Addis Ababa University

Addis Ababa Institute of Technology

School of Railway Engineering

Investigation of Ballast Degradation on Bike- Dewele Railway Line.

A research submitted to the African Railway Center of Excellence (ARCE) in partial fulfillment of the requirements for the Addis Ababa Institute of Technology's Masters of Science in Railway Engineering
(Civil Infrastructure)

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APPROVAL PAGE

The undersigned have examined the thesis entitled **"Investigation of Ballast Degradation on Bike-Dewele Railway Line"** presented by Yohannes Embibel Gobena, submitted to African Railway Center of Excellence, Addis Ababa Institute of Technology, School of Graduate Studies in partial fulfillment of the requirement of the award of Degree of Masters of Science in Railway Engineering (Civil Infrastructure).

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DECLARATION

This is to declare that the work presented here in this thesis with the title **"Investigation of Ballast Degradation on Bike-Dewele Railway Line"** is original, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been suitably cited.

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ABSTRACT

Rail tracks are often placed on ballast which offers the desirable resiliency to cyclic loads. Modernization of railway transportation in terms of increasing axle load and speed focused on ballast layer as a key component of conventional railway track. The ballast layer undergoes gradual and continuing degradation with usage and time due to increasing traffic passage, loads and speed. The rate and magnitude of ballast degradation depends on ballast quality, environmental exposure, geometry profile, speed, and number and magnitude of axle loadings. Intolerable degradation cause track geometry deterioration due to track settlement as a result of excessive permanent deformation of the ballast layer. Understanding the degree of ballast bed degradation under cyclic loadings helps to either making standardization or planning for maintenance schedule.

This study was conducted to determine the extent of ballast degradation along the Bike-Dewele section of the Ethio-Djibouti railway line following five years of operation. This study collects data on ballast degradation through visual inspections in the field and laboratory tests. Visual inspections were conducted following such as vegetation growth, surface fines, crib and shoulder ballast missing, cobles on the main track, more degraded ballast sections. On samples of ballast collected from ten (10) locations along the Bike-Dewele sections, laboratory tests including gradation (sieve analysis), Los Angeles Abrasion, shape tests (Elongation and Flakiness) and Fouling index were conducted, as well as design and as-built data reviewed. Gradation was determined by calculating the percentage shift of each PSD curve from the as-built PSD curve limits. Additionally, other tests were compared to the recommended standard at each location.

The investigation discovered that the ballast on the Bike-Dewele section within five years of operation, there is significant deterioration of ballast, as shown by the PSD curves shifting above the as-built maximum values of 40-115 percent. Improper ballast aggregate addition has been found, as indicated by PSD curves dropping below the as-built minimum value of 41-180 percent. The majorities of ballast aggregates throughout the Bike-Dewele stretch are broadly graded and fall within as-built data, while others are even more broadly graded than as-built data. The resistance of the present ballast to abrasion is between 76 and 87%, when the values are compared to the recommendations in various standards, it can be concluded that the ballast is still capable of carrying the imposed loads. The shape property index tests show that particle shape has been rapidly changing (highest FI value is 37% and highest EI value is 46%) and the material is deteriorating. While conducting a field investigation, discovered that several portions of the ballast were highly fouled, but that sampling was not permitted.

Keywords: Ballast; Degradation; Investigation; Laboratory tests; Field Inspections

List of Acronyms

AREMA	American Railway Engineering Maintenance of Association
ASTM	American Standard Testing for Material
AASHTO	American Association of State Highway and Transportation Officials
BS	British Standard
PSD	Particle Size Distribution
NSC	Norfolk Southern Corporation
EN	European Standard
LAAV	Los Angeles Abrasion Value
C_U	Coefficient of Uniformity
C_C	Coefficient of Gradation
FI	Flakiness Index
EI	Elongation Index
FI	Fouling index

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1. Introduction

Railway ballast is a critical element in the railway track support structure. The ballast is often overlooked when inspection tools are developed for track. When the ballast is not functioning properly, the strength of the track structure may be inadequate and thus compromise track stability. The ability of a ballast layer to perform its intended functions is dependent on the ballast being free of fine-grained particles (fines). The process of fines accumulating within the ballast void space is referred to as ballast degradation (sometimes also referred to as ballast fouling).

In railway track, repeated wheel loads transferred from sleepers to the ballast layer cause abrasion and degradation of ballast aggregates over time which contributes to the fouled (degraded) content in the ballast layer and alter the gradation. To predict and prolong ballast life thereby reducing maintenance cost and providing a good ballast layer knowing the degradation (strength) condition of the ballast is fundamental.

Bike-Dewele Railway route is part of Ethio-Djibouti Railway line is a standard gauge ballasted railway line Constructed five years ago Using class II Chinese railway standards. Bike-Dewele railway route is the single track and has a length of 272 km. the design speed reaches 120km/h for passenger trains and 80km/h for freight trains. From Chinese standard, the ballast used for the line is class I Crushed stone. Passengers and freight trains have been operating on the line for around five years.

Therefore, this study is planned to investigate the degradation level of the Bike-Dewele railway line. The research area's map is depicted in Figure 1.

Figure 1: Map of study area showing route alignment

Railroads are a low-energy mode of transport that comprises the world's largest network, providing rapid and secure public and freight transportation. Ballasted tracks, which consist of a ballast layer sandwiched between sleepers and a sub ballast layer, are the most widely used railway tracks worldwide [1]. A rail track's structure is classified into two types: substructure and superstructure (Selig and Waters 1994). (Figure 2). The superstructure is composed of tracks, a fastening system, and sleepers, while the substructure is composed of a ballast layer, a sub ballast layer, and a subgrade. However, in many parts of Europe, the ballast may be considered to be a component of the superstructure [3].

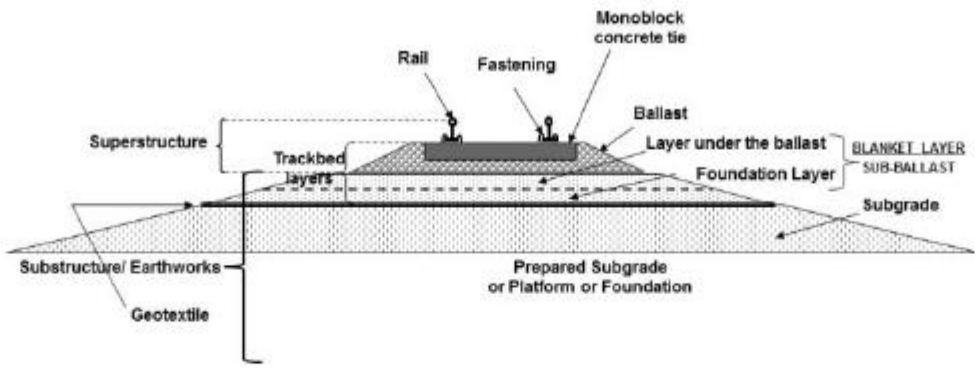

Figure 2: cross section of ballasted track

Railways can be advantageous as they are characterized by the following:

- Limited use of space compared to large transport capacity
- Reliability and safety
- High degree of automation and management
- Moderate environmental impact

The most important function of ballast layer (Robnett et al. (1975) and Selig and Waters (1994)) discussed as follows:-

- Retain the track in its required position by withstanding vertical, lateral and longitudinal forces applied to the sleepers
- Provide the required degree of elasticity and dynamic resilience to track superstructure
- Distribute stresses from the sleeper bearing area to acceptable stress levels for the underlying material
- Facilitate maintenance surfacing and lining operations by an ability to rearrange ballast particles with tamping
- Provide immediate drainage of water falling onto the track
- Provide sufficient voids for storage of fouling material in the ballast, and to accommodate the movement of particles through the ballast.

