2 and 3 above

Representative Section	Approximate Location		Section Length (Km)	Average Track Ballast Removal in %age	Severity		
	X	Y			Fair	Moderate	Sever
A	472854	995682	32	95.8	8.3	22.3	65
B	530227	944942	97	82.2	7	19.3	56
C	627381	992798	128	82.2	7.1	19.3	56

Appendix II: Laboratory Test Result

Ballast Gradation Result

Table 8. Ballast aggregate sieve analysis result and for gradation analysis

Sieve Size	Retained(g)			%age Retained			Cumulative %age Retained			Cumulative %age Passed		
	A	B	C	A	B	C	A	B	C	A	B	C
63	0	0	0	0	0	0	0	0	0	100	100	100
50	3561.4	852.4	2329.7	17.71	4.55	12.61	17.7	4.6	12.6	82.29	95.45	87.4
37.5	7282.8	4619.8	5665.2	36.22	24.66	30.67	53.9	29.2	43.3	46.07	70.79	56.7
28	4532.1	5146.1	5272.5	22.59	27.47	28.54	76.5	56.7	71.8	23.53	43.31	28.2
25	698.6	1121.6	1104	3.47	5.99	5.98	79.9	62.7	77.8	20.06	37.32	22.2
20	1235.5	1007.2	726.4	6.14	5.37	3.93	86.1	68.1	81.7	13.91	31.95	18.3
16	632	344.5	244.9	3.14	1.84	1.32	89.3	69.9	83.1	10.77	30.11	16.9
12.5	454.4	2662.2	621.6	2.26	14.2	3.36	91.5	84.1	86.4	8.511	15.89	13.6
10	320	252	349.5	1.59	1.34	1.89	93.1	85.5	88.3	6.92	14.55	11.7
4.75	316.6	2084.5	1496.2	1.57	11.13	8.10	94.7	96.6	96.4	5.345	3.421	3.5
0.2	231.2	434	348.7	1.15	2.32	1.89	95.8	98.9`	98.3	4.195	1.104	1.7
Pan	843.6	206.8	311.4	4.20	1.10	1.69	100	100	100	0	0	0
Total	20108.2	18731	18470.1									

Elongation

Table 9. Lab result and analysis of ballast aggregate elongation

Sieve Size	Retained			Opening Size	Elongation Retained(G)			Elongation Passed(G)		
	A	B	C		A	B	C	A	B	C
63	0	0	0	37.5-50	1955.9	2132.1	2452.1	4773.6	5203.6	5985
50	3561.3	4236.8	2563.4							
37.5	3169.4	3621.6	4061.2	28-37.5	4275.2	3772.4	3147.4	4490.5	3962.4	3306
28	5390.9	4891.3	5161.8							
20	1962.5	1651.5	2278.1	20-28	4538.2	4158.8	3681.7	2730.6	2502.3	2215
12.5	935.2	468.7	1236.4							
pan	239.4	342.1	412.3	12.5-20	154	465.5	651.3	844.8	844.8	3573
total	15019.3	14870	15300.9							
						10529	9932.5	12840	12513	15079
								23763	23042	25011

%age Retained			%age Passed		
A	B	C	A	B	C
12.82	14.016	15.6054	31.284	34.207	38.0867
10.19	9.1882	7.12664	10.698	9.6509	7.48553
4.295	4.0111	3.34339	2.5841	2.4134	2.01169
0.055	0.1707	0.22627	0.3044	0.3097	1.24126

EI for sample A = $(10923/23763)*100 = 45.97$
 EI for sample B = $(10529/23042)*100 = 45.69$
 EI for sample C = $(9932.5/25011.5)*100 =$

