Addis Ababa University

Addis Ababa Institute of Technology

African Railway Centre of Excellence

Department of Railway Engineering (Msc. Civil Infrastructure)

Effect of Gradation and Type of Fouling Material on Drainage Performance of Railway Ballast: A case study on AALRT

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University in Partial Fulfillment for the Degree of Master of Science in Railway Engineering

By

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Declaration

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

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Abstract

A railroad track is a huge structure with different components. Among that ballast is the main structural component used to support the load from railroad ties and to facilitate drainage of water. The drainage efficiency of railway ballast is heavily influenced by aggregate gradations as well as fouling material. It is critical to understand how the gradation of ballast aggregate and fouling material influences railway ballast drainage performance. The main goal of this research is to evaluate the effect of different gradations of ballast aggregate and type of fouling material, and their combined effect on drainage performance of railway ballast on selected sites of Addis Ababa Light Rail Transit (AALRT). In the present study, the hydraulic conductivity of clean as well as fouled ballast specimens are evaluated considering three different American Railway Engineering Maintenance of Association (AREMA) gradation types and about 43 % of three different types of fouling materials. A sieve analysis is conducted to evaluate the gradation and degree of fouling on the track, and the percentage of fouling is also calculated. The hydraulic conductivity of clean and fouled ballast aggregate was then estimated using a constant head permeability test. The Fouling Ratio approach was used to determine the level of fouling at Kality Depot, Transition at Kality, and Gurd Shola. The experimental result of this study revealed that, the extent of fouling at transition is almost reaching to the category of moderately fouled ballast with the value of about 9 %. More uniformity of gradation of clean ballast AREMA No. 3 leads to higher values of hydraulic conductivity than AREMA No. 4 by about 15% and AREMA No. 24 by about 19%. In addition, the clean ballast fouled by clay has shown reduction of hydraulic conductivity by about 4.5 %, 8.5 %, and 32.5 % of AREMA No. 24, AREMA No. 3 and, AREMA No. 4 respectively. It is necessary to create a solution whereby the highway meets the railway line along the transition.

Keywords: Ballast, Ballast Fouling, Gradation, Drainage, Permeability, Hydraulic Conductivity

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Nomenclatures

ARCE	African Railway Center of Excellence
AALRT	Addis Ababa Light Rail Transit
AREMA	American Railway Engineering Maintenance of Association
ASTM	American Standard Testing for Material
C_u	Coefficient of uniformity
C_c	Coefficient of curvature
EN	European Standard
FI	Fouling Index
FR	Fouling Ratio
k	Hydraulic Conductivity Value
MB	Mass of clean ballast
MF	Mass of fouling material
NSC	Norfolk Southern Corporation
PSD	Particle Size Distribution
U. S	United States
USCS	Unified Soil Classification System

Chapter One

1. Introduction

1.1. Background

The railway track is an essential part of the transportation system and plays a vital role in the country's economy. As compared to roadway transport railway transport is a more reliable transport system due to several reasons. One of the best reasons is that train service is much faster especially as the road ways are often delayed by traffic jam. Most rail tracks are ballasted tracks for various reasons, including economy, drainage, and simplicity of maintenance. The ballast layer's primary function is to keep the rail track in its intended position by withstanding vertical, lateral, and longitudinal stresses applied on the sleepers and ensuring proper water drainage in the track [1][2].

In order to provide suitable hydraulic conductivity and mechanical properties, an optimal particle size distribution is often recommended for aggregate. However, poor water seepage from the track structure as a result of ballast contamination inevitably causes the ballast layer and track bed to become saturated [1].

The ballast gradation varies during the track's service life as a result of:

- Mechanical particle degradation during construction and maintenance work and under traffic loading,
- Chemical and mechanical weathering degradation from environmental changes, and
- Migration of fine particles from the surface and the underlying layers. Thus the ballast becomes fouled and loses its characteristics so that the ability of the ballast to perform its important function decreases and ultimately may be lost [3].

Fouling of ballast over time is the primary reason why track geometry deteriorates. Ballast fouling significantly increases settlement and poor drainage problems [4]. The degradation of performance happens mostly when the fouling materials comprise silt and clay size particles. Both types of particles impede drainage and hence will increase the possibility of significant ballast deterioration since water is critical for severe ballast maintenance problems [3]. Railway renewal and maintenance require a huge investment. Therefore, it's necessary to keep the ballast layer's drainage in good condition.

Using a method known as the fouling ratio (FR), this study assessed the level of fouling on selected sites of the Addis Ababa Light Rail Transit (AALRT). The hydraulic conductivity values for three distinct gradations and three different types of fouling materials were studied, and their influence on the drainage capacity of the ballast layer was assessed using a constant head permeability device in a series of tests.

1.2. Statement of the Problem

The ballast stratum is a major structural component of the railroad, and it is where the sleepers are laid on. Because aggregates deteriorate over time as a result of traffic and environmental exposures, selecting the correct ballast for rail track is crucial. Due to heavy repeated train loads, finer materials (i.e., materials smaller than new ballast) combine with fresh ballast, cause ballast fouling. In many nations across the globe, ballast fouling is recognized as the leading cause of track damage. It reduces the ballast layer's drainage effectiveness and load-bearing capability. To guarantee optimal track performance, enough drainage inside the ballast layer must be maintained. As a result, because appropriate drainage within the ballast layer is dependent on aggregate gradation and fouling material size, a thorough understanding of the influence of initial gradation of ballast aggregate and fouling material on drainage performance of railway ballast is critical.

1.3. Objectives

1.3.1. General Objective

The general objective of this study is to evaluate the impact of various gradations of ballast aggregate and type of fouling material and their combined effects on draining performance of railway ballast by conducting different laboratory tests.

1.3.2. Specific Objectives

- To assess the extent and type of fouling materials in the selected sites of Addis Ababa Light Rail Transit (AALRT)

- To evaluate the effect of gradation of ballast aggregate on drainage performance of ballast.
- To evaluate the impact of different fouling materials on the drainage performance of ballast.
- To estimate the combined impact of gradation of ballast aggregate and different fouling material on draining performance of ballast by analyzing the hydraulic conductivity (k) value.

1.4. Research Questions

This study will answer the following questions:

- How do we estimate the extent of fouling on selected areas of AALRT?
- How do we classify different gradations of ballast and different types of fouling material?
- What type of gradation is appropriate for the drainage performance of the ballast layer?
- Which type of fouling material has a higher adverse effect on the drainage performance of the ballast layer?

1.5. Significance of the Study

The finding of this study is important for the worldwide industry of railway. Nowadays railway is serving a large capacity of passengers having significant social, economic, and environmental benefits. The performance of the railway track is mainly dependent on drainage. Therefore, the outcome of this study helps to direct the type of gradation that should be used to maintain the drainage quality of the track and to analyze which type of fouling material highly affects the drainage performance of ballast. It is also serves as a primer for the coming researchers interested in ballast gradation and fouling materials and an initial overview of the effect of various features of the ballast layer.

1.6. Methodology

In this study, to evaluate the degree of ballast fouling on the selected sites of railway track from mass based measures Fouling Ratio method has been used, to account for all types of ballast fouling by mass which is the material passing 9.5mm sieve. To meet the aim of this research, testing objectives were set for a series of tests after field investigation has been done to determine the critical areas of ballast that is invaded by fouling material.

After conducting a series of sieve analyses to determine the extent of fouling and differentiate the type of gradation, the hydraulic conductivity of clean ballast and fouled ballast aggregate has been evaluated by conducting a constant head permeability test. For all tests carried out, the main comparison was made based on standards.

1.7. Scope and Limitation of the Study

1.7.1. Scope of the Study

This study focuses on identifying the extent and type of fouling on the track, hydraulic conductivity of ballast aggregate by considering different types of ballast gradation and fouling material, and evaluating their effect on drainage performance of the track by conducting a series of constant head permeability test.

1.7.2. Limitation of the Study

This research is mainly limited to quantifying ballast fouling, and evaluating the drainage performance of the different types of gradation of clean ballast and fouled ballast aggregate without assessing the cause of degradation of ballast and sources of ballast fouling in different sites on Addis Ababa Light Rail Transit (AALTR).

1.8. Thesis Structure

Following an introduction, this study is organized into five chapters. Chapter one explains the thesis introduction which includes the general introduction to railway ballast and ballast fouling, problem formulation, objectives, methodology, scope, and limitation of the study, as well as the significance of the study.

Chapter two describes the literature review of previous studies of ballast and fouling materials. A general review about railway track, railway ballast, ballast fouling, and hydraulic conductivity of railway ballast was also described.

Chapter three briefly illustrates the study area and critical sites for conducting the test in the line. The methods used to assess the extent of fouling and to estimate the hydraulic conductivity value are briefly described, and the materials and procedures used to attain this study are also presented in this chapter.

Chapter four discusses the identified results of laboratory tests and field investigations of the study. The discussion assesses the extent of fouling and the types, type of gradation, and briefly explains the result of permeability test tests and their implications concerning the standards.

Chapter five conclude the research conclusions based on the completed test results and gives further recommendations.

Chapter Two

2. Literature Review

2.1. Introduction

Ballast contamination caused by fine particle penetration from the subgrade is referred to as a conventional source of ballast fouling. Fouling and water retained by fouling weaken ballast aggregate by lowering hydraulic conductivity and strength properties [5]. The deterioration or breaking of ballast aggregates under traffic loads is the most common source of fouling, although other fine material penetrating into a clean and consistently graded ballast layer can also contaminate ballast aggregates [6]. Many studies researched the behavior of clean ballast aggregates mixed with smaller components like, mineral filler, sand, coal dust and subgrade clay in deteriorated ballast to get a better understanding of the fouling influence on ballast behavior [6]. By establishing various gradations of ballast aggregates and sub-ballast particles, Mehdi et al. [7] evaluated the filtering efficacy of the sub-ballast layer buried between ballast course and the subgrade. As an underlying layer, two distinct subgrade kinds were chosen: clay (type I) and silt (type II). An upward water flow is given to prepared layers to determine the degree of fine particle percolation into the ballast layer. The granular specimen used as ballast material is crushed aggregate. To determine the efficiency of aggregate gradation, four distinct initial gradations for ballast particles were evaluated. Then the fouling ratio was calculated also the permeability of sub-ballast samples with different amounts of compaction was tested in a categorized gradation. After conducting series tests with different gradation and sub-grade types they conclude that ballast material placed over silt sub-grade is more contaminated than clay sub-grade and sub-ballast material consisting of more uniform particle size demonstrates a deficiency infiltration.

Under the cyclic loading of trains, railway ballast deforms and deteriorates, and then the fine particles subsequently accumulate inside the particle voids, resulting in a reduction in drainage quality. Zhenyu et al.[8] carried out constant-head permeability tests to measure the permeability of each fouling material at various fouling levels of the sample. After test results, they suggested that different fouling ratios and fouling materials play an important role in the performance of ballast permeability observed, and as the permeability decreases with the fouling ratio increase. Cassio et al.[9] follow almost the same procedure with a little difference in fouling ratio.

Trung et al.[10] used specific gravities of ballast fouling and clean ballast material to assess ballast fouling by calculating the void contamination index. Washed, dried, and sieved through specific size samples of ballast were taken and saturated for 24 hours at various clay fouling levels, then subjected to normal stress, axial strain, and volumetric change were recorded from triaxial testing equipment. At the end of each test, the ballast was again sieved to analyze the amount of breakage. From the result of the triaxial test, they conclude that the shear strength of the ballast was lowered due to fouling materials.

It is critical to ensure ballasted track has sufficient drainage in order to maintain good performance [11]. Minimizing maintenance costs requires a thorough understanding of ballast properties and the use of appropriate tests [12]. Sadeghi et al.[12] suggested that based on the evaluation of track ballast through required experiments, physical, mechanical, environmental, and geometry of ballast profile properties conceivable to ensure the better overall track structure performance.

The previously listed research efforts have greatly emphasized the understanding of ballast fouling and its effects on permeability of ballast aggregate; however, all the fouled ballast specimens were prepared by mixing new, fresh ballast with fouling materials, as an example sand, coal dust, clay, and mineral filler. This procedure is unable to completely capture the effect of individual ballast particle gradation and each fouling material furthermore their combined effect on ballast aggregate hydraulic conductivity. It is essential to establish a better awareness of the influence of different gradation and different types of fouling material on drainage performance of railway ballast for adopting proper track maintenance practices and improving the safety and reliability of the railroad [6].