The performance of railroad track depends greatly on the stability of the ballast. Ballast will eventually break down under high loads and tons. The ballast fracture that occurs, however, may momentarily improve stability by aiding in the interlocking of nearby particles when ballast is kept free of contaminants and allowed to drain freely (Sussmann, Ruel, and Chrismer, 2016).

However, the breakdown will take up vacant space, perhaps obstruct drainage, and shorten the life of the ballast. When ballast breakdown becomes contaminated with other ballast-fouling material, the common muddy fouled ballast problem develops as a result of the presence of silt and clay that can blow or wash into the track structure or be pumped or mixed from other track structural layers [4].

1.1 Problem statement

The ballast itself is the key element of ballasted track, the focus of maintenance, and the component that contributes most significantly to the overall safety of the track. High permeability for quick drainage and high stiffness for effectively dispersing train loads to the sub-base are two competing needs that must be met by ballast. Maintaining the ballast bed's required strength and standard is essential to ensuring these two fundamental needs [7].

According to numerous studies and examinations [2], ballast degradation is the primary cause of fouling, which is also the main cause of ballasted track settling and high maintenance costs. Greater transportation needs lead to greater running speeds and traffic loads on the track, which obviously hastens the deterioration of the ballast and accelerates the loss of track geometry. Accidents and regular maintenance will be reduced if the ballast degradation is known and early breakdowns are avoided. Every railway line needs to have its deterioration causes and mechanisms investigated because each track's construction features and materials have varied degradation levels. Daily and recurring thorough investigation results are essential for predicting and extending ballast life and achieving effective maintenance while also lowering maintenance expenses.

1.2 Objective

1.2.1 General objective

The General objective of the study is to investigate ballast degradation on Bike-Dewele Railway Line.

1.2.2 Specific objective

The Specific objectives of the study are:

- Assessment of ballast bed degradation on the field through visual inspections.
- Evaluate the current condition/level of degradation in the Bike-Dewele railway line through laboratory test.
- Evaluate the data and compare the quality of the present ballast with the specifications for the ballast.

1.3 Research Questions

- What level of quality is the ballast currently on the Bike-Dewele Railway Line?
- Is the current quality satisfactory or does it require maintenance or replacement?

1.4 Significance of the Research

The results of this study endeavor may be useful to practitioners and researchers. in addition to;

- Increasing awareness on the current degradation extent of ballast in railway line ballast as well as design requirements to suggest ways to maximize ballast lifespan of railways ballast.
- To better comprehend the signs of ballast bed degradation in railways.
- To comprehend the anticipated behavior before the ballast layer's repair or rehabilitation time and probable degradation.
- Determination of whether the ballast should be maintained or replaced to prolong the track's life and ensure safe riding.
- To inform the current ballast performance for the firm in charge.

1.5 Scope and Limitations of the study

Different investigative techniques used in this investigation of the ballasted rail track on the Bike-Dewele railway line in Ethiopia. Due to the accessibility of the line by car and the available time, the sampled places for the inspection and laboratory tests are constrained.

2. Literature review

2.1 Ballast

The top layer of the substructure, which is normally between 250 and 350 millimeters thick and into which sleepers are inserted to support the rails, is known as ballast and is described as a chosen mixture of crushed granular materials with a size range of 10 to 60 millimeters [8]. The major purpose of the ballast, a crucial structural component of the railroad, is to safely transfer the induced loads from the superstructure to the subgrade while also ensuring proper drainage. Ballast is ideally composed of coarse aggregates sourced from either blasted igneous rock, metamorphic or, well-cemented sedimentary rock quarries [9]. The aggregates that often fail to perform as ballast would include various types of sandstones mainly because of softening upon wetting and the inability to withstand high cyclic loads [5]. Blast furnace slag can be used as ballast, however it cannot support as much weight as recently mined natural rock aggregates. A good ballast should be solid, firm, and easy to work with. It should also drain properly, be simple to clean and re-clean, and resistant to deformation underweight. Historically, aggregates possessing the following characteristics have been regarded as the optimal ballast material [10].

- Angular, crushed,
- Hard stones and rock
- Uniformly graded
- Free of dust, dirt, and resistance to cementing action

Ballast must be capable of withstanding many forces. Extremely large cyclic loadings, vibrations of varying frequencies and intensities, repeated wetting and drying involving crystallization of rain dissolved soluble salts, plus other factors caused deterioration of the ballast. Ballast must also be easy to handle during maintenance [12].

The selection of the ballast used for railway track support is of major importance in establishing and maintaining the characteristics of the track response and, consequently, the riding quality. For ballasted track, elastic, non-cemented, stable and weather-resistant ballast bed, well laid and compacted on a stable, compact sub-ballast and subgrade, is the first condition for low maintenance expenditures. Figure 3 shows Railroad ballast parent rock classification for selection of ballast aggregate.

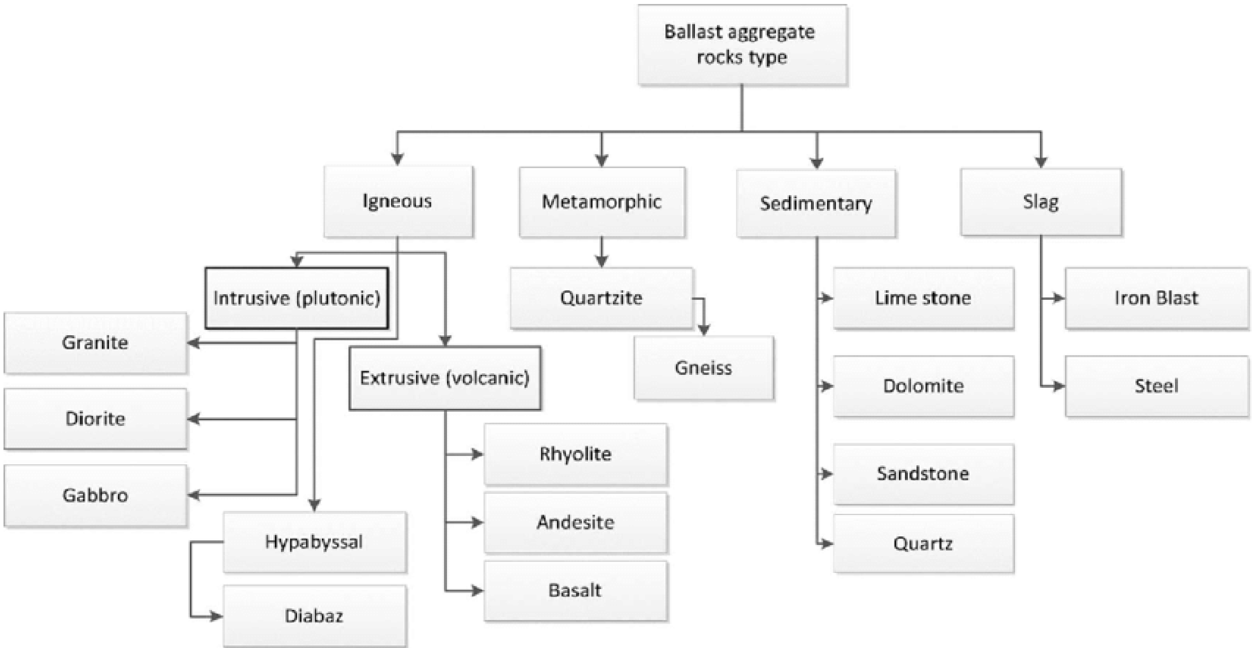

Figure 3: Railroad ballast parent rock classification for selection of ballast aggregate