39.71

Flakiness

Sieve Size	Retained			Opening Size	Flakiness Retained(g)			Flakiness Passed(g)		
	A	B	C		A	B	C	A	B	C
63	0	0	0	50-63	4308.2	3268.1	5123.7	2421.1	3854.9	1333
50	3561.3	4236.8	2563.4							
37.5	3169.4	3621.6	4061.2	37.5-50	2920.8	2524.3	1954.1	2648.5	2620.9	4166
28	5390.9	4891.3	5161.8							
20	1962.5	1651.5	2278.1	28-37.5	1087.6	1562.2	1092.5	862.1	789.7	923.1
12.5	935.2	468.7	1236.4							
Pan	239.4	342.1	412.3	20-28	386.8	487.5	654.2	544.5	269.2	347.3
total	15019.3	14870	15300.9							
				10_20	348.5	562.3	456.4	348.5	383.5	285.9
					9051.9	8404.4	9280.9	6824.7	7918.2	7055
								15877	16323	16336

%age retained			%age passed			Total
A	B	C	A	B	C	
28.23	21.484	32.60	15.867	25.341	8.482	6729.3
6.958	6.148	4.42	6.3096	6.3835	9.433	5569.3
1.029	1.506	0.99	0.8159	0.7616	0.838	1949.7
0.139	0.1787	0.22	0.1962	0.0987	0.120	931.3
0.049	0.0803	0.061	0.0489	0.0548	0.038	697

FI for sample A = $(6824.7/15877)*100 = 42.99$

FI for sample B = $(7918.2/8404.4)*100 = 48.51$

FI for sample C = $(7055/9280.9)*100 = 43.19$

Table 10. Lab result and analysis of ballast

aggregate flakiness

LAA for Small Sized Ballast Aggregate (Between 12.5mm and 10mm)

LAA for sample A

Mass of sample prepared (Grade A) =5000gm

Mass after crushing (12 balls) =3844.7gm

Calculation

$$\% \text{ loss} = (5000 - 3844.7) * 100 / 5000 = 23.106\%$$

LAA for sample B

Mass of sample prepared (Grade A) =5000gm

Mass after crushing (12 balls) = 3761.3gm

Calculation

$$\% \text{ loss} = 5000 - 3761.3 / 5000 * 100 = 24.774\%$$

LAA for sample C

Mass of sample prepared (Grade A) =5000gm

Mass after crushing (12 balls) =3562.8gm

Calculation

$$\% \text{ loss} = (5000 - 3562.8) * 100 / 5000 = 22.744\%$$

For Large Sized Ballast Aggregate (size between 37.75mm and 24mm)