In this research, a detailed experimental study has been employed to characterize the ballast aggregate gradation, to quantify and differentiate the type of fouling material in selected sites, and finally to analyze the effect of gradation and type of fouling material on drainage performance of ballast by using sieve analysis and constant head permeability tests. In this chapter, for better knowledge of railway track and system components, furthermore, the function and defects of ballast on drainage performance of ballast were described in this chapter.

2.2. Railway Track Structure

The rail track is an essential part of the transportation system and plays the best role in the country's economy. In many countries, millions of dollar has been spent on railroad track construction and repair[4]. The railway can be advantageous over other modes of transportation because of limited use of space, reliability, and safety, high degree of automation and management, and moderate environmental impact. As compared to roadway transport railway transport is a more reliable transport system due to several reasons. One of the best reasons is that train services are much faster especially as the roadways are often delayed by traffic jams [13].

There are two types of railways tracks commonly used worldwide. These two types are namely slab track and conventional ballasted track. In conventional ballasted track-type the rails are firm on the sleepers which are embedded on compacted ballast whereas in slab track types the ballast is replaced by concrete or asphalt. Most rail tracks have been found on conventional ballasted track for the economy, drainage, and ease of maintenance [4], but the main reason for slab track application is the scarcity of good ballast and the desire to provide stronger and durable structure to carry heavy haul freight loading [13].

The followings are the main advantages of ballasted track:

- Relatively low construction cost and use of indigenous material
- Maintenance work are simple to complete
- High permeability of track structure and
- Ease of design and construction

2.2.1. Components of a ballasted track

The efficiency and safety of a rail track is depending on railway track system components and it is necessary to understand the track performance by knowing the role of each track components, (i.e. superstructure and substructure components) [4]. The superstructure component consists of rails, a fastening system, and sleepers (ties). The substructure consists of a ballast, sub-ballast, and subgrade.

Rails: Rails are the longitudinal steel members that support and guide the train wheel and transfer concentrated wheel load to the supporting sleepers. Rails need to be stiff to carry stress without excessive deflection [4].

Fastening system: Steel fasteners are important to firm the rails on the top of the sleepers to ensure their structural connection to restrict longitudinal, lateral, or vertical moments. The fastening structure shall be as simple as possible with enough strength, fastening load, proper elasticity, gauge, horizontal adjustable volume, good insulating, and anti-corrosion performance [14].

Table 1. Type of Fastenings [14]

Type of Track-bed	**Type**	**Fastenings**	**Way of connecting with sleeper**
Ordinary monolithic Track bed	Elastic separated	With bolt spring clip, without bolt spring clip	Embedding sleeve in sleeper
Monolithic track bed on elevated bridge		With bolt spring clip, little resistance	
Ballast bed with concrete sleeper	Elastic in-separated	With bolt spring clip, without bolt spring clip	Embedding bolt or steel plate in sleeper
Ballast bed with wood sleeper			Using screw spike
Monolithic track bed and manhole in parking shed	Elastic separated	With bolt spring clip, without bolt spring clip	Embedding sleeve in the sleeper of vertical post

Sleepers (ties): Sleepers are typically formed as rectangular blocks and laid between rail and ballast aggregate to maintain a resilient, even and flat platform for holding the rails, and form of the rail basis of the fastening system.

Ballast: In railway, engineering ballast means the coarse aggregate placed over the sub-ballast and subgrade to act as a load-bearing platform for the superstructure. The ballast layer provides free drainage, tracks resilience, absorbs noise, and inhibits vegetation growth. The ballast bed thickness in the ballast channel on the bridge shall not be less than 250 mm. The thickness difference of the track bed with the track bed at the ends shall be of linear decline no less than 10 m outside the abutment [14].

Table 2: Thickness of Ballast bed [14]

Type of subgrade	**The thickness of the track-bed (mm)**		
	Mainline		Yard track
Non-permeable soil subgrade	Double-layer	Ballast 250	
		Bottom ballast 200	
Rock, permeable soil subgrade	Single-layer ballast 300		Single-layer 250

Sub ballast: Sub ballast is an aggregate placed between the ballast and subgrade. The sub-ballast layer prevents overstressing of subgrade and migration of fine materials from the subgrade.

Subgrade: Subgrade is the ground or formation where the rail track structure is built. It can be natural ground soil or a combination of filler material and it must provide a stable and suitable base for the construction of sub-ballast and ballast layers.

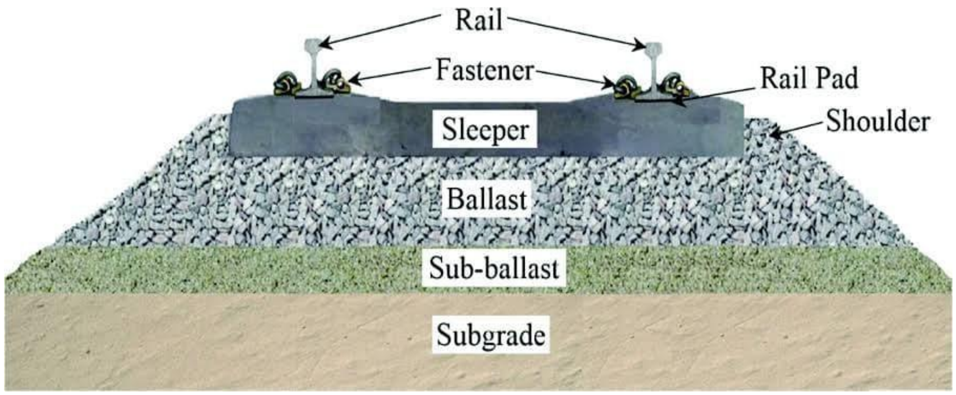

Figure 1: Components of Railway Track [3]

2.2.2. Track Requirements

The railway track is designed for a long period of service time. To maintain the lifetime of the track many requirements should be met. According to technical standards of AALRT [14], there are many provisions for all components of railway track. Some of the requirements are formulated as:

- The rails and switches must be safe for running the train at permissible speed and axle load. The correct geometry must be maintained under traffic loading and equilibrium state.
- Tracks must allow comfort for passengers. An improper combination of switches, curves and reverse curves may result in an unpleasant moment for the passenger.
- The track must be electrically insulated so that the track circuits required signaling even under unfavorable weather condition.
- The track must not cause excessive environmental pollution of noise and vibration.
- The track must be cost-effective for construction and during service life.

2.3. Railway Ballast

Ballast is a courser aggregate placed above the sub-ballast or subgrade to perform load-bearing support that comes from the track superstructure. Even if there is no worldwide consensus, exists related to the proper specification for the ballast material, crushed angular hard stones and rocks having a uniform gradation and free of dust have been considered as good ballast material [4]. Ballast is the primary geotechnical component of the rail track foundation and the main function is to control stress projected to the subgrade, decrease maintenance cost, and promote rapid drainage through the substructure.

2.3.1. Function of Ballast

Ballast should perform the following functions [15]:

- Provide a stable load-bearing platform and support sleepers uniformly
- Transmit high impressed load to the sleepers/ballast interface at a reduced and acceptable level
- Provide acceptable stability to the sleepers against longitudinal, vertical, and lateral forces generated by typical train speed
- Provide dynamic sufficient resiliency for the entire track
- Provide adequate resistance against crushing, biochemical and mechanical degradation, weathering and attrition
- Provide minimal plastic deformation to the track structure during the typical maintenance cycle
- Provide sufficient permeability for drainage
- Facilitate maintenance operation
- Inhibit weed growth by reducing fouling
- Absorb noise
- Provide adequate electric resistance

The ballast layer must meet four major geotechnical properties to perform the above functions: constituting particle characteristics (size, shape, surface roughness, particle crushing strength and resistance to attrition, etc.), bulk properties of granular structure (void ratio or density, degree of saturation and particle size distribution), loading characteristics (applied stress path, previous stress history, and current state of stress), and particle degradation (aggregate characteristics, combined effect of grain properties, and loading) [15].

2.3.2. Factors Governing Ballast Behavior

According to Indraratna and Salim the mechanical characteristics of ballast is governed by four main factors: [16]

a) Characteristics of constituting particles (size, shape, surface roughness, particle crushing strength, resistance to attrition and weathering, etc.)
b) Bulk properties of granular assembly (PSD, degree of saturation , and void ratio or density)
c) Loading characteristics (confining pressure, number of load cycles, and frequency of loading) and
d) Particle degradation is the combined effect of aggregate characteristics, grain properties, and loading.

Characteristics of Constituting Particles

Particle Size

The ballast aggregate size normally vary from 10 mm to 60 mm. Change in size may occur due to transportation, handling, placement, compaction, and the movement of heavy construction machines over the ballast layer.

Particle Shape

Angularity increases the frictional bond between the aggregate as a result it increases the shear strength of ballast. Most specifications limit the percentage of misshapen particles, where the term 'misshapen particles' means flat and elongated grains.

Surface Roughness

Surface roughness or texture is considered as the main factor that govern the angle of internal friction those are the basics for stability and strength of ballast. Because of grains internal friction under cyclic loading (increasing number of train passage), the surface roughness of ballast deteriorates with time and produces fines which are the source of ballast fouling. This is the best sign that the roughness of the surface significantly affects the mechanical behavior of ballast and track stability.

Parent Rock Strength

Degradation of ballast is a directly affected by the parent rock strength and therefore lateral deformation and settlement of rail track is indirectly affected by parent rock strength. Grain breakage and plastic settling are increased by weak particles compared to strong particles.

Particle Crushing Strength

Particle degradation, including grain splitting and breakage of sharp corners under loading, is governed by particle crushing strength. Particle crushing strength primarily depends on parent rock strength, grain geometry, the loading point, and loading direction.

Resistance to Attrition and Weathering

Ballast degradation is also governed by the characteristics of individual grains 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.

Aggregate Characteristics

The qualities of the overall granular mass that govern ballast behavior include particle size distribution (PSD), void ratio (density), and the degree of saturation.

Particle Size Distribution

The ballast gradation has a significant influence on track deformation behavior. Since ballast is expected to be coarse, free-draining medium, the optimum gradation should be between uniformly graded coarse aggregates and that give instantaneous drainage and broadly graded aggregates that provide higher strength and less settlement. Nevertheless, optimum grading should provide adequate drainage (hydraulic conductivity) along with sufficient initial density, shear strength, and resilient modulus.

Void Ratio (Density)

Void ratio is the ratio of volume of void by the volume of solid in a porous medium. It has been well established that an aggregate having a lower initial void ratio (higher initial density) is stronger in shear and generates a smaller settlement than the aggregate with a higher initial void ratio (lower initial density). Track stability can be improved by increasing ballast bed bulk density or by using broadly graded aggregates.

Degree of Saturation

In saturated conditions, subgrade soils soften and mix with water and form slurry, which under cyclic loading can be pumped up to the ballast layer. Water significantly affects the layer of ballast and leads to track settlement and particle breakage.

Loading Characteristics

Confining Pressure

Many studies indicated that the angle of internal friction granular mass decreases with increasing confining pressure. Indraratna [17] conducted a laboratory experiment on railway ballast (latite ballast) and observed that the drained ballast internal friction angle decreased from 67 % to about 46 % by increasing the confining pressure from 1 kPa to 240 kPa also revealed that the breakage of latite ballast may increase by 10 times as the confining pressure increase.

Number of Load Cycles

The accumulation of plastic deformation of ballast and other granular media is influenced by the number of load cycles. The settling and lateral deformation of granular ballast aggregates increase as the total number of load cycles increases [16].

Frequency of Loading

Train speeds vary from place to place, where train speed increases the dynamic forces and stresses increase on the ballast bed. AREMA clearly stated that as rail loading and speed increased, track geometry deterioration became a problem for the industry [18].

Particle Degradation

Geotechnical characteristics of materials made of granules, including the stress-strain behavior and strength, volume change and pore pressure development, and variation in permeability depend on the integrity of the particles or the particle crushing quantity that occurs from stress change. Particle degradation affects the behavior of ballast and other granular aggregates [16]. Abrasion and breakage of aggregate particles in many cases under traffic loading is the main cause of ballast fouling. Fouling is mostly caused by ballast aggregates degradation or breakage under traffic loads, but other fine debris intruding into a ballast layer which is clean can also contaminate ballast layer [6].