2.1.1 Functions of ballast

The ballast should perform the following functions [5]

i. Resist external loads to keep the track in place.
ii. Ensure efficient drainage of water.
iii. Improve the convenience of track surface and alignment maintenance.
iv. Provide the required robustness to withstand heavy and dynamic loads.
v. Provide enough void space for the storage of ballast fines without interfering with how the ballast particles interact.
vi. Prevent weed growth by reducing fouling.
vii. Reduce noise and offer adequate electrical resistance.

According to Robnett et al. (1975) and Selig and Waters (1994) discussed “the ballast layer functions of which the most important are:-

- Retain the track in its required position by withstanding vertical, lateral, and longitudinal forces applied to the sleepers
- Provide the required degree of elasticity and dynamic resilience to track superstructure
- Distribute stresses from the sleeper bearing area to acceptable stress levels for the underlying material
- Facilitate maintenance surfacing and lining operations by an ability to rearrange ballast particles with tamping
- Provide immediate drainage of water falling onto the track
- Provide sufficient voids for storage of fouling material in the ballast and to accommodate the movement of particles through the ballast”

2.1.2 Ballast Portions

The ballast aggregate is laid above the sub-ballast layer, between the sleepers (crib), and beyond the sleeper ends (shoulder) [6]

a. 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 the track and preventing longitudinal movement of the sleepers.

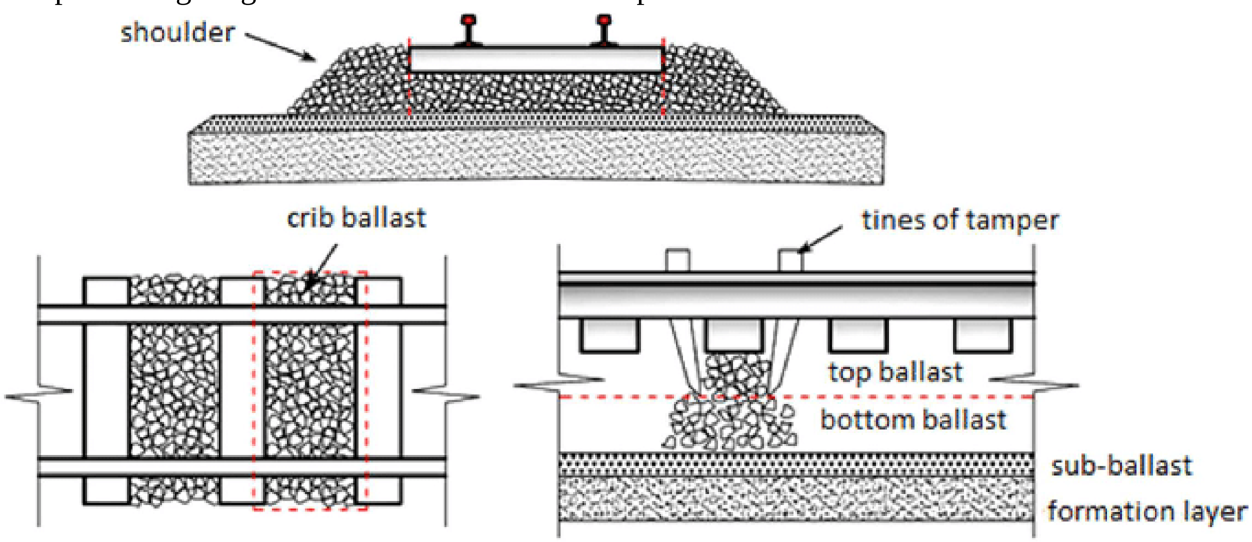

Figure 4: Schematic of ballast zones in railway track

b. Shoulder ballast: The shoulder ballast is located beyond the sleeper ends down to the bottom of the ballast layer. The main function of shoulder ballast is to protect the track from buckling.
c. Top ballast: The top ballast is located below the sleepers and is disturbed by tamping.
d. Bottom ballast: It is located under the sleepers and is not disturbed by the maintenance process and is commonly the more fouled portion. The contribution of each part in playing the roles of ballast function to perform duties is presented in Table 1 [6].

Table 1: Contribution of ballast portions to perform ballast duties

Ballast Duties	**Crip Ballast**	**Shoulder Ballast**	**Bottom Ballast**	**Top Ballast**
Vertical Strength			✓	✓
Lateral Strength	✓	✓		✓
Longitudinal Strength	✓			✓
Resiliency			✓	✓
Adjusting and Track Leveling	✓		✓	✓
Drainage	✓	✓	✓	✓
Load Distribution and Dispersing			✓	✓
Prevent Growth of Plant	✓		✓	✓
Shock Absorption and Noise Attenuation	✓	✓	✓	✓

Electrical Resistivity	✓			✓
Subgrade Protection Layer	✓	✓	✓	✓

2.2 Ballast Assessment

In order to choose a suitable quarry or estimate the remaining life of the ballast, it is crucial to evaluate the physical, mechanical, and environmental aspects of the ballast. There are various specifications, including AREMA Specifications, European Specifications, Australian Specifications, and Canadian Specifications, for determining if ballast is suitable for railroad track [6]. To perform well in track, the aggregate for ballast must have the following properties [9]

i. The ability to withstand the crumpling effects of overlaid track and dynamic traffic loading.
ii. Hardness to withstand wear and to survive abrasion at particle interactions.
iii. Resistance to collapse via fracturing when subjected to impact loads.
iv. Resistance to weathering and abrasion.
v. Stability; in order to achieve this, the ballast must be properly graded and shaped.

2.2.1 Load resistant characterization

Commonly available load resistance tests into an assemblage of grains are as follows [9]:

i. Impact test: The relative measure of a ballast aggregate's resilience to rapid shock loads. A prepared sample of aggregates is layered in a steel mold in three roughly equal layers and each layer is given 25 tamping rod blows. The sample is subjected to 15 hits from a 14 kg hammer that falls freely from a 380 mm height. The amount of fine material created after 15 blows is reported as a percentage of the sample's total mass. The smaller the percentage, the better the material; conversely, the higher the percentage, the worse the material.

ii. Crushing value test: The relative resistance of ballast aggregates to crushing when subjected to progressive loading. Three equal layers of aggregates are placed in a measuring cylinder and each layer is given 25 blows of the tamping rod. The material is transferred to the steel mold and leveled with a plunger in preparation for the crushing test. At the top of the specimen, a compression force is introduced and gradually increased to 400 kN within 10 minutes. The fine material created by the 400 kN application is reported as a percentage of the sample's total mass. The smaller the percentage, the higher the quality of the material; conversely, the higher the percentage, the poorer the quality of the material.