Mass of sample prepared (Grade A) =5000gm

LAA for sample A

Mass of sample prepared (Grade 3) =10000gm

Mass after crushing (12 balls) = 7619.7gm

Calculation

$$\% \text{ loss} = (10000 - 7619.7) * 100 / 10000 = 23.803\%$$

LAA for sample B

Mass of sample prepared (Grade 3) =10000gm

Mass after crushing (12 balls) = 7659.4gm

Calculation

$$\% \text{ loss} = (10000 - 7659.4) * 100 / 10000 = 23.406\%$$

LAA for sample C

Mass of sample prepared (Grade 3) =10000gm

Mass after crushing (12 balls) = 7572.8gm

Calculation

$$\% \text{ loss} = ((10000 - 7572.8) * 100) / 10000 = 24.272\%$$

Fouling Material for Rural Section

Materials Finer than 75- μm (No. 200) Sieve in Mineral aggregates by washing

Sample A

Sample A before washing = 3245.8gm

Sample A after washing and oven dry=3214.55gm

$$\% \text{ finer} = (3245.8 - 3214.56) / 3245.8 * 100 = \mathbf{0.96\%}$$

Sample B

Sample B before washing = 3882.6gm

Sample B after washing and oven dry= 3865.9gm

$$\% \text{ finer} = (3882.6 - 3865.9) / 3882.6 * 100 = \mathbf{0.43\%}$$

Sample C

Sample B before washing = 3487.4gm

Sample B after washing and oven dry= 3456.8gm

$$\% \text{ finer} = (3487.4 - 3456.8) / 3487.4 * 100 = \mathbf{0.89\%}$$

Fouling Material for Urban Section

Sample A

Sample B before washing = 4152.6gm

Sample B after washing and oven dry= 3258.5gm

$$\% \text{ finer} = (4152.6 - 3258.5) / 4152.6 * 100 = \mathbf{21.53\%}$$

Sample B

Sample B before washing = 3658.3gm

Sample B after washing and oven dry= 3125.8gm

$$\% \text{ finer} = (3658.3 - 3125.8) / 3658.3 * 100 = \mathbf{14.56\%}$$

Sample C

Sample B before washing = 4325.4gm

Sample B after washing and oven dry= 3745.2gm

$$\% \text{ finer} = (4325.4 - 3745.2) / 4325.4 * 100 = \mathbf{13.41\%}$$

Fouling Index

Sample A

Sample finer than 4.75mm = 1074.8gm

Sample finer than 200 μ m (0.2mm) = 843.6gm

FI = 1074.8+843.6 = 1918.4gm

Sample B

Sample finer than 4.75mm =640.7gm

Sample finer than 200 μ m (0.2mm) = 206.7gm

FI = 640.7+206.7 = 847.4gm

Sample C

Sample finer than 4.75mm =660.1gm

Sample finer than 200 μ m (0.2mm) = 311.4gm

FI = 660.1+311.4= 971.5gm

ACV for aggregate size between 12.5mm and 10mm

ACV for sample A

Mass of sample prepared (Grade A) =2059.5gm

Mass after compression (400 KN) = 1793.3gm

Calculation

% loss = (2059.5- 1793.3) *100 / 2059.5= **12.92 %**

ACV for sample B

Mass of sample prepared (Grade A) =2435.8gm

Mass after compression (400 KN) = 1793gm

Calculation

% loss = (2435.8- 1793) *100/ 2435.8 = **26.39 %**

ACV for sample C

Mass of sample prepared (Grade A) =2315.3gm

Mass after compression (400 KN) = 1793gm

Calculation

% loss = (2315.3- 1793) *100/ 2315.3 = **22.56%**

ACV for aggregate size between 37.75mm and 25mm

ACV for sample A

Mass of sample prepared (Grade A) =2178.8gm

Mass after compression (400 KN) = 1497gm

Calculation

$$\% \text{ loss} = (2178.8 - 1497) * 100 / 2178.8 = \mathbf{31.29\%}$$

ACV for sample B

Mass of sample prepared (Grade A) = 2596.4gm

Mass after compression (400 KN) = 1945.3gm

Calculation

$$\% \text{ loss} = (2596.4 - 1945.3) * 100 / 2596.4 = \mathbf{25.08\%}$$

ACV for sample C

Mass of sample prepared (Grade A) = 2935.2gm

Mass after compression (400 KN) = 2285.3gm

Calculation

$$\% \text{ loss} = (2935.2 - 2285.3) * 100 / 2935.2 = \mathbf{22.14\%}$$

Impact value

Sample A

Mass of sample prepared (Grade A) = 297.5gm

Mass after impact (15 blows) = 234.3gm

Calculation

$$\% \text{ loss} = (297.5 - 234.3) * 100 / 297.5 = \mathbf{21.24\%}$$

Sample B

Mass of sample prepared (Grade A) = 293.1gm

Mass after impact (15 blows) = 225.2gm

Calculation

$$\% \text{ loss} = (293.1 - 225.2) * 100 / 293.1 = \mathbf{23.17\%}$$

Sample C

Mass of sample prepared (Grade A) = 308.4gm

Mass after impact (15 blows) = 245.2gm

Calculation

$$\% \text{ loss} = (308.4 - 245.2) * 100 / 308.4 = \mathbf{20.49\%}$$

Specific gravity and % Absorption

Sample A₁

Wt. of sample air dried = 3000gm

Wt. of sample immersed in water = 1753.6gm

Wt. sample after oven dried = 2923gm

Sample A₂

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Wt. of sample air dried=3159.3gm