2.3.3. Ballast Zone

Railway ballast in the track may be divided into four zones. These zones are Crib ballast, Shoulder ballast, Top ballast, and Bottom ballast [3].

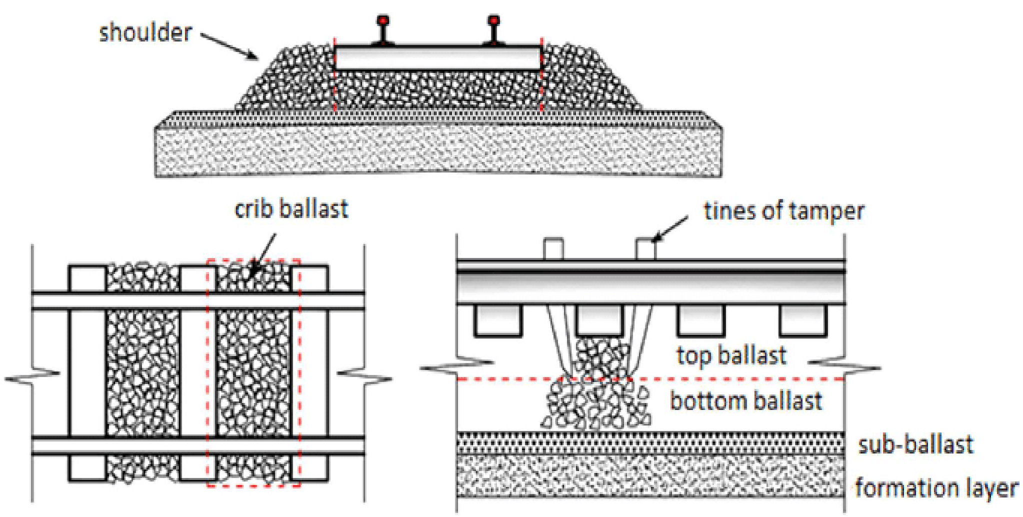

Figure 2: Ballast Zones [3]

i. Crib ballast. Crib ballast is the ballast located between the sleepers. The crib ballast provides pressure on the ballast below the sleepers, increasing the stability of railway and preventing longitudinal movement of the sleepers.

ii. Shoulder ballast. The shoulder ballast is located beyond the sleeper ends down to the bottom of the ballast. The main function of shoulder ballast is to protect the track from buckling due to temperature-induced rail stresses, with or without trains present.

iii. Top ballast. The top ballast is located below the sleepers and is disturbed by tamping.

iv. Bottom ballast. The ballast layer located at the bottom, under the sleepers and is not disturbed by the maintenance process and is commonly the more fouled portion.

2.4. Ballast Gradation

The optimum grading of ballast should ideally be in between uniformly and broadly graded aggregates that provide higher strength and less settlement. The optimum grading should still give sufficient hydraulic conductivity along with sufficient initial density, shear strength, resilient modulus, and be easy to be maintained. Ballast gradation is a prime factor for the stability, safety, and drainage of tracks. Ballast gradation must provide two key objectives: [18]

- Ballast must have adequate shear strength to give enhanced stability. and minimal track deformation. This can be attained by specifying broadly graded (well-graded) ballast.
- Ballast must have high permeability to provide adequate drainage, thus excess flow of water is quickly dissipated, and effective stresses are increased. This can be achieved by maintaining uniformly graded ballast.

PSD curve is extremely essential for coarse-grained soils and the permeability of coarse-grained soil depends to large extent on the particle size of the material.

2.4.1. Measure of Gradation

Soil gradation can be determined using uniformity coefficient (Cu) and coefficient of gradation (Cc). These coefficients help to classify the soil as well-graded or poorly graded ones [19].

Uniformity Coefficient (C_u)

The coefficient of uniformity (Cu) is calculated by dividing D_{60} to D_{10}. According to USCS, Cu values greater than 4 to 6 classifieds as well graded. If the Cu values is less than 4, the soil is classified as poorly graded or uniformly graded soil.

$$C_u = {}^{D_{60}}/_{D_{10}} \qquad 2.1$$

Where C_u is the uniformity coefficient, D_{60} and D_{10} are the diameters of the sieves by which passed 60% and 10% of the sample's total mass respectively.

The particles in uniformly graded soil are identical and have a Cu value of around 1. When the uniformity coefficient is 2 or 3, the soil is considered poorly graded. Beach sand comes under this category.

Higher value of C_u shows that the soil mass consists of soil particles with different size ranges.

Coefficient of Curvature (C_c)

The coefficient of curvature is calculated by:

$$C_c = \frac{(D_{30})^2}{D_{60} \times D_{10}} \qquad 2.2$$

The value of Cc must be between 1 and 3 in order for the soil to be well graded. Any single-sized soil mass, the value of both C_u and C_c is 1. In this research to classify the gradation as well-graded or uniformly graded the uniformity coefficient (C_u) is used as a measure of aggregate gradation.

2.4.2. Different Ballast Gradation Specifications

The ballast specifications of different countries vary widely use the coefficient of uniformity value ranges from 1.5 to 3.0 with a mean in the order of 2.0 or less. The reason for the choice of this gradation is not clearly defined. The ballast gradation plays a vital role in the strength, deformation, degradation, stability, and drainage of the track. Denser packaging with better frictional interlock and thus lesser settlement attained by well-graded ballast. However, all ballast requirements stipulate that the gradation be uniform for free drainage [16].

Australian Ballast Specification

According to the Australian Railway Specification ballast has been specified to be uniformly graded for the upper and lower limits of gradation range and the maximum percentage of dust and fine-grained materials (passing 0.075 mm sieve) in ballast is restricted to 1 %, as shown in the Table 3.

Table 3: Australian Railway ballast grading requirements [13]

Sieve size (mm)	% Passing (by mass) Nominal size, (mm)			
	60	60	50	50
63.0	100	100	-	-
53.0	85-100	95-100	100	100
37.5	20-65	35-70	90-100	70-100
26.5	0-20	15-30	20-55	-
19.0	0-5	5-15	0-15	40-60
13.2	0-2	0-10	-	-
9.5	-	0-1	0-5	10-30
4.75	0-1	-	0-1	0-20
1.88	-	-	-	0-10
0.075	0-1	0-1	0-1	0-1

American Ballast Specification

The ballast gradation material is a prime consideration of ballast materials. The grading system must provide the means to develop the compact or density requirement for the ballast section and provide necessary void space to allow proper runoff of groundwater. Ballast should be graded uniformly from the top limit to the lower limit to provide density, uniform support, elasticity and to reduce deformation of the ballast section from repeated track loadings [18]. The AREMA mainline ballast is graded in three sizes from 75 mm to 2.36 mm. AREMA No. 4 grading is identical to American Standard Testing for Material (ASTM) C33 grading 4 and ASTM C33 grading 56 is very similar to AREMA grading No. 5. Most railway companies in the U.S implement AREMA grading; only Norfolk Southern Corporation (NSC) has modified AREMA grading No. 3 for heavy tonnage tracks and uses AREMA grading No. 5 for the yard [13].

Table 4: AREMA Railway ballast grading requirements [13]

Size No. (See Note 1)	Nominal Size Square opening	% Passing									
		75	63	50	37.5	25	19	12.5	9.5	4.75	2.36
24	63	100	90-100		25-60		0-10	0-5	-	-	-

25	63	100	80-100	60-85	50-70	25-50	-	5-20	0-10	0-3	-
3	50				35-70	50-70	-	0-5	-	-	-
4A	50				60-90	0-15	0-10	-	0-3	-	-
4	37.5				90-100	10-35	0-15	-	0-5	-	-
5	25				100	20-55	40-75	15-35	0-15	0-5	-
57	25				100		-	25-60	-	0-10	0-5
Note 1: AREMA specification numbers 24, 25, 3,4A, and 4 are mainline ballast materials. Yard ballast materials are specified in specifications 5 and 57.											

2.5. Ballast Fouling

Ballast deteriorates as angular corners and sharp edges of aggregate break, , as well as mud-pumping from the subgrade, and from the surface infiltration of fines under train loading. When the ballast voids are fully or partially occupied due to the intrusion of fouling materials, the ballast can be considered to be "fouled". Fouling is the term that defines fines that fill the ballast void. As the ballast fouled the track performance will be in question due to settlement and drainage problems. The saturation of the ballast material and track-bed is inevitable as a consequence of poor water seepage from the track structure due to ballast fouling [6]. It is crucial to establish a better understanding of ballast degradation and fouling mechanisms in the field for adopting proper track maintenance practices and improving the safety and reliability of the railroad network [6].

2.5.1. Fouling index and Percentage of Fouling

Ballast fouling can be accessed through both visually inspecting it as well as determining its particle size distribution. Particle size distribution information is used in particular to quantify the extent of fouling, which is used to estimate residual fouling of track and to give away for cleaning or replacing consideration of the ballast. When the level of fouling is determined to be equal to or greater than the limit indicated by the chosen methods of quantification, the ballast has to be either cleaned or replaced [20]. Selig and Waters [3] introduced the fouling index (FI) to describe ballast fouling based on gradations obtained for representative samples of ballast in North America.

$$FI = P4 + P200 \qquad 2.3$$

P4 and P200 are percentages of ballast particles passing the No. 4 sieve (4.75 mm) and No. 200 sieve (0.075 mm) respectively.
A related index to FI is the percentage of fouling (% fouling) which is the ratio of the dry unit weight of material passing 9.5 mm sieve to the dry unit weight of the total sample.

Fouling ratio is computed as:

$$FR = {}^{MF}/_{MB} * 100 \qquad 2.4$$

Where, FR = Fouling ratio (%)

MF = Mass of fouling finer than 9.5 mm size (kg)

MB = Mass of the ballast sample (kg).

There are several methods of assessing the extent of ballast fouling. From those methods Percentage of Fouling (Fouling Ratio) and Fouling Index (FI) methods are mass-based measures. The category of Fouling extent by both of mass-based methods are explained in the Table 5:

Table 5: Category of ballast Fouling [16] [3]

Fouling category	**Fouling index (%)**	**Percentage of fouling (%)**
Clean	<1	<2
Moderately clean	1 - 9	2 - 9.5
Moderately fouled	10 - 19	9.5 - 17.5
Fouled	20 - 39	17.5 - 34
Highly fouled	>39	≥34

2.5.2. Sources of Ballast Fouling

Different studies have been conducted to present the source of fouling materials within railway ballast. Selig and Waters [3] found that ballast fouling was caused through five primary modes and concluded that ballast breakage is the most significant source of fouling which contributes to more than three-quarters of total fouling. These sources of ballast fouling are:

- Abrasion and breakdown of ballast due to rail loading, tamping, and freeze/thaw
- Degradation of rail ties
- Migration of subgrade material into the ballast aggregate
- Migration of sub-ballast or subgrade material into the ballast aggregate
- Migration of environmental material into the surface of the ballast

Dynamic loading of the track leads to ballast attrition, resulting in the breakage of ballast particles. The amount of fines produced reduces the permeability of the ballast as well as its ability to maintain track geometry. Ballast breakage accounts for between 70% and 76 percent of the fines produced [20].

2.5.3. Effect of Ballast Fouling

The saturation of the ballast material and track-bed is inevitable due to poor water seepage from the track structure due to ballast contamination. In other studies, The most problematic fouling material is fine materials from subgrade (such as clay) in the ballast layer, Their presence has a negative impact on railway track performance. Sussmann et al. [21] reveal that ballast fouling particularly due the presence of silt and clay materials, the internal friction between angular particles is reduced. Also, a decrease in ballasted railway hydraulic conductivity with an enormous quantity of fouling has been reported. As the ballast progressively becomes fouled (contaminated with particles of sand and silt–clay size), As the space between particles that is void fills, the hydraulic conductivity steadily decreases, and the layer susceptible to rapid moisture-related deterioration. The necessary free movement of nearby particles is impeded when the void area in the ballast layer becomes filled with fouling material, and the compaction and consolidation process does not take place.

As ballast fouls, the vacant space is partially filled by fouling material, temporarily increasing the layer's strength and stability. However, due to a lack of drainage capacity and continuous loading of heavily fouled ballast, the fouling material frequently forces the ballast particles apart by the fouling material either by mechanical movement of the particles under load in contact with fouling material or because the fouling material reduces friction at interparticle contact regions, some interparticle compressive force is released, decreasing the ballast stability and the entire track structure [21].