iii. Los Angeles abrasion test: The Los Angeles abrasion test is a widely used procedure for determining the toughness and abrasion characteristics of aggregates. Toughness is directly related to resistance to crushing and degradation, both of which are known to be major contributors to ballast settlement [15]. In this test, a sample of aggregates of either grade A-D or 1-3 and 12 steel balls of 5000g weight in total is placed on a large cylindrical drum and allowed to rotate at a speed of 30-33 rev/min for 1000 revolutions. The fine material generated after 1000 revolutions is expressed in a percentage of the total weight of the sample. The lower the percentage the better is the material and vice versa.

iv. Deval abrasion test: This test was developed in England for testing highway materials before being adopted by the railway sector. According to BR, this test is the most accurate predictor of ballast performance in service. It can be used to specify the minimal durability required to achieve the target ballast life with concrete sleepers in the British environment. A 5 kg specimen mass is rotated in a cylinder mounted on a shaft with the cylinder's axis inclined 30 degrees to the shaft's axis of rotation. The cylinder is rotated 1000 times at a 30-33 revolutions per minute rate (rpm). Attrition is defined as the mass of particles created smaller than a 2.36 mm sieve, given as a percentage of the initial specimen mass. This test can be performed with dry ballast particles or with an equal mass of clean water added to the dry specimen.

v. Mill abrasion test: This is a wet abrasion test in which 3 kg of ballast and water are rotated for 10,000 revolutions at roughly 33 rpm in a 229 mm exterior diameter porcelain jar. This method of rolling wears out ballast without crushing it. The Mill abrasion value is the mass of material finer than a 0.075 mm sieve created by the test in comparison to the weight of the original sample. The mill abrasion test determines the aggregate mineral hardness, which was determined to be the most influential factor affecting the rate of buildup of permanent vertical deformation.

vi. Clay lumps and friable particle test: Clay lumps and friable particles are defined in this test as those that can be broken with the fingers after the aggregate has been soaked in water for 24 ± 4 hours. Additionally, this test can be used in conjunction with the PSD test of ballast to assess the fines content, which may potentially fill in ballast voids.

2.2.2 Assessment of weathering

The following two tests are frequently used to determine if aggregates could deteriorate or weaken as a result of weathering:

i. Soundness test: This test mimics an aggregate's weathering characteristics or, more accurately, its resistance to the weathering process. The genuine soundness test involves immersing ballast particles alternately and drying them with a salt solution. Although magnesium sulphate was advised as a more suitable solution to use in this test, AREMA has advocated using sodium sulfate instead. In areas with the highest levels of freeze-thaw and atmospheric pollution, the soundness test will be particularly important.

ii. Freeze-thaw breakdown: This test employs oven-dry ballast particles that are partially or totally submerged in water or a water-alcohol solution to evaluate the material's resistance to swelling, frost action, and softening. The test reveals whether the ballast particles can hold onto water that may otherwise freeze and degrade throughout daily freeze-thaw cycles or might interact chemically with minerals. The rainfall during the time of year when freeze-thaw cycles occur as well as the pollutants in the local rainwater where the material is to be utilized are taken into consideration during this absorption test. Particles having broken surfaces might allow for increased water infiltration and subsequent freeze-thaw degradation. Compared to smooth, spherical particles, elongated, angular particles have a larger surface area.

2.2.3 Cementing characteristics of ballast

Cemented ballast describes a range of conditions, including heavily polluted, dry, and conditions where coarse particles are bound together in a matrix structure. Bonding in ballast can be produced by chemical processes, capillarity attraction (caused by fouling materials), or a secondary bonding mechanism. One can tell what kind of cementing has happened by soaking the ballast in water. While other types of bonds would decay and dissolve in the water, chemical linkages would remain strong.

2.2.4 Assessment of Stability Properties

Properties of ballast that relate to its ability to provide stable support are:

A. Bulk density

The performance of the track in terms of vertical and lateral movement resistance (holding capacity) is significantly influenced by the bulk density of the ballast. The track holding capacity increases along with the increase in track mass. The following are additional material characteristics that are related to or have an impact on bulk density:

i. Particle specific gravity: This is a critical factor in determining the bulk density of ballast (unit weight), which can be measured using the water displacement method. A higher specific gravity indicates that the track is made of a heavier material and has a greater degree of stability.
ii. Absorption: Water absorption is a measure of a rock's porosity, which is proportional to its strength. The specific gravity test also includes an absorption component. Excessive absorption can result in rapid degradation during wetting and drying cycles, as well as freezing and thawing.
iii. Rodded unit weight: The dry density of the ballast is determined in this test by compacting the ballast into a rigid cylindrical container with the aid of a steel rod. The container size is determined by the aggregate particle size and is typically 0.028 m3 in capacity with a height and diameter of 33 cm. Ballast is deposited in three equal-height layers and each layer is vigorously tamped with steel rods twenty-five times.

B. Particle shape and texture

In association with Canadian railroad research, Raymond created a form factor for railroad ballast. The creation of ballast is thought to affect the shape and texture of particles. A minimum amount of elongated or flaky particles, such as the rejection of slate-like rock sources, are necessary for effective ballast particle interlock. According to a study on the effects of shape properties on ballast, the minimum shear stress level required by the Chinese standard for flaky ballast is met by a 25% aggregate limit by weight for misshapen particles, while a 20% increase in the percentage of flaky aggregates results in a 14.7 percent decrease in shear strength and a 5.2

percent decrease in friction angle, respectively [18]. In the absence of ballast breaking, flaky and elongated particles produce a slight increase in shear strength due to volumetric compaction; nonetheless, adverse effects of ballast fouling and degradation have been recorded [21].

i. Flatness or flakiness: Flatness and flakiness are different names for the same shape characteristic. The British Standard (BS), BS EN933-3:1997 [9] defines a flaky particle as one in which the ratio of thickness to width is less than 0.6. The flakiness index is the percentage by weight of flaky particles passing the gauge shown in Figure 5.

ii. Elongation: The British standard defines an elongated particle as one with a length-to-width ratio of more than 1.8. In both cases, the elongation index is the percentage by weight of elongated particles smaller than the slot on the gauge shown in Figure 6.