Wt. of sample immersed in water=1823.5gm

Wt. sample after oven dried= 3082.5gm

Sample B₁

Wt. of sample air dried=3019.6gm

Wt. of sample immersed in water=1774.6gm

Wt. sample after oven dried= 2951.6gm

Sample B₂

Wt. of sample air dried=2968.7gm³⁰⁰

Wt. of sample immersed in water=1596.3gm

Wt. sample after oven dried= 2896.3gm

Sample C₁

Wt. of sample air dried=3264.3gm

Wt. of sample immersed in water=1841.2gm

Wt. sample after oven dried= 3196.3gm

Sample C₂

Wt. of sample air dried=3156.7gm

Wt. of sample immersed in water=1725.6gm

Wt. sample after oven dried= 3086.8gm

Specific gravity of each sample= Wt. air/Wt. water

Sg A1=3000gm/1753.6gm= 1.71

Sg A2=3159.3gm/1823.5gm=1.73

- Sg A= (1.71+1.73)/2= 1.72

Sg B1=3019.6gm/1774.6gm=1.70

Sg B2=2968.7gm/1596.3gm=1.86

- Sg B= (1.70+1.86)/2= 1.78

Sg C1=3264.3gm/1841.2gm=1.77

Sg C2=3156.7gm/1725.6gm=1.83

- Sg C= (1.77+1.83)/2= 1.80

%age water Absorption capacity = (Wt. air-Wt. oven)/ Wt. oven*100

%age Abs of A1= (3000-2923)/3000*100 =2.57

%age Abs of A2= (3159.3-3082.5)/3159.3*100=2.43

- Average % age Abs of B= $(2.57+2.43)/2=2.5$

%age Abs of B₁= $(3019.6-2951.6)/3019.6 *100 =2.53$

%age Abs of B₂= $(2968.7-2896.3)/2968.7 *100 =2.43$

- Average % age Abs B= $(2.53+2.43)/2=2.48$

%age Abs of C₁= $(3264.3-3196.3)/ 3264.3*100 = 2.08$

%age Abs of C₂= $(3156.7-3086.8)/ 3156.7*100 = 2.21$

- Average % age of Abs B= $(2.08+2.21)/2=2.145$

Unit wt. for sample A₁

Wt. of the cylinder considered = 4252gm

Volume of the cylinder=3739.28 cm³

Loss unit wt.

Wt. of the cylinder + wt. of loss =8352.3gm

Loss unit wt. for sample A₁ = $(8352.3-4252) \text{ gm}/3739.28 \text{ cm}^3 = 1.09655\text{gm}/ \text{cm}^3 =1096.55 \text{ kg}/ \text{m}^3$

Unit wt. for sample A₂

Wt. of the cylinder + wt. of loss =8783.5gm

Loss unit wt. for sample A₂ = $(8783.5-4252) \text{ gm}/3739.28 \text{ cm}^3 = 1.2119\text{gm}/ \text{cm}^3 =1211.86 \text{ kg}/ \text{m}^3$

- Average loss unit wt. for sample A = $(1.09655+ 1.2119)/2 \text{ gm}/ \text{cm}^3= 1.15422\text{gm}/ \text{cm}^3$
=1154.22 kg/ m³

Unit wt. for sample B₁

Wt. of the cylinder considered = 4252gm

Volume of the cylinder=3739.28 cm³

Loss unit wt.