As Selig and Waters [3] explained the loss of performance of track is mainly affected when the fouling materials are composed of clay and silt and the higher quantity will cause severe problems. In addition, both fouling materials impede drainage and increase the possibility of significant ballast deterioration. Ballast that has become fouled must be cleaned and replaced to keep stability and safety, the level and alignment of the track [22].

2.6. Hydraulic Conductivity of Ballast

Drainage plays a fundamental role in the safety and stability of track structures. The primary function of track drainage is to remove water from the substructure as fast as possible and maintain the load-bearing stratum relatively dry. Excess pore water pressure might develop up under train loads due to poor drainage. If the permeability of the substructure is excessively low the excess pore water pressure cannot be dissipated before the next imposed load. To avoid this problem the load-bearing layer ballast is usually composed of coarse and uniformly graded aggregates with large size voids ensuring sufficiently high permeability. Track substructure should be adequately designed and constructed to drain the infiltrated water out of the load-bearing layer to the nearby drainage ditches or pipes. Internal drainage is usually insured by placing a sub-ballast layer having appropriate gradation [16]. In the case of inadequate drainage, the following problems may occur in the track:

- Decrease in ballast shear strength, stiffness, and load-bearing capacity
- Increase track settlement
- Softening of subgrade
- Under cyclic loads, slurry formation and clay pumping
- Ballast attrition due to jetting action and water freezing
- Sleeper degradation caused by water jetting

All of these issues will deteriorate the track and require more maintenance cost. To prevent these problems adequate drainage is imperative in ballasted track. Water that influences the track performance may enter through the structure either by precipitation, surface flow, or surface seepage. Excess water from substructure, specifically when it creates a saturated state, causes a huge increase in track maintenance cost because each source of water requires a different drainage method [3].

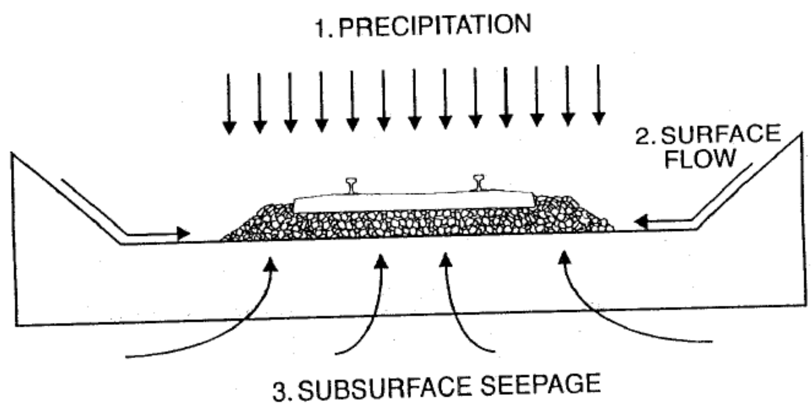

Figure 3: Sources of water entering track structure [3]

According to Addis Ababa Light Rain Transit (AALRT) technical standard it is clearly defined that subgrade shall be provided with a perfect drainage system, and be conveniently combined with municipal drainage facilities. The drainage facilities shall be laid out reasonably. When the connection is made with such drainage facilities as bridges and culverts, tunnels and stations, etc., smooth drainage shall be ensured. Necessary waterproof and drainage facilities shall be provided around the base, preventing leakage of water on the earth's surface. In addition, it is stated that for the soft and weak subgrade, the drilling should reach 20 to 30 m below the original surface, the impact of groundwater on the construction of the project shall be predicted, and the treatment and prevention measures be proposed. However, there is no general provision related to different types of fouling materials effect and their remedy actions [14].

2.6.1. Determination of Hydraulic Conductivity Value (k)

The permeability of coarse-grained soil depends to a large extent on the particle size of the material. An approximate value of the permeability coefficient can be determined by particle size. The coefficient of permeability has the dimension of velocity, it can be measured in mm/sec, cm/sec, m/sec, or any other velocity units [19].

The coefficient of permeability (hydraulic conductivity) can be determined using the following methods: [19]

a) Laboratory Methods
   - Constant head permeability test
   - Falling head permeability test

b) Field Methods
   - Pumping-out test
   - Pumping-in test

c) Indirect Methods
   - Computation from particle size or specific surface
   - Computation from consolidation data

d) Capillarity-Permeability Test

The appropriate way to evaluate the value of k for a particular porous medium is by conducting field and laboratory experiments such as falling head and constant head permeability tests. However, many researchers have presented several empirical formulae based on the characteristic grain size of the medium to model permeability [16].

As Indraratna and Salim [16] stated the flow through porous media such as ballast and sub-ballast is usually determined using Darcy's law:

$$v = k \times i \qquad 2.5$$

Where v = average velocity of the fluid, i = hydraulic gradient, and

k= the coefficient of permeability (hydraulic conductivity). They also state the Equation 2.6 Hanzen's formula to estimate the permeability of granular aggregates.

$$k = C \times (D_{10})^2 \qquad 2.6$$

Where k is the coefficient of permeability, C is an empirical constant that varies from 40 - 150, and D_{10} is the diameter of the sieves by which 10% of the sample's total mass passed.

The soils having the coefficient of permeability greater than 10^{-3} mm/sec are classified as pervious and those with a value less than 10^{-5} mm/sec as impervious. The soils with the coefficient of permeability between 10^{-5} to 10^{-3} mm/sec are designated as semi- previous [16].

Table 6: Drainage Properties of Soil [16]

No.	Soil type	Coefficient of permeability(mm/sec)	Drainage properties
1	Clean gravel	10^{+1} to 10^{+2}	Very good
2	Coarse and medium sands	10^{-2} to 10^{+1}	Good
3	Fine sand, loose silt	10^{-4} to 10^{-2}	Fair
4	Dense silt, clayey silts	10^{-5} to10^{-4}	Poor
5	Silty clay, clay	10^{-8} to 10^{-5}	Very poor

The drainage potential of ballast due to fouling materials as well as the intrusion of external fine material (from subgrade and surface) will be highly affected. For the ballast having different degrees of fouling typical values of k have presented in Table 7: [3]

Table 7: Representative k values of Ballast [16] [3]

Fouling category	Fouling index (%)	Percentage of fouling (%)	Representative k values (mm/sec)
Clean	<1	<2	25-50
Moderately clean	1 to 9	2 to <9.5	2.5-25
Moderately fouled	10 to 19	9.5 to <17.5	1.5-2.5
Fouled	20 to 39	17.5 to <34	0.005-1.5
Highly fouled	>39	≥34	<0.005

Chapter Three

3. Materials, Methods, and Procedures

3.1. Description of Study Area

This study will be in different sites of Addis Ababa Light Rail Transit (AALRT). It is electrified light rail transit with design speed of 80 km/hr. This line extends from the city center to different areas of the city. The total length of the line segment is 34.25 kilometers with 39 stations, the east-west line is the first of two rail lines 17.35 kilometers (10.8 mi), crossing via Megenagna and extending from Ayat to Torhailoch, Meskel Square Legehar, and ending Mexico Square. The second is the 16.9-kilometer (10.5 mi) north-south line. in length, passes through Menelik II Square, Merkato, Lideta, Legehar, Meskel Square, Gotera, and Kaliti. However, a 2.7 kilometer shared track connects the two lines. The elevated stretch across the southern running east to west perimeter from Meskel to Mexico Square, and beyond to Lideta, is the common track. The north-south route has blue and white trains, whereas the east-west line has green and white trains. Fares range from 2 to 4 Ethiopian birr.

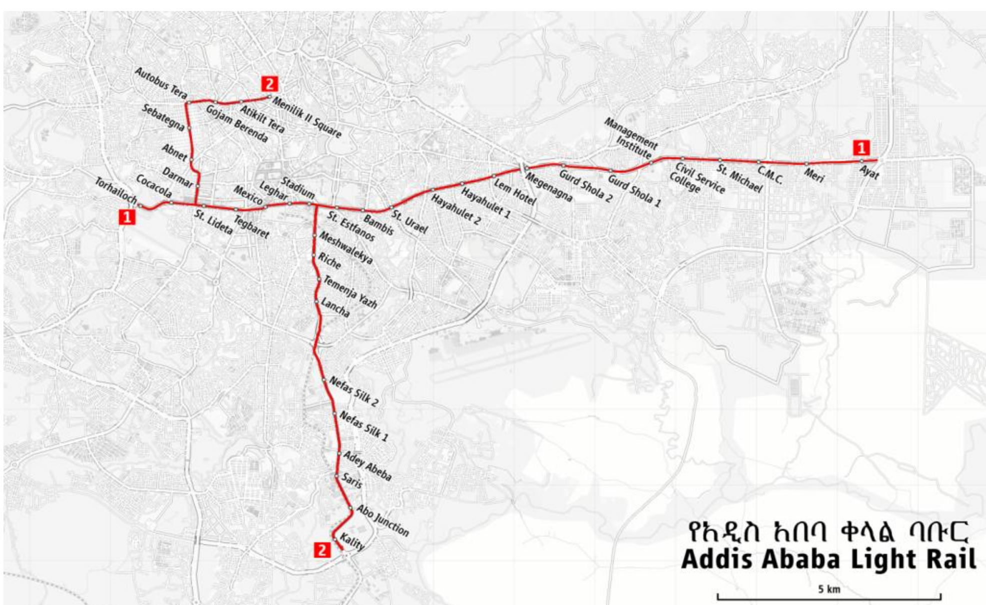

Figure 4: Map of AALRT

3.2. Sampling

To meet the main goal of this study, an inspection of ballast was very essential and the sampling method developed had to capture the fine material, along with the coarse ballast, to later produce the fine materials to alter the drainage performance of ballast from sieving. Hence, drainage plays a vital role in track performance and stability it is critical to identify the ballast condition and find techniques for systematic evaluation of ballast. Therefore, before evaluating the ballast fouling condition, the first task that should be undertaken is assessing the selected areas to determine critical fouled sites and to choose sampling places. During the visual inspection, it was very easy to suggest where the ballast is fouled and where the ballast is relatively clean but the fouling ratio should be computed to conclude which area is highly fouled and which type of fouling material impedes the ballast aggregate. In this study, attention was given to the three mainline critical points of Addis Ababa Light Rail Transit (AALRT) due to the following reasons:

- At transition, there will be contamination of ballast due to intrusion of fine particles from the highway roads.
- At curves and turnouts, there will be more fatigue and degradation of ballast aggregate due to high friction and vehicle load.
- At the depot, there will be relatively clean ballast, which is used as a comparison for this study.

Figure 5: Railway line along transition

Figure 6: Railway line at Kality Depot

3.3. Materials

3.3.1. Properties of Railway Ballast Aggregate

Three different initial gradations are examined to characterize the effect of aggregate gradation for ballast particles on the basis of American Railway Engineering and Maintenance of Way Association (AREMA) specification. Table 8 shows the general characteristics of a described particle size distributions (PSDs) of fresh ballast aggregate.

Table 8: Properties of characterized gradation

Gradation type	D_{max} (mm)	D_{10}(mm)	D_{60} (mm)	$C_u=D_{60}/D_{10}$ (mm)
AREMA- 3	50	28	41.2	1.53
AREMA- 4	37.5	16	26.3	1.85
AREMA-24	63	19	37.5	1.97

3.3.2. Size of Fouling Materials

In this research, three different fouling materials are used. Table 9 presents the size of fouling materials with different sizes. By considering different studies, As fine sand, the size spans between 0.075 mm and 0.425 mm, silt extending from 0.002 mm to 0.075 mm, and clay ranging from 0.002 mm or less are characterized for fouling particles.

Table 9: Size of characterized fouling materials

Type of soil	Fine Sand	Silt	Clay
Particle Size (mm)	0.075 to 0.425	0.002 to 0.075	<0.002

3.4. Procedures

In this study, all test procedures have been conducted according to the corresponding ASTM and AREMA standards. Laboratory tests namely Gradation for different ballast and fouling materials and Permeability tests with a constant head to determine their Hydraulic Conductivity value have been performed per these standards. The findings were also compared with the requirements of the standards.