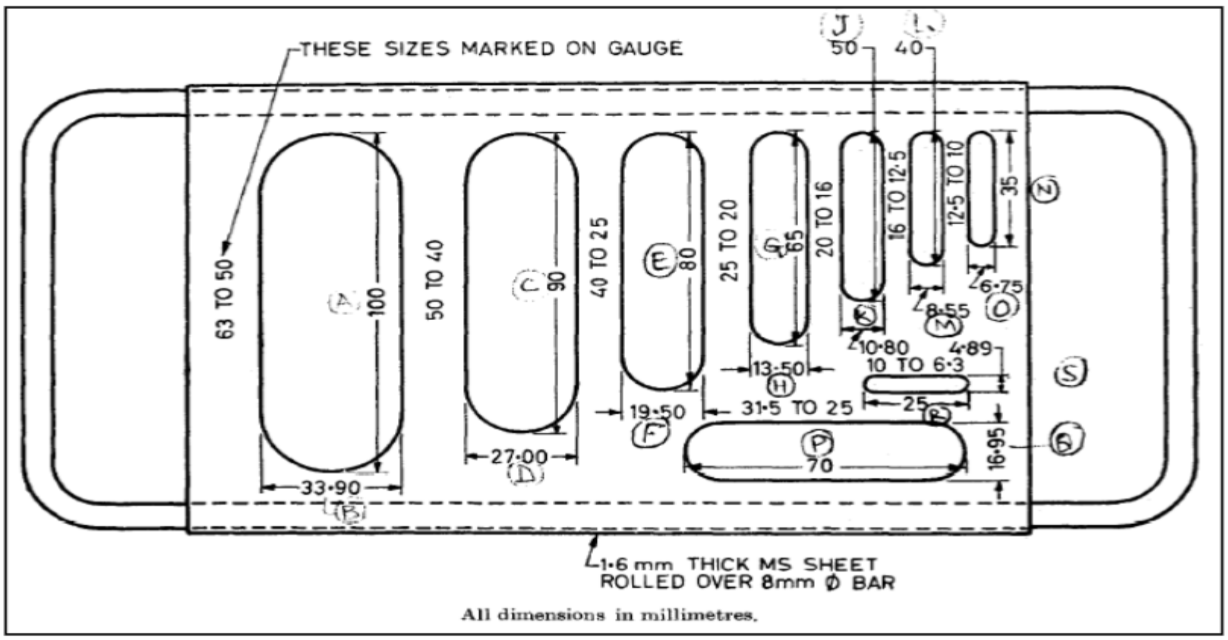

Figure 5: Flakiness index gauge

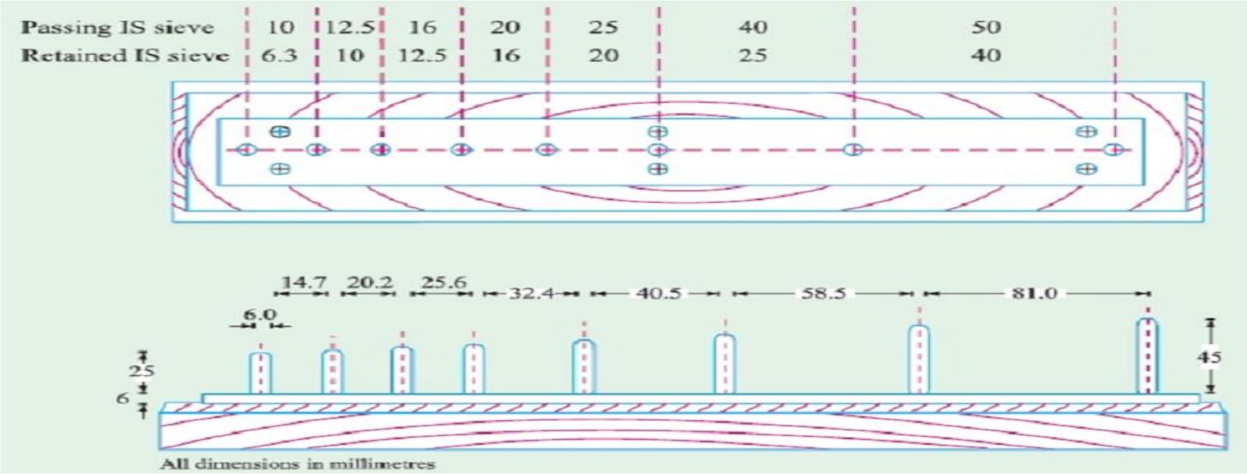

Figure 6: Elongation index gauge

2.3 Ballast Gradation (Particle Size Distribution)

A common method for calculating the volume of in-service ballast is to grade (or specify) the grain size distribution of the ballast [22]. For track strength, deformation, degradation, stability, and drainage, ballast gradation is essential [3]. Correctly graded ballast produces denser packing, better frictional interlock, and less settlement. In terms of strength, wider ballast gradations are preferred to narrower gradations. However, in addition to durability, fines storage volume, and size segregation must be considered. All ballast requirements, on the other hand, require uniform gradation to ensure proper drainage. Ballast that is uniformly graded settles faster and is also more prone to breaking than ballast that is well graded [5]. Typically, standards for mainline ballast specify a rather restricted range of particle sizes to maximize interparticle void volume [22]. This enormous void volume allows for drainage and storage of ballast fouling particles. The specifications for ballast grading demand a uniform grading with a uniformity coefficient of 1.5 to 3 [18]. To minimize ballast deformation and degradation, Indraratna et al. (2006) recommended using slightly graded ballast (Cu =2.3-2.6) rather than the more common uniform grading with Cu of about 1.5. When compacted sufficiently, narrowly graded ballast performs admirably and provides excellent drainage and fouling material storage. Although more broadly graded ballast provides increased strength and resistance to deformation due to the particles' denser packing arrangement, it is expected to have a lower void volume than narrowly graded ballast. While a more extensively graded ballast may provide increased deformation resistance and adequate drainage and fouling material storage capacity, the ultimate issue becomes material handling and transport, as the particles will tend to segregate during transport to the site [22]. The gradation of the ballast as it is placed is important to its function and is frequently the most difficult to determine. Keeping in mind the American Society of Testing Materials (ASTM) sample size standards, it is also critical to adhere to sampling guidelines when analyzing field placement [22].

2.3.1 American ballast specification

In the early days of the railroad industry in the United States, a variety of materials were utilized as ballast to support the superstructure of the track. Almost any cheaply-available ballast material was used, and it was discovered that it was suitable when put under traffic loading [9]. In the United States, ballast materials such as granite, trap rocks, quartzite, dolomites, and hard limestone were all frequently accepted. Limestone is not the greatest ballast material if alternative hard rock material is economically available since it dissolves into fine particles that cement together. The following ballast grading is recommended by AREMA in Table 2. Figure 7 shows the railway ballast gradation that is most usually employed.

Table 2: Recommended AREMA ballast grading (after AREMA, 2000)

AREMA No	Nominal size (mm)	Percentage passing (%)									
		75 mm	63 mm	50 mm	37.5 mm	25 mm	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm
24	63–19	100	100-90		60-25		10-0	5-0	-	-	-
25	63–9.5	100	100-80	85-60	70-50	50-25	-	20-5	10-0	3-0	-
3	50-25	-	100	100-95	70-35	15-0	-	5-0	-	-	-
4A	50-19	-	100	100-90	90-60	35-10	10-0	-	3-0	-	-
4	37.5-19	-	-	100	100-90	55-20	15-0	-	5-0	-	-
5	25-9.5	-	-	-	100	100-90	75-40	35-15	15-0	5-0	-
57	25-4.75	-	-	-	100	100-90	-	60-25	-	10-0	5-0
Note 1: Grading number 24, 25, 3, 4A, and 4 are main line ballast materials. Grading number 5 and 57 are yard ballast materials.											