Wt. of the cylinder + wt. of loss =8236.8gm

Loss unit wt. for sample B₁= $(8236.8-4252) \text{ gm}/3739.28 \text{ cm}^3 = 1.06851\text{gm}/ \text{cm}^3 =1068.51 \text{ kg}/ \text{m}^3$

Unit wt. for sample B₂

Wt. of the cylinder + wt. of loss =8725.8gm

Loss unit wt. for sample B₂ = $(8758.8-4252) \text{ gm}/3739.28 \text{ cm}^3 = 1.20526\text{gm}/ \text{cm}^3 =1205.26\text{kg}/ \text{m}^3$

- Average loss unit wt. for sample B = $(1.06851+ 1.20526)/2 \text{ gm}/ \text{cm}^3= 1.13688\text{gm}/ \text{cm}^3$
=1136.88 kg/ m³

Unit wt. for sample C₁

Wt. of the cylinder considered = 4252gm

Volume of the cylinder=3739.28 cm³

Loss unit wt.

Wt. of the cylinder + wt. of loss =8345.6gm

Loss unit wt. for sample C₁ = (8345.6-4252) gm/3739.28 cm³ = 1.09476gm/ cm³ =1094.76 kg/ m³

Unit wt. for sample C2

Wt. of the cylinder + wt. of loss =8625.3gm

Loss unit wt. for sample C₂ = (8625.3-4252) gm/3739.28 cm³ = 1.16956gm/ cm³
=1169.56 kg/m³

- Average loss unit wt. for sample C = (1.09476+ 1.16956)/2 gm/ cm³= 1.13216gm/ cm³
=1132.16 kg/ m³

Compacted unit wt.

Compacted unit wt. for sample A₁

Wt. of the cylinder + wt. of compacted =8965.3gm

Compacted unit wt. for sample A = (8965.3-4252) gm/3739.28 cm³ = 1.20483gm/ cm³ =1260.48 kg/m³

Compacted unit wt. for sample A₂

Wt. of the cylinder + wt. of compacted =9369.7gm

Compacted unit wt. for sample A₂ = (9369.7-4252) gm/3739.28 cm³ = 1.36863gm/ cm³ =1368.63 kg/m³

- Average compacted unit wt. for sample A = (1.20483+ 1.36863)/2 gm/ cm³= 1.28673gm/ cm³ =1286.73 kg/ m³

Compacted unit wt. for sample B₁

Wt. of the cylinder + wt. of compacted =8896.4gm

Compacted unit wt. for sample B₁ = (8896.4-4252) gm./3739.28 cm³ = 1.24205gm/ cm³ =1242.05 kg/m³

Compacted unit wt. for sample B₂

Wt. of the cylinder + wt. of compacted =9045.5gm

Compacted unit wt. for sample B₂= (9045.5-4252) gm./3739.28 cm³ = 1.28193gm/ cm³ =1281.93 kg/m³

- Average compacted unit wt. for sample B = (1.24205+ 1.28193)/2 gm./ cm³= 1.26199gm/ cm³ =1262 kg/ m³

Compacted unit wt. for sample C₁

Wt. of the cylinder + wt. of compacted =9187.4gm

Compacted unit wt. for sample C₁ = (9187.4-4252) gm./3739.28 cm³ = 1.32342gm/ cm³ =1323.42 kg/m³

Compacted unit wt. for sample C₂

Wt. of the cylinder + wt. of compacted =9078.6gm

Compacted unit wt. for sample C₂= (9078.6-4252) gm./3739.28 cm³ = 1.29078gm/ cm³ =1290.78 kg/m³

- Average compacted unit wt. for sample C= (1.29078+ 1.32342)/2 gm./ cm³= 1.3071gm/ cm³ =1307.10kg/ m³

Table 11. Summary of lab results

sample	LAA value %age Value		fouling content		ACV		impact value	Specific gravity and absorption		unit wt.	
	finer	coarser	rural	urban	finer	coarser	average	Specific gravity	absorption	loss	compacted
A	23.1	23.8	0.96	21.53	12.9	31.29	21.24	1.72	2.5	1154.2	1286.7
B	24.8	23.4	0.43	14.56	26.4	25.08	23.17	1.78	2.48	1136.9	1262
C	22.7	24.3	0.89	13.41	22.6	22.14	20.49	1.8	2.1	1132.2	1307.1