The fouling ratio method was used to determine the level of fouling material intrusion into the ballast aggregate, and the fouling materials were sieved through a smaller sieve set. To analyze the drainage performance of the ballast, using constant head permeability the hydraulic conductivity (permeability) of clean and fouled ballast samples was measured as per ASTM 2434 [23]. In this study, three different gradation types and three different fouling materials were used to evaluate the effect of gradation and fouling materials on the drainage performance of ballast. Figure 6 presents a flow chart that describes the main goal of the study and the process through which the gradation and the fine materials are used.

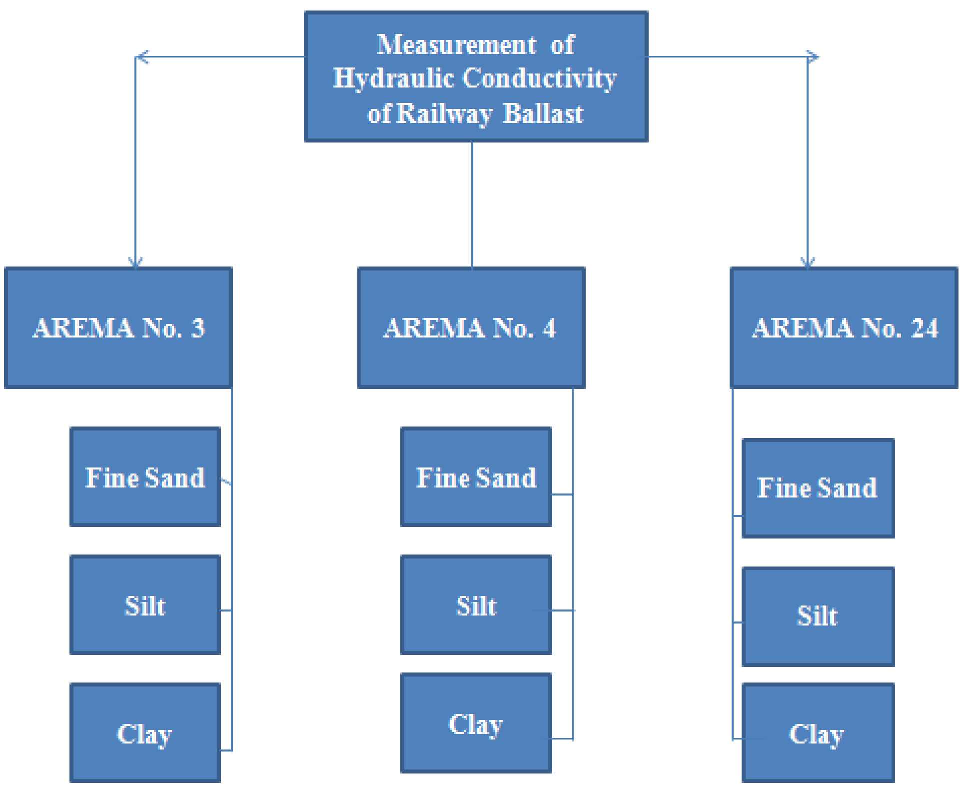

Figure 7: Flowchart of considered conditions for evaluation of hydraulic conductivity

3.5. Laboratory Tests

3.5.1. Gradation of Ballast

The gradation of ballast aggregates was determined by conducting a sieve analysis test. The particle size distribution to describe different gradations and the extent of fouling was analyzed by the sieve analysis. Ballast aggregates were sieved with a sieve manually and the sieve used to separate different particle sizes was having the openings from 63 mm and ending at 9.5 mm.

According to ASTM C136, the sample sizes were chosen depending on the aggregate Nominal Maximum Size. In this study, 35 kg were chosen as a test sample and dried in an oven at 110 $\pm 5°$ C for 24 hours then cooled to room temperature. In each sieve the amount of material retained was noted down and expressed in percentage [24].

The sieving process in the laboratory has been done in two ways. During the first sieving stage, the whole ballast sample was run through different-sized large sieves designed for aggregate. The second sieve stage involved splitting the fines accumulated during the large sieving and sieving them with a smaller set. The materials passing 9.5 mm sieve are called fouling materials which are used for calculating the percentage of fouling in the given sample and fine materials used for differentiating the type of fouling materials were sieved by smaller sieve sizes.

Three samples have been taken from the mainline by considering critical areas susceptible to fines resulting in fouling and at the depot for comparison. Kality Depot, Transition at Kality, and Gurd Shola2 were the areas of track sections.

In order to classify the gradation as well-graded or uniformly graded the coefficient of uniformity (Cu) is used as a measure of aggregate gradation. Equation 2.1 is used to calculate C_u:

$$C_u = D_{60}/D_{10} \qquad 3.1$$

Where C_u is the coefficient of uniformity, D_{60} and D_{10} are the diameters of the sieves by which passed 60% and 10% of the sample's total mass respectively. Figure 8 represents AREMA specification for gradation to characterize the type of gradation used.

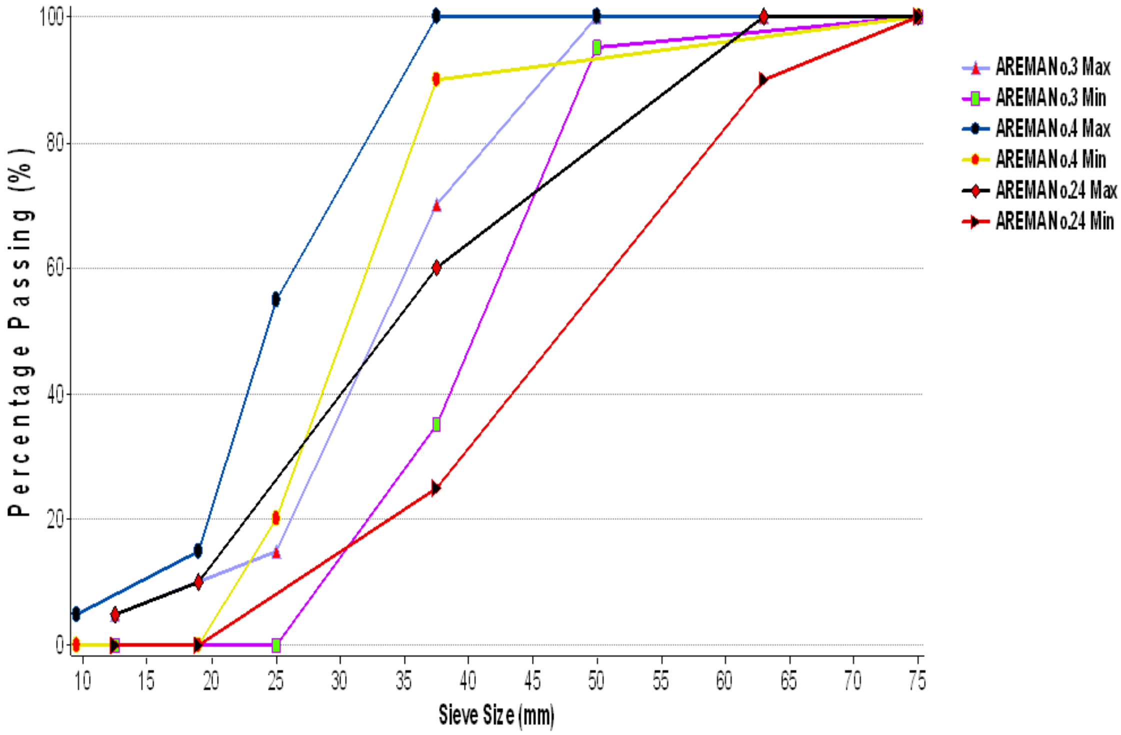

Figure 8: Selected AREMA Specification Limits

3.6. Percentage of Ballast Fouling

Fouling material has been defined as the material passing the 9.5 mm size sieve [3]. To consider all materials passing these sieves, the present study used the fouling ratio (FR) method used to quantify the amount of contamination of ballast. Fouling ratio is computed by Equation 2.4.

$$FR = {}^{MF}/_{MB} * 100 \qquad 3.2$$

FR = Fouling Ratio (%)

MF = Mass of the fouling material finer than 9.5 mm size (kg)

MB = Mass of the ballast sample (kg).

After calculating the percentage of fouling, to categorize whether the ballast sample is clean or fouled ballast Table 13 is used.

Table 10: Category of ballast

Fouling category	Percentage of fouling (%)
Clean	<2
Moderately clean	2 to 9.5
Moderately fouled	9.5 to 17.5
Fouled	17.5 to 34
Highly fouled	≥34

3.6.1. Classification of Fouling Material

In this study the fouling material types and characteristics were different for those selected sites of the track, one is found fouled with predominantly clay, while others were fouled with sand. Sieve analyses have been conducted to accumulate different sizes of fouling materials used for the permeability test. Fouling materials are materials passing 9.5 mm sieve, to differentiate fouling materials sieving has been done with different smaller sieve sets.

By considering different studies, materials characterized for fouling the particle size ranges from 0.075 mm to 0.42 mm as fine sand, silt extending from 0.002 mm to 0.075 mm, and clay ranging from 0.002 mm to less than 0.002 mm.

Table 11: Fouling material types on the area

Type of soil		Fine Sand	Silt	Clay
Particle Size (mm)		0.075 to 0.42	0.002 to 0.075	<0.002
Kality Depot	Mass Retained (g)	80	-	-
Transition at Kality		329	1489	1686
Gurd Shola		501	470	328

Figure 9: Fouling materials

3.7. Hydraulic Conductivity of Ballast

In this study, the hydraulic conductivity of clean and fouled ballast samples was measured using a constant head permeability tester. Permeability tests were performed in a specially designed test box to determine the hydraulic conductivity of the sample. The box is composed of clear glass to promote visual inspection. The constant head permeability testing device was made up of a circular cylindrical chamber with the length of 14.5 cm and area of 45.34 cm^2 as illustrated in Figure 10.

Figure 10: Constant Head Permeability machine

This study was performed in compliance with ASTM D2434 permeable granular media by presuming laminar flow conditions. Based on the proposed law, the relationship is expressed by Equation 3.3:

$$Q = k\left(\frac{dh}{L}\right) = k \times i \qquad 3.3$$

Q = Flow velocity (cm/s)

k = Hydraulic conductivity coefficient (cm/s)

dh= Head difference between two points (cm)

L = Length of the porous specimen along the flow direction (cm)

For clean and fouled ballast hydraulic conductivity was measured on an average basis. In this study to evaluate the fouling effect, 42.86% by mass of fouling used to alter the hydraulic conductivity, materials have been used i.e. 1260 g of ballast aggregate for each gradation and 540 g of fouling materials for each type of fouling. After many trials, the value of the average hydraulic conductivity was used and the values of hydraulic conductivity for clean and fouled ballast is presented in APPENDIX C of this paper.

Chapter Four

4. Results and Discussion

4.1. Sieve Analysis Test Results

4.1.1. Gradation Results

Ballast gradation is a prime factor for the stability, safety, and drainage of tracks. The particle size distribution is extremely essential for coarse-grained soils and the permeability coefficient of coarse-grained soil depends to large extent on the size of the particle. The coefficient of uniformity (C_u) and the gradation coefficient (C_c) are soil gradation measurements. The coefficients contributes in soil classification as well-graded or uniformly graded. The ballast material which has been tested for this study, is crushed aggregate from the mainline track of Addis Ababa Light Rail Transit (AALRT) in which the particles range from 63 mm to 9.5 mm.

AREMA requirement states that ballast must have high permeability to provide adequate drainage, to readily dissipate pore water pressure that is too high and increasing the effective stresses. This can be ensured by specifying uniformly graded ballast. The gradation of ballast samples on the track completely fulfills the AREMA requirement to meet this specific objective. The samples have been found with values of C_u smaller than 4, this signifies that all of the samples were uniform.

Table 12: Measure of Gradation for Samples

Sample	D_{60} (mm)	D_{10} (mm)	$C_u=D_{60}/D_{10}$ (mm)
Kality Depot	34.22	21.50	1.59
Transition at Kality	34.55	17.83	1.94
Gurd Shola	35.69	20.07	1.78

Table 17 shows the gradation at each selected site and the corresponding plots are shown in Figure 11.