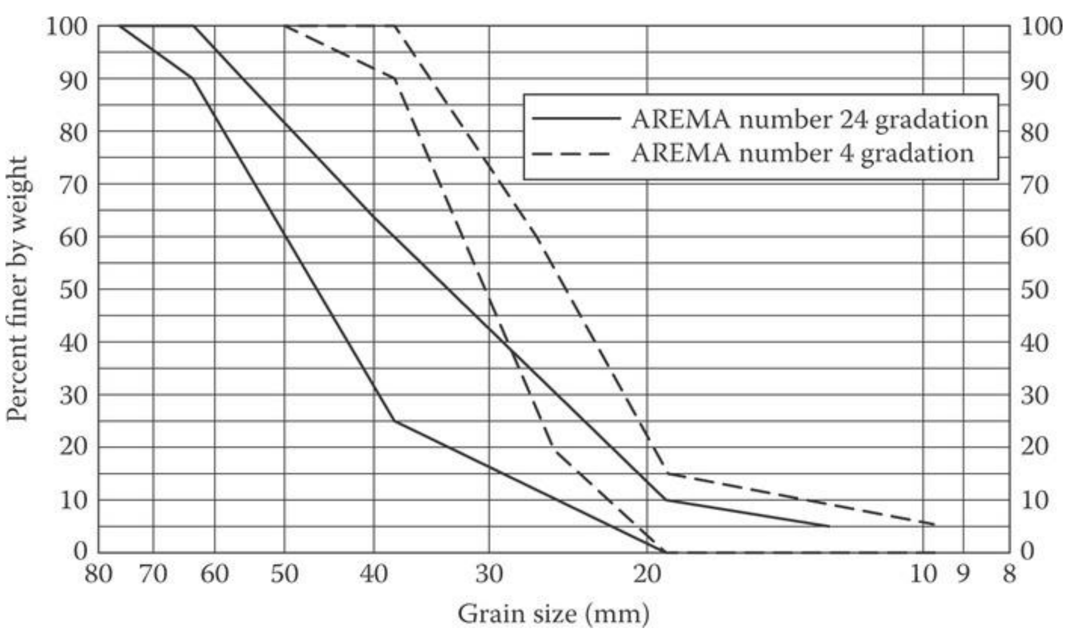

Figure 7: AREMA No.24 and No.4 ballast gradation particle size range

Table 3: Modified AREMA No.3 grading (after Norfolk Southern Corporation, 2011)

Sieve Size (mm)	Percentage passing (%)	
	AREMA 3	**Modified 3**
63.0	100	100
50.0	100-95	100-95
37.5	70-35	65-30
25.0	15-0	15-0
12.5	5-0	5-0

The AREMA No. 4 classification corresponds to the American Standard Testing for Material (ASTM) C33 classification. Furthermore, ASTM C33 grade 56 is quite close to AREMA grade 5. The majority of railroads in the United States employ AREMA grading's; Norfolk Southern Corporation (NSC) modified AREMA grading No. 3 for heavy tonnage lines and uses AREMA grading No. 5 for the yard [9]. Table 3 summarizes the modifications made by NSC to the AREMA No 3 grading. Figure 8 demonstrates that NSC has increased the amount of larger ballast particles.

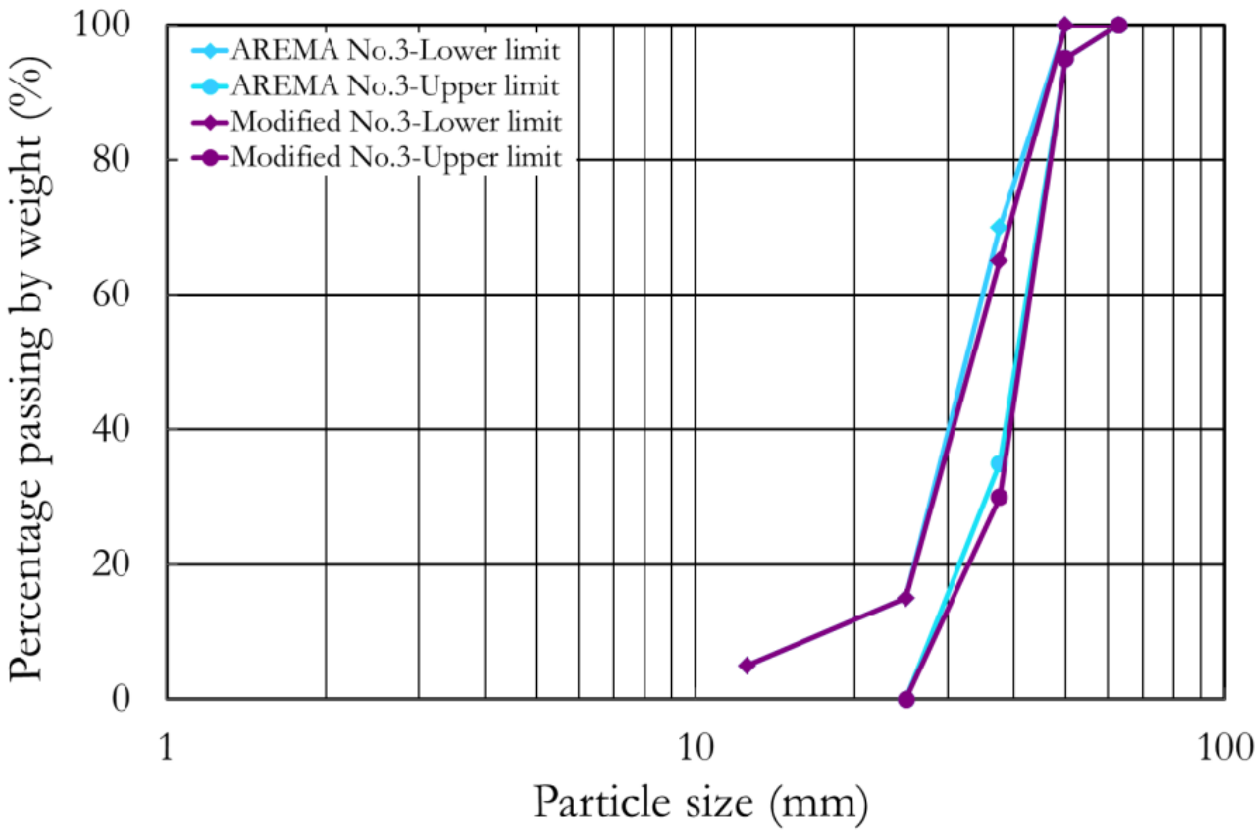

Figure 8: PSD of modified AREMA No.3 used by NSC

2.4 Ballast degradation

Is the degradation of the ballast aggregate, wherein the creation of small grains is caused by the fracture and abrasion of large, angular particles [11]. Sharp corner loss is the primary cause of ballast degradation, hence less sharp-cornered ballast particles should be utilized in ballast beds [13].