Table 13: Gradation of ballast sample

Sample	Kality Depot	Transition at Kality	Gurd Shola
Sieve size (mm)	% Passing		
75	100.00	100.00	100.00
63	100.00	100.00	100.00
50	95.46	92.36	88.16
37.5	73.76	69.92	66.16
25	21.31	27.88	23.60
19	1.89	12.91	7.04
12.5	0.38	9.56	4.06
9.5	0.22	8.80	3.56

Figure 11 shows the ballast gradation difference between the samples from the track. This will help to predict the extent of fouling in each selected sample.

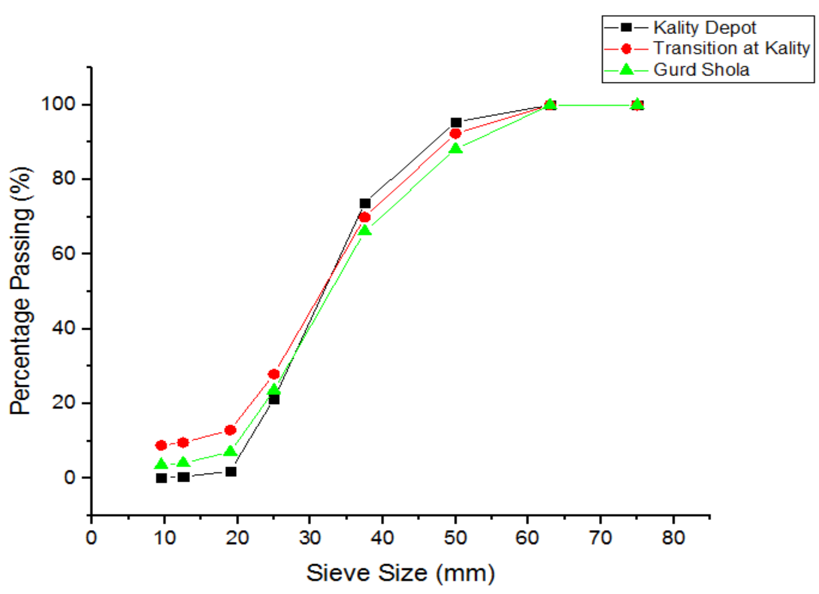

Figure 11: PSD curve for selected sample

4.1.2. Percentage of Fouling Results

Ballast fouling has an influence on the ballast layer permeability by its deleterious behavior, and this leads in drainage performance reduction of the railway track. The influence of ballast fouling resulting from the degradation of aggregate as well as the intrusion of fine materials from the environment affects the permeability of railway ballast. Attention has to be given to the quantification and reduction of ballast fouling before reaching catastrophic failure for the track.

In this study the fouling material types and characteristics were different for those selected sections, one is found fouled with predominantly clay others were fouled with sand. The effect of each fouling material on hydraulic conductivity value is different and discussed in the next section on fouled ballast hydraulic conductivity. The percentage of fouling is determined to be clean for Kality Depot and moderately clean for Transition at Kality and Gurd Shola samples. The results show that if the line is not given attention to cleaning the ballast is reaching the next level of moderately fouled ballast within its short period of service life and its cumulative effect will result in deterioration of the track.

Table 14: Percentage of Fouling on the samples

Sample	Kality Depot	Transition at Kality	Gurd Shola
% Fouling	0.22	8.80	3.56

During site investigations on selected sites of the one at transition, the Transition at Kality is highly susceptible to fouling from the corresponding highway line and the ballast will be filled with fine particles and lead to track deterioration. It is expected that the line will be in serious condition if it is not given attention.

4.2. Permeability Test Results

The stability and safety of the track structure are highly dependent on the drainage performance of track components. Poor drainage results in the build-up of excess pore water pressure under train loading. The primary function of ballast is to maintain the drainage performance of the track. Due to many reasons, the ballast layer may not able to perform its functions. Popular reasons of the ballast reducing its drainage performance is ballast fouling. On the other hand, the gradation of ballast also affects the drainage performance of ballast. In this study, by constant head the permeability of fouled and clean ballast aggregate was tested. For a different type of fouling and gradation type, the hydraulic conductivity value has been found different. Table 19 summarizes the experimental results on both clean ballast and fouled ballast specimens. Different trials and detailed experiment results are attached in the APPENDIX C of this paper.

Table 15: Constant Head Permeability Test Results

No.	Tests	Test methods	Test Results					
			AREMA-24	AREMA-24 + Sand	AREMA-24 + Silt	AREMA-24 + Clay	AREMA-3	AREMA-3 + Sand
1	Permeability (cm/sec) k	ASTM (2434)	$2.90X10^{-2}$	$4.63X10^{-2}$	$7.70X10^{-3}$	$1.30X10^{-3}$	$1.51X10^{-1}$	$6.0X10^{-2}$
No.	Tests	Test methods	Test Results					
			AREMA-3 + Silt	AREMA-3 + Clay	AREMA-4	AREMA-4 + Sand	AREMA-4 + Silt	AREMA-24 + Clay
2	Permeability (cm/sec) k	ASTM (2434)	$2.94X10^{-2}$	$1.29X10^{-2}$	$2.30X10^{-2}$	$4.86X10^{-2}$	$6.62X10^{-2}$	$7.46X10^{-3}$

4.2.1. Hydraulic Conductivity of Clean Ballast

In this study to demonstrate gradation effect on drainage performance of clean ballast sample, three different types of gradation were used, namely AREMA No. 3, AREMA No. 4, and AREMA No. 24. The hydraulic conductivity coefficient that has been calculated under flow conditions is greater for ballast that has been uniformly graded (AREMA No. 3) than for ballast that has been graded more broadly (AREMA No. 4 and AREMA No. 24) by 15.2 % and 19.2 %

respectively, due to a lack of porosity. Furthermore, higher uniformity of gradation of clean ballast aggregate results in lower estimated hydraulic conductivity values.

4.2.2. Hydraulic Conductivity of Fouled Ballast

The hydraulic conductivity of fouled ballast and the combined effect of initial gradation with three different AREMA classification of gradation was investigated. The clean ballast was fouled with intrusion of fouling material particles by 42.86% of fouling ratio, and then the constant head permeability test was performed. It's found that fouling materials highly affect the drainage performance of ballast by altering its hydraulic conductivity value. The permeability of clay-fouled ballast is significantly less than all the ballast samples fouled by fine sand and silt fouling materials. The clean ballast fouled by clay has shown hydraulic conductivity reduction by 4.48 % in AREMA No 24, 8.52 % in AREMA No. 3, and 32.47 % in AREMA No 4 of selected gradations. The experimental results conducted on fouled ballast specimens with different initial gradations contaminated by clay particles are summarized in Table 20.

Table 16: Reduction of Hydraulic conductivity due to Fouling

Gradation	Clean ballast k-value (cm/sec)	Fouled ballast k value (cm/sec)	Percentage reduction (%)
AREMA No. 3	0.151	0.01287	8.52
AREMA No. 4	0.023	0.00746	32.47
AREMA No. 24	0.029	0.0013	4.48

Chapter Five

5. Conclusions and Recommendations

5.1. Conclusions

The primary goal of the present study was to assess the hydraulic conductivity (permeability) of clean ballast aggregate by considering different gradations of clean ballast prepared from the sample as well as different sizes of fouling materials. In this regard, permeability tests with a constant head were carried out on clean and contaminated ballast samples with a specific focus on the effect of ballast aggregate gradation, the effect of different fouling material, the combined effect of ballast aggregate gradation and different fouling material on ballast drainage performance by analyzing the hydraulic conductivity (k) value.

Based on the findings of the present study, the gradation of ballast samples on the track fulfills the AREMA requirement to ensure proper drainage by maintaining uniform gradation. The percentage of fouling in the line was found clean for Kality Depot and moderately clean for Transition at Kality and Gurd Shola but if attention is not given for the case of the track along with transition its cumulative effect will result in deterioration of the track.

The test of constant head permeability results reveal that for a different type of fouling and gradation type the value of hydraulic conductivity is different. The hydraulic conductivity value less than 10^{-4}mm/sec is characterized as an unacceptable condition for ballasted railway tracks. As a result of the higher permeability of sand in comparison to the conventionally considered fouling materials (silt and clay), the drainage condition of ballast samples is still acceptable. However, hydraulic conductivity (k) value under the given condition is higher for uniformly-graded ballast (AREMA No. 3) and lesser for more broadly graded gradation (AREMA No. 4 and AREMA No. 24).

The fouling materials highly affect the drainage capacity of ballast by altering its hydraulic conductivity value. The permeability of clay-fouled ballast is significantly less than all the ballast samples fouled by fine sand and silt fouling materials.

5.2. Recommendations

Ballast cleaning is a cost-effective recycling maintenance procedure that extends the life of ballast while lowering total maintenance costs. It is possible to achieve a more cost-effective operation by better planning of proactive ballast-cleaning cycles. One means to accomplish this is by better estimating fouling extent of the ballast layer. It is recommended to experience conventional checking and estimating the percentage of fouling for better utilization of the line.

From the specified locations of field samples collected even though the gradation subjected to mechanical sieving were identified met the requirement to maintain proper drainage, the problematic spots belonging to the main lines by having the undesirable extent of fouling. Cleaning considerations have to be given before the track reaching to the category of fouled ballast and loses its intended function.

In wet conditions, fouling material inhibits the track's drainage performance, resulting in internal pore water pressures. Furthermore, ballast particles fouled by migrated fine particles especially clay reduce the permeability of the ballast layer. It is crucial to create a solution whereby the highway meets the railway line along with the transition.

Despite the negative impact that fines have on railway track performance, it is critical to have appropriate criteria for estimating the extent of fouling and drainage performance of the ballast layer.

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APPENDIX A

Particle size distribution curve of ballast for each site

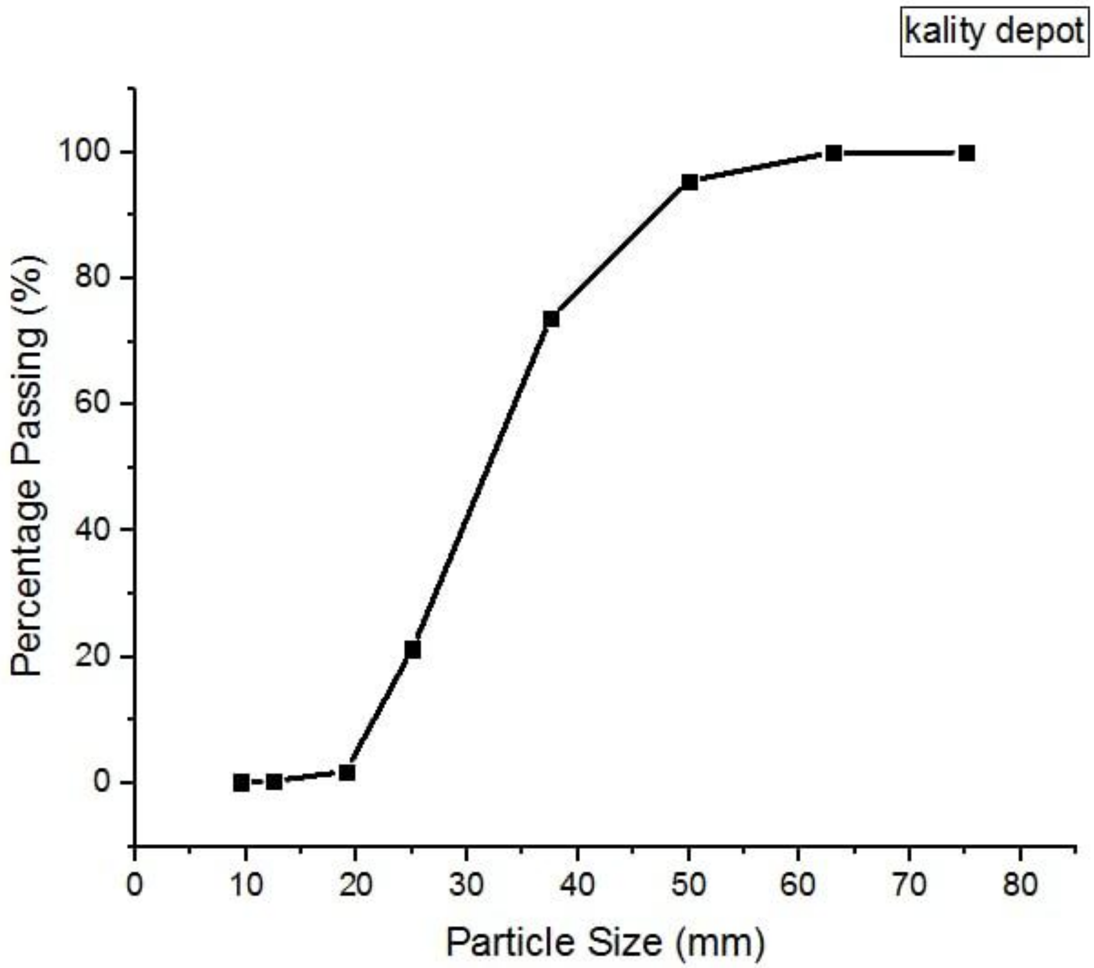

Figure 12: PSD curve for Kality Depot sample

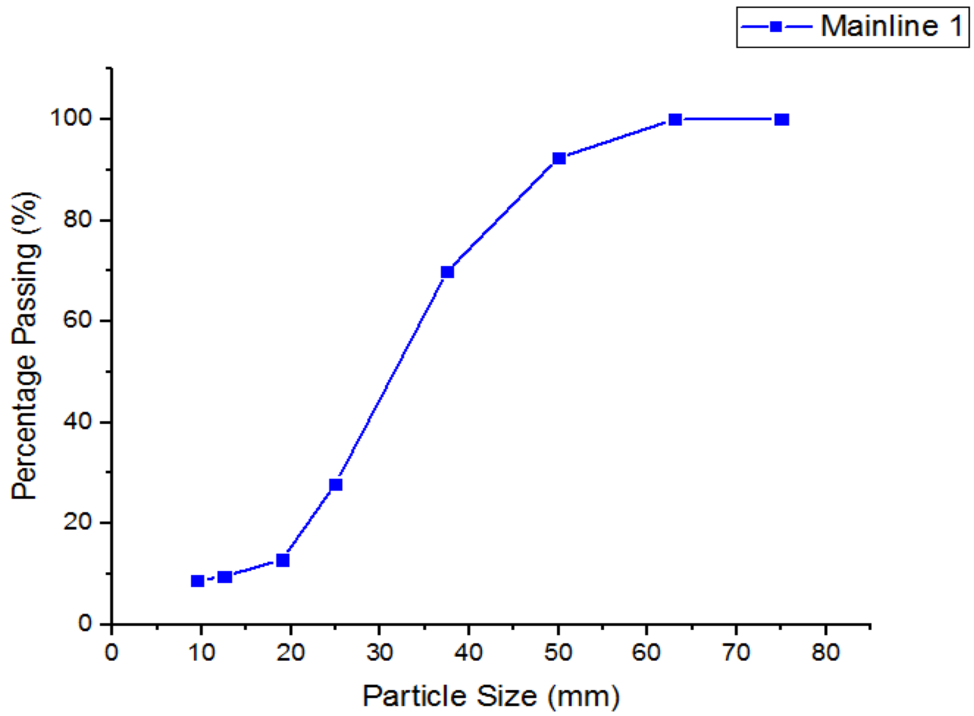

Figure 13: PSD curve for Kality transition sample

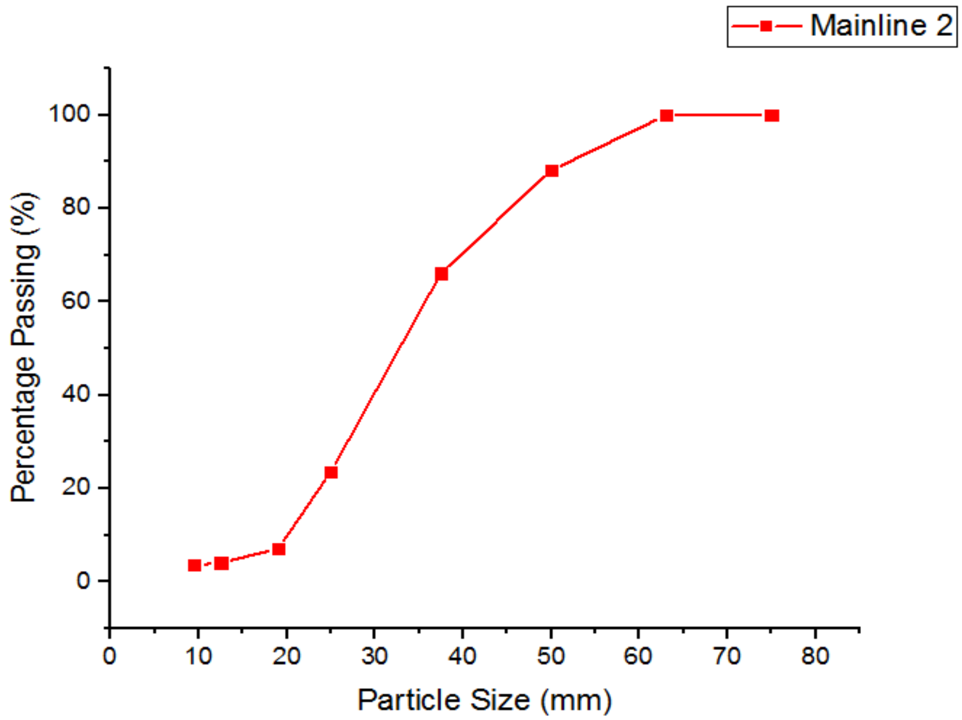

Figure 14: PSD curve for Gurd Shola sample

APPENDIX B

Test Procedures:

Sieve Analysis:

1) Take note of each sieve and the pan weight at the bottom that will be used in the analysis.
2) Keep a record of the dry soil sample's weight.
3) Assemble the sieves in increasing order of sieve numbers, making sure they're all clean. Fill the soil sample at the top sieve and cover it with the cap.
4) Shake the sieve stack for 10 minutes in the mechanical shaker.
5) Weigh and record the weight of each sieve with the soil that was kept after removing the stack from the shaker. Keep a record of the weight of the bottom pan.

Data Analysis:

1) Subtract mass of the sieve with retained soil to the weight of the empty sieve to get the retained mass of soil on each sieve, and record this amount as the percentage retained on the data sheet. The sum of these preserved masses should be close to the soil sample's starting mass. A drop of more than 2% is undesirable.
2) Divide the percentage retained on each filter by the initial sample mass to get the percentage retained at different sieve.
3) Compute the percent passing (or percent finer) by subtracting the fraction retained on each filter from 100 percent in a cumulative approach.
4) Plot grain size versus percent finer.

Permeability Test:

1) Measure the pan's initial mass as well as the dry soil (M1).
2) Pull the cap and upper chamber apart by unscrewing the knurled cap nuts, uninstall the permeameter's top and upper chamber. The internal diameter of the upper and lower chambers should be measured. Compute the permeameter's average inner diameter (D).
3) One porous stone must be placed on the chamber's base's inner support ring, covered by a filter paper.
4) To prevent particle size segregation after placement into the permeameter, mix the soil with a suitable amount of distilled water. A sufficient amount of water should be added to allow the mixture to flow freely.
5) Fill the prepared soil using a scoop at the lower chamber to a depth with a circular motion. It is required to build a uniform layer.
6) Compact the soil layer with the tamping tool.
7) Replace the upper chamber portion, and don't forget to replace the rubber gasket that connects the chambers. If the soil has already been compacted, take care not to disrupt it. Carry on with the installation. Level the soil's top layer, then add a layer of filter paper, followed by the topmost porous stone.
8) Replace the chamber cap and its sealing gasket after placing the compression spring on the porous stone. Cap nuts are used to maintain the cap in place.
9) Calculate the average length by measuring the sample length at four spots around the circumference of the permeameter. Make a note of it as the sample length.
10) In the drying oven, keep the pan with the remaining soil.
11) Set the funnel's level so that the steady level of water in it stays a couple of inches above the soil's surface.
12) Attach the funnel's tail with flexible tube to the permeameter's bottom outlet, and preserve the permeameter's top valves open.
13) Connect the top outlet to the sink with tubing to catch any water that may flow.
14) Allow water to flow into the permeameter by opening the bottom valve.
15) Close the control valve as soon as water starts to flow out of the top control (Dearing) valve, allowing water to flow out of the exit for a while.

16) Disconnect the tubing at the bottom by closing the bottom outflow valve. Join the funnel tubing together with the port on the upper side of the funnel.
17) To produce a reasonable steady flow of water, the bottom outlet valve should be opened and the funnel should be lifted to a convenient height.
18) Give sufficient time for the flow pattern to become stable.
19) Using the graduated cylinder, time how long it takes to fill a volume of water, then check the temperature of the water. Calculate the average time, average volume, and average temperature by repeating the process three times. The values should be written as t, Q, and T, correspondingly.
20) Record the data that vertical distance between the funnel head level and the chamber outflow level as h.
21) Steps 17 and 18 can be repeated with varying vertical distances.
22) Take the pan out of the drying oven and weigh it along with the dried dirt to determine its total mass (M2).

Data Analysis:

Compute the permeability by using equation given:

$$k = QL/Ath$$

Where:

k = Permeability coefficient, cm/sec.

L = Specimen length, centimeters

t = Discharge time, seconds

Q = Volume of discharge, cm^3

A = Area, cm^2

h = Hydraulic head difference, cm

APPENDIX C

Constant head permeability test results

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Ethiopian Construction Design & Supervision Works Corporation

Title: Geotechnical Laboratory Report	Document No: OF/ECDSWC/0996	Issue No. 1	Page No. 1 of 9

Lab No : 197/14-208/14
Submitted by : Suzan Aemero
Project : Research
Station : -
Test Requested : As Stated Below
Reported to : Suzan Aemero

Client Ref: -
Received on: 19/8/2021
Reported on: 7/9/2021

№	Tests	Tests methods	Test Results					
			BALLAST (AREMA-24) 197/14	BALLAST (AREMA-24) + 30% Sand 198/14	BALLAST (AREMA-24) + 30% Silt 199/14	BALLAST (AREMA-24) + 30% Clay 200/14	BALLAST (AREMA-3) 201/14	BALLAST (AREMA-3) + 30% Sand 202/14
1	Permeability (cm/sec) k	ASTM D2434	2.90×10^{-2}	4.63×10^{-2}	7.70×10^{-3}	1.30×10^{-3}	1.51×10^{-1}	6.0×10^{-2}

№	Tests	Tests methods	Test Results					
			BALLAST (AREMA-3) + 30% Silt 203/14	BALLAST (AREMA-3) + 30% Clay 204/14	BALLAST (AREMA-4) 205/14	BALLAST (AREMA-4) + 30% Sand 206/14	BALLAST (AREMA-4) + 30% Silt 207/14	BALLAST (AREMA-4) + 30% Clay 208/14
2	Permeability (cm/sec) k	ASTM D2434	2.94×10^{-2}	1.29×10^{-2}	2.30×10^{-2}	4.86×10^{-2}	6.62×10^{-2}	7.46×10^{-3}

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A for
Senior Geotechnical Engineer

Approved by Getu D
Geotechnical Lab S/P Manager

Among the major services rendered by the Geotechnical and Material Laboratory Testing s/processes of Ethiopian Construction Design & Supervision Works Corporation are:

- *In Geotechnical Laboratory: -Testing the engineering properties of Soil Mechanics and Rock Mechanics.*
- *In Material Testing Laboratory: - Testing the engineering properties of various Construction materials, such as Aggregates, Asphalts/Bitumen/, Cements, Rocks, Water, Reinforcement steel bars, Hollow Blocks, Bricks, Ceramics, Tiles, Asphalt & Concrete Core Tests, Concrete Mix Designs, Asphalt Mix Designs, Sampling of the soil and construction materials, and so on.*

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Constant Head Permeability

AREMA-24

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	K_T (Average)	Temperature (°C)
Trial 1	120	87	78	9	100	14.50	45.34	0.02961166	0.029	18
Trial 2	180	83	74.5	8.5	120	14.50	45.34	0.02508282		
Trial 3	150	94	75	19	110	14.50	45.34	0.01234339		
Trial 4	150	84	76	8	110	14.50	45.34	0.02931554		
Trial 5	180	80	73	7	140	14.50	45.34	0.03553399		
Trial 6	210	79	71	8	150	14.50	45.34	0.0285541		