2.4.1 Ballast fouling

Ballast fouling, also known as fines infiltration from beneath layers, coal fines, and surface spills, is the contamination of ballast with fines as a result of particle breakage brought on by heavy traffic loads, sleeper wear, and fines infiltration. Ballast fracture, which accounts for around 76% of the fines, is the primary cause of ballast fouling [20]. When first put, the ballast layer has approximately 45% vacant space [23], with asperities of one particle resting on the surfaces of other particles to form a stable ballast matrix with a high shear resistance. The point of contact between asperities and particle surfaces is referred to as the interparticle contact point, and it is utilized to transfer load from one particle to another and ultimately to the under layers (sub-ballast and subgrade). The majority of energy is absorbed within the ballast structure during the load transfer mechanism, while the remainder is transferred, which is why ballast aggregates must be strong. Asperities will break and fill the spaces between the particles due to the passage of traffic, forming a durable ballast layer. The ideal resilience in a ballast layer is elastic, which means that deformation is reversible and the ballast returns to its pre-loading position [20]. Due to the large loads involved and the narrow contact area, each ballast particle deforms significantly, potentially resulting in particle breakage or contact wear when the applied stress approaches or surpasses the strength. Ballast resilience is achieved through the inter particle contact sites between the ballast particles, which allow for significant vertical and lateral elastic deformation as long as the ballast stress is tolerable and the ballast does not degrade. The passage of traffic compacts and consolidates the ballast layer, resulting in a transient increase in the layer's strength and stability as a result of densification. As loading cycles and magnitudes increase, abrasion and crushing of the particles occur, resulting in progressive plastic deformation and reduction of inter particle voids with time and usage. When the void space in the ballast layer becomes clogged with fouling material, the necessary free movement of nearby particles is restricted, preventing the compaction and consolidation process from occurring. As ballast fouls, it partially fills the vacuum area, resulting in decreased drainage capacity. However, decreased drainage capacity and repeated loading of heavily fouled ballast frequently result in the ballast particles being forced apart by the fouling material, either mechanically or because the fouling material reduces friction at inter particle contact points, thereby releasing some of the inter particle compressive force and reducing the ballast's and track structure's stability. The most obvious sign of fouling material is frequently a muddy slurry. When loaded with big particles in dry conditions, fouled-ballast tends to shift the weight to the weak fines, resulting in random dispersion of the large particles. When particles reach saturation, mud and slurry are formed.

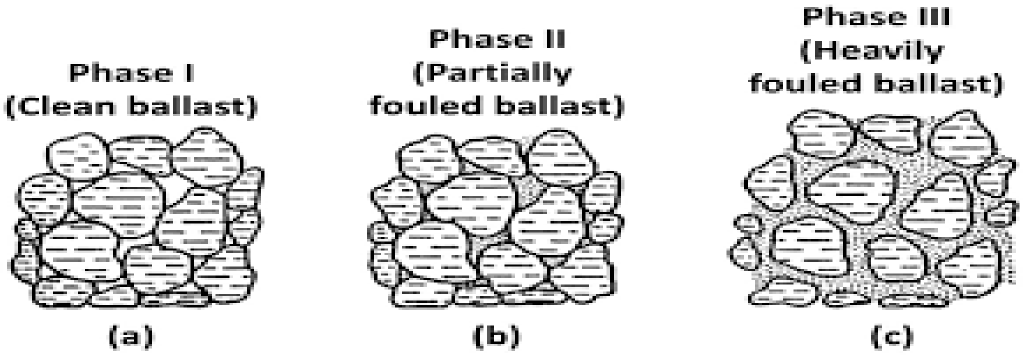

Figure 9: Critical ballast fouling phases

2.5 Causes of ballast degradation

Ballast deterioration is primarily brought on by high cyclic loads, vibration, temperature, and moisture changes, as well as the impact load placed on the ballast as a result of severe braking. According to Raymond and Diyaljee (1979), there are three ways that ballast particles might deteriorate:

- The breakage of particles into approximately equal parts (this is responsible for the long-term stability and safety of the track)
- The breakage of angular projections, which influences the initial settlement
- The grinding-off of small-scale asperities (the presence of fines can cause fouling and reduce drainage) [14].

2.6 Effect of ballast degradation on the track

According to the majority of literary works, ballast degradation is the primary cause of fouling, which is the primary cause of track settlement. Ballast breakdown under load is the main cause of ballast-fouling material, according to Sussmann, Ruel, and Chrismer (2016). Muddy fouled ballast zones with gravel from ballast breakdown mixed with fine-grained clay and silt particles from ballast deterioration or that may fall or blow onto the railway are the fouled ballast problem areas that are most frequently investigated.

The impact of fouling is described by these writers (Sussmann, Ruel, and Chrismer, 2016) as interparticle ballast contact sites, which allow for significant vertical and lateral elastic deformation as long as the ballast stress is bearable and the ballast is not compromised, are how ballast resilience is generated. Elastic resilience, or the ability to rebound from deformation and return to the position it held before to loading, is what is wanted in a ballast layer. The majority of the time, the deformation of fouled ballast is inelastic, meaning that it frequently only partially recovers with large plastic (permanent) deformation. Track settlement and faults in the track geometry occur in these spots as a result of the plastic ballast deformation. According to Selig and Waters, the ballast layer is generally the largest source of track settlement [19]. Ballast-related track settlement can affect as little as one tie in the initial stages, and shortwave length track geometry parameters such as cross-level, short-wavelength profile, or shortwave length warp can be the initial indication of track support problems. As the track is repeatedly loaded, another inelastic deformation mechanism may occur in the ballast, and for this fouling 76% of the cause is degradation. The breakage (degradation) of ballast causes differential track settlement and excessive lateral movement. Accumulation of crushed particles in the void spaces between larger aggregates decreases the permeability of ballast [14]. In conclusion, fouled ballast has a considerable impact on track settlement, with an increase in ballast fouling resulting in an increase in track settlement. Ballast fouling is a term used to describe the contamination of railway ballast produced by ballast particle deterioration, external debris fouling from surface spills, and clay fouling from subgrade pumping. The presence of these particulates in the ballast layer might obstruct the quick drainage required for excellent track performance.

2.7 Investigation methods of ballast degradation

Internationally extensive literature exists on a variety of study areas linked to the degradation of railroad ballast material. These techniques were employed by the researchers:

- Laboratory tests
- DEM (discrete element method) simulations and/or 3D particle shape developments
- FEM (finite element method) simulations
- Field tests [15]

Moaveni et al. [16], investigated the morphological characteristics of railroad ballast degradation trends in the field and laboratory to gain a better understanding of the effect of heavy axle load traffic on ballast degradation. The Los Angeles abrasion test was used to determine the abrasion

of the ballast, as well as the installation of ballast steel boxes in both the curve and tangent zones, where surface and form changes were captured using an Image Analyzer. The study's findings indicate that the magnitudes and rates of deterioration and breakage, as well as changes in the morphological features of particles, were quite different between the LA abrasion test and field degradation caused by frequent traffic loading. The author concluded that a complete investigation employing improved ballast sample and testing methodologies is necessary to elucidate the mechanisms of ballast degradation.

Guo et al. [17], performed Los Angeles Abrasion Test and Image Analysis to determine and evaluate how individual particle morphology (size and shape) changes during ballast degradation, and to verify the assumptions that ballast degradation is primarily caused by sharp corner loss and that flaky or elongated particles are more prone to break. The test results indicate that ballast degradation is directly related to the morphology of the ballast particles as follows: (a) LAA loss is greater for flaky or elongated particles than for cubic particles, implying that flaky or elongated ballast particles will deteriorate more severely; (b) flaky or elongated particles are more prone to cracking than cubic particles, and (c) larger ballast particles crack more easily. The author stated that the method, which combines LAA testing with 3-D image analysis, enables quantification of ballast deterioration, particularly in cases of abrasion degradation of individual ballast particles.

To investigate the effects of ballast aggregate breakdown and degradation on the mechanical behavior (shear strength) [11], performed the two laboratory tests which are the Los Angeles abrasion test and the large scale triaxial test. The triaxial testing efforts focused on (a) the effects of gradation considering those finer materials or fines, i.e. particles less than 9.5 mm (3/8 in.), generated through ballast degradation, and (b) the effects of aggregate shape properties, such as angularity and flatness and elongation, for particles larger than 9.5 mm (3/8 in.). Accordingly, triaxial tests were also performed only on those aggregate particles still kept after the LA abrasion tests larger than 9.5 mm (3/8 in.) in size, which would constitute the skeleton of the fouled ballast layer in the field [11].