Constant Head Permeability

AREMA-4

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	K_T (Average)	Temperature (°C)
Trial 1	737	87	78	9	390	14.50	45.34	0.0188036	0.023	18
Trial 2	759	83	74.5	8.5	430	14.50	45.34	0.02131544		
Trial 3	2545	94	75	19	110	14.50	45.34	0.00072751		
Trial 4	242	84	76	8	150	14.50	45.34	0.02477835		
Trial 5	296	80	73	7	170	14.50	45.34	0.0262389		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A
Senior Geotechnical Engineer

Approved by Getu. D
Geotechnical Lab S/P Manager

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Constant Head Permeability

AREMA-3

Test trials	Time (Second)	h1	h2	dh	Q (cm^3)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	746	45	44	1	355	14.50	45.34	0.15218646	0.151	18
Trial 2	717	46	45	1	350	14.50	45.34	0.15611167		
Trial 3	811	44	43	1	370	14.50	45.34	0.14590405		
Trial 4	963	44	43	1	450	14.50	45.34	0.14944201		

Constant Head Permeability

AREMA-24 (70% Gravel + 30% Sand)

Test trials	Time (Second)	h1	h2	dh	Q (cm^3)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	562	65	59	6	260	14.50	45.34	0.02465882	0.04635	18
Trial 2	448	61	58	3	250	14.50	45.34	0.05948771		
Trial 3	518	60	56	4	195	14.50	45.34	0.03009756		
Trial 4	360	60	57	3	260	14.50	45.34	0.07699031		
Trial 5	360	61	57	4	270	14.50	45.34	0.05996361		
Trial 6	180	80	72	8	120	14.50	45.34	0.02665049		
Trial 7	360	62	58	4	230	14.50	45.34	0.05108011		
Trial 8	420	60	57	3	260	14.50	45.34	0.0659917		
Trial 9	240	69	62	7	180	14.50	45.34	0.03426492		
Trial 10	240	68	61	7	180	14.50	45.34	0.03426492		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A
Senior Geotechnical Engineer

Approved by Getu. D
Geotechnical Lab S/P Manager

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Ethiopian Construction Design & Supervision Works Corporation

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Received on:19/8/2021
Reported on:7/9/2021

Constant Head Permeability

AREMA-24 (70% Gravel+ 30% Silt)

Test trials	Time (Second)	h1	h2	dh	Q (cm^3)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	600	96.5	71	25.5	390	14.50	45.34	0.00815192	0.00770	18
Trial 2	780	98.5	71	27.5	520	14.50	45.34	0.00775287		
Trial 3	780	98	71	27	500	14.50	45.34	0.00759273		
Trial 4	600	99	71	28	410	14.50	45.34	0.00780479		
Trial 5	660	99.5	71	28.5	435	14.50	45.34	0.00739583		
Trial 6	780	99.5	71	28.5	530	14.50	45.34	0.0076247		
Trial 7	540	99	71	28	350	14.50	45.34	0.00740291		
Trial 8	480	100	71	29	315	14.50	45.34	0.00723699		
Trial 9	420	100	71.5	28.5	300	14.50	45.34	0.00801519		
Trial 10	420	100	71.5	28.5	300	14.50	45.34	0.00801519		

REMARK: -The samples were collected and submitted to the laboratory by the client.

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Ethiopian Construction Design & Supervision Works Corporation

Title: Geotechnical Laboratory Report	Document No: OF/ECDSWC/0996	Issue No. 1	Page No. 5 of 9

Lab No : 197/14-208/14
Submitted by : Suzan Aemero
Project : Research
Station : -
Test Requested : As Stated Below
Reported to : Suzan Aemero

Client Ref: -
Received on: 19/8/2021
Reported on: 7/9/2021

Constant Head Permeability

AREMA-24 (70% Gravel + 30% Clay)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	K_T (Average)	Temperature (°C)
Trial 1	2013	100	77.4	22.6	100	14.50	45.34	0.00070297	0.00130	18
Trial 2	2146	100	84.5	15.5	90	14.50	45.34	0.0008653		
Trial 3	1399	100	93	7	48	14.50	45.34	0.00156752		
Trial 4	1560	100	92.5	7.5	43	14.50	45.34	0.00117536		
Trial 5	4620	100	91.5	8.5	51	14.50	45.34	0.00041533		
Trial 6	1666	100	92	8	44	14.50	45.34	0.00105578		
Trial 7	1743	100	93.5	6.5	45	14.50	45.34	0.00127025		
Trial 8	1675	100	92.5	7.5	49	14.50	45.34	0.0012474		
Trial 9	1140	100	94.5	5.5	27	14.50	45.34	0.00137715		
Trial 10	1022	100	93.5	6.5	27	14.50	45.34	0.00129983		
Trial 11	848	100	94	6	23	14.50	45.34	0.00144566		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A for
Senior Geotechnical Engineer

Approved by: Getu. D
Geotechnical Lab S/P Manager

Among the major services rendered by the Geotechnical and Material Laboratory Testing s/processes of Ethiopian Construction Design & Supervision Works Corporation are:

- *In Geotechnical Laboratory: -Testing the engineering properties of Soil Mechanics and Rock Mechanics.*
- *In Material Testing Laboratory: - Testing the engineering properties of various Construction materials, such as Aggregates, Asphalts/Bitumen/, Cements, Rocks, Water, Reinforcement steel bars, Hollow Blocks, Bricks, Ceramics, Tiles,Asphalt & Concrete Core Tests, Concrete Mix Designs, Asphalt Mix Designs, Sampling of the soil and construction materials, and so on.*

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Ethiopian Construction Design & Supervision Works Corporation

Title: Geotechnical Laboratory Report	Document No: OF/ECDSWC/0996	Issue No. 1	Page No. 6 of 9

Lab No : 197/14-208/14
Submitted by : Suzan Aemero
Project : Research
Station : -
Test Requested : As Stated Below
Reported to : Suzan Aemero

Client Ref: -
Received on: 19/8/2021
Reported on: 7/9/2021

Constant Head Permeability

AREMA-3 (70% Gravel + 30% Sand)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	$K_{T\,(Average)}$	Temperature (°C)
Trial 1	660	100	76	24	365	14.50	45.34	0.00736926	0.05990	19
Trial 2	240	81	78	3	180	14.50	45.34	0.07995148		
Trial 3	660	100	73.5	26.5	460	14.50	45.34	0.00841113		
Trial 4	720	100	73	27	470	14.50	45.34	0.00773193		
Trial 5	180	83.5	79.5	4	145	14.50	45.34	0.06440536		
Trial 6	210	82	77.5	4.5	150	14.50	45.34	0.05076284		
Trial 7	180	82	77.5	4.5	150	14.50	45.34	0.05922332		
Trial 8	180	84	79.5	4.5	130	14.50	45.34	0.05132687		
Trial 9	240	84.5	78	6.5	175	14.50	45.34	0.03587566		
Trial 10	240	81	78	3	175	14.50	45.34	0.0777306		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A
Senior Geotechnical Engineer

Approved by Getu. D
Geotechnical Lab S/P Manager

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Title: Geotechnical Laboratory Report	Document No: OF/ECDSWC/0996	Issue No. 1	Page No. 7 of 9

Lab No : 197/14-208/14
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Station : -
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Reported to : Suzan Aemero

Client Ref: -
Received on: 19/8/2021
Reported on: 7/9/2021

Constant Head Permeability

AREMA-3 (70% Gravel + 30% Silt)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	23	100	93	7	20	14.50	45.34	0.03972744	0.02947	19
Trial 2	29	100	91	9	27	14.50	45.34	0.03308337		
Trial 3	18	100	94	6	16	14.50	45.34	0.04737865		
Trial 4	36	100	86	14	29	14.50	45.34	0.01840153		
Trial 5	39	100	87	13	29	14.50	45.34	0.01829265		
Trial 6	33	100	90	10	26	14.50	45.34	0.02519683		
Trial 7	37	100	90	10	28	14.50	45.34	0.02420153		

Constant Head Permeability

AREMA-3 (70% Gravel + 30% Clay)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	720	85	73.5	11.5	435	14.50	45.34	0.0168014	0.01287	19
Trial 2	600	89	73.5	15.5	370	14.50	45.34	0.01272346		
Trial 3	600	100	71	29	400	14.50	45.34	0.00735186		
Trial 4	540	100	72.5	27.5	350	14.50	45.34	0.00753751		
Trial 5	720	100	68	32	480	14.50	45.34	0.00666262		
Trial 6	780	100	68	32	495	14.50	45.34	0.0063423		
Trial 7	180	100	74	26	180	14.50	45.34	0.01230023		
Trial 8	240	100	72	28	190	14.50	45.34	0.00904213		
Trial 9	180	100	80	20	120	14.50	45.34	0.0106602		
Trial 10	180	100	72.5	27.5	125	14.50	45.34	0.00807591		
Trial 11	120	100	77.5	22.5	100	14.50	45.34	0.01184466		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A for
Senior Geotechnical Engineer

Approved by Getu. D
Geotechnical Lab. S/P Manager

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Ethiopian Construction Design & Supervision Works Corporation

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Client Ref: -
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Reported on: 7/9/2021

Constant Head Permeability

AREMA-4 (70% Gravel + 30% Sand)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	1026	98	97	1	70	14.50	45.34	0.02181912	0.04865	18
Trial 2	672	98	97.5	0.5	80	14.50	45.34	0.07614426		
Trial 3	647	95	94	1	90	14.50	45.34	0.04448614		
Trial 4	368	96	95	1	60	14.50	45.34	0.05214227		
Trial 5	1772	100	70	30	70	14.50	45.34	0.00042111		
Trial 6	914	100	76	24	130	14.50	45.34	0.00189528		
Trial 7	922	100	96	4	30	14.50	45.34	0.00260146		

Constant Head Permeability

AREMA-4 (70% Gravel + 30% Silt)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	$K_{T (Average)}$	Temperature (°C)
Trial 1	600	76	73.5	2.5	330	14.50	45.34	0.0703573	0.06618	19
Trial 2	600	77.5	74	3.5	375	14.50	45.34	0.0571082		
Trial 3	480	77.5	74	3.5	340	14.50	45.34	0.06472262		
Trial 4	480	82	74	8	320	14.50	45.34	0.02665049		
Trial 5	360	77.5	74	3.5	265	14.50	45.34	0.06726077		
Trial 6	300	78.5	76	2.5	190	14.50	45.34	0.0810175		
Trial 7	180	82	78	4	155	14.50	45.34	0.06884711		
Trial 8	240	82	77	5	160	14.50	45.34	0.04264079		
Trial 9	180	82.5	78	4.5	140	14.50	45.34	0.0552751		
Trial 10	300	77	74	3	210	14.50	45.34	0.07462138		
Trial 11	240	79	76	3	180	14.50	45.34	0.07995148		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A
Senior Geotechnical Engineer

Approved by Getu. D
Geotechnical Lab. S/P Manager

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Constant Head Permeability

AREMA-4 (70% Gravel + 30% Clay)

Test trials	Time (Second)	h1	h2	dh	Q (cm³)	L	A	K = QL/ Ath	K_T (Average)	Temperature (°C)
Trial 1	900	100	72	28	570	14.50	45.34	0.00723371	0.00746	19
Trial 2	540	100	72	28	360	14.50	45.34	0.00761443		
Trial 3	420	100	72	28	290	14.50	45.34	0.00788637		
Trial 4	480	100	71	29	320	14.50	45.34	0.00735186		
Trial 5	420	100	71.5	28.5	285	14.50	45.34	0.00761443		
Trial 6	420	100	71.5	28.5	287	14.50	45.34	0.00766786		
Trial 7	600	100	71	29	415	14.50	45.34	0.00762755		
Trial 8	660	100	70	30	440	14.50	45.34	0.0071068		
Trial 9	660	100	72	28	425	14.50	45.34	0.00735484		
Trial 10	660	100	71	29	430	14.50	45.34	0.00718477		

REMARK: -The samples were collected and submitted to the laboratory by the client.

Reported by Bethlehem. B
Senior Geotechnical Engineer

Checked by Biruk. A
Senior Geotechnical Engineer

Approved by Getu. D
Geotechnical Lab S/P Manager

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APPENDIX D

Photos during laboratory test

Figure 15: Fouled ballast sample

Figure 16: Oven for drying aggregate sample

Figure 17: Sieve shaking manually

Figure 18: Data recording