Since it is mandatory to identify the degree of fouling which is mostly caused by the degradation of ballast and to remove the fine materials before critical problems occur, to increase the performance of the rail track. The scales that are widely used to determine fouling quantities are the Fouling Index, Percentage of Fouling, the D-Bar method, and Percentage Void Contamination. The percentage of fouling (% fouling) is the ratio of the dry weight of material passing through a 9.5 mm sieve to the dry weight of the total sample. The first three measures are commonly used; the fourth one is used by Queensland Railways. These methods are laboratory-based and require field sampling and testing, which are normally carried out by digging out trenches with even spacing. These processes require a lot of resources (i.e., time, money, and manpower). The nondestructive testing of ground penetration radar, infrared imaging, seismic surveys, and electrical resistivity are the other popular methods for identifying fouling in the field. Various studies have been carried out using non-destructive testing of Ground Penetration Radar (GPR) to map the subsurface of ballast sections. GPR is a modern geophysical approach, which can provide information about the formation of the track-bed interface. Most GPR results depend on a visual interpretation and are qualitative. However, a railway engineer still needs quantitative numbers to establish an appropriate design and maintenance program. GPR can be used to obtain information on fouling depth but it cannot clearly define the degree or type of fouling. it measured shear wave velocity and density in the model track sections and estimated the shear modulus of clean and fouled ballast. Authors have highlighted that MASW gives shear stiffness of ballast bed and are more effective than any other method but it may require more time to carry out the test in the field (Anbazhagan, Buddhima, and Amarajeevi, 2011).

In conclusion, the majorities of GPR findings are qualitative and depend on visual interpretation. On the other hand, a railway engineer needs quantitative data to create an appropriate design and maintenance schedule. GPR may be used to determine the depth of fouling, but it cannot accurately determine the degree or kind of fouling. It evaluated the shear modulus of clean and fouling ballast by measuring shear wave velocity and density in model track sections.

2.8 Maintenance and Renewal of Degraded Ballast

As the track strength and stability are greatly dependent on the appropriate functioning of the ballast [24]. The ballast is considered as the main component in any railway track maintenance. The effectiveness of a ballast maintenance approach is dependent on the accuracy of the recording and assessment of ballast conditions Still current years, the assessment of the ballast is made based on only track geometry conditions [25]. The considered track geometry conditions include track profile, gauge, alignment, and twist. Various geometry indices have been developed based on these parameters.

In other words, the current practice concentrates on the ballast short-term behavior and its long-term behavior has been omitted. While the track geometry conditions may appear normal, the track can be on the verge of failing due to severe ballast fouling. It means that track geometry by itself cannot lead to precise maintenance planning. Addressing this limitation, the current ballast maintenance approach was improved by developing a new maintenance algorithm that takes into account both short and long terms behavior of the ballast. For this purpose, two ballast conditions indices called BFI and BGI are developed. A ballast fouling index (BFI) was developed to indicate the level of ballast contamination which has been known as the main cause of ballast mechanical deterioration. This index was developed by analyzing the results obtained from GPR machines. For this purpose, compressive laboratory tests were carried out to derive a correlation between ballast contamination levels and the output of GPR machines. The correlation was used to drive a mathematical expression for the ballast contamination (BFI). A ballast geometry index (BGI) was developed based on the ballast geometry deviations in the vertical and lateral directions. It was made by analyses of the track geometry parameters deviations obtained from a track recording car.

The main futures of these indices are:

- They directly reflect both short and long term behavior of the ballast;
- They are easy to be derived as the required data are obtained from automated inspections (i.e., cost-efficient method) [26].

From the study of" Principles of Degraded Ballast and Their Track Safety Implications" [27] stated that the trend of ballast settlement increases at a decreasing rate under loading, even when it is fouled. After considering possible mechanisms under which fouled ballast settlement could affect safety, it is concluded that the main effect of high levels of fouling on ballast settlement is to allow the track to more quickly return to the rough profile that it had before tamping. Following surfacing maintenance, the ballast layer compacts under traffic at a decreasing settlement rate, and the overall stability of the ballast layer increases. However, a potential source of a safety-critical increase in the ballast settlement rate could be the formation of voids under the tie due to the buildup of slurry and erosion of ballast support directly under the tie. If ballast remains in track beyond its life, the slurry of fine material can form under and around the tie which also allows the formation of voids between the bottom of the tie and ballast, increasing track deflection under load. To avoid this condition, it is recommended that ballast be replaced before its permeability decreases to the fouling level associated with the end of ballast life. This amount of fouling is estimated as 30 using the Selig Fouling Index. Once ballast fouling exceeds a Fouling Index of approximately 30, ballast maintenance becomes less effective and renewal of the ballast layer thorough cleaning or replacement becomes necessary. Left untreated, the ballast layer can eventually deteriorate to the point where voids and slurry begin to form around the tie, which can be a potentially unsafe condition [27].

Worldwide, rail track maintenance is an expensive and routine exercise. A major portion of the maintenance budget is being spent on geotechnical problems. Maintenance is mandatory because of ballast fouling and the weakening of track subsurface layers (sub-ballast and subgrade). The major fouling reported worldwide is attributed to the breakdown of ballast (fine ballast), outside contamination by coal dust from trains carrying coal, and soil intrusions from the base. Fouled ballast can cause many major problems including a reduction in vertical resistance, reduction in the void space thereby leading to a considerable decrease in the movement of particles through the ballast, poo, or drainage of water falling on the track and vegetation growth over the rail track. It is therefore mandatory to identify the degree of fouling and to remove the fine materials before critical problems occur, to increase the performance of the rail track (Anbazhagan, Buddhima, and Amarajeevi, 2011).

Worldwide Ballast cleaning and renewal is an expensive and time-consuming process that is also highly disruptive to train traffic. Thus, the need for this process must be considered carefully. Ballast cleaning and renewal are required when the ballast becomes extremely fouled that it cannot fulfill its functions. Many modern non-destructive tests such as ground penetration radar (GPR), infra-red imaging, seismic surveys, and electrical resistivity are widely used for identifying fouling in the field. Most of the GPR testing was carried out on actual railway lines. There are a lot of uncertainties within the actual rail track and it is difficult to calibrate the GPR data with actual ground conditions because of a limited number of trenches and time constraints. Most of these GPR results are dependent on a visual interpretation and are qualitative. However, a railway engineer still needs quantitative methods to establish an appropriate design and maintenance program. GPR can be used to obtain information on fouling depth but it cannot clearly define the degree or type of fouling [27].

In conclusion, a wide range of sophisticated non-destructive methods, including electrical resistivity, ground penetrating radar (GPR), infrared imaging, seismic surveys, and infrared imaging, are frequently used in the field to find fouling. On actual railroad lines, GPR testing was conducted for the most part. There are many uncertainties inside the real rail track, and due to a limited number of trenches and time restrictions, calibrating the GPR data with actual ground conditions is problematic. The majorities of these GPR data are qualitative and rely on visual interpretation. A railway engineer, on the other hand, need quantitative methodologies to develop an acceptable design and maintenance schedule.

3. Methodology

3.1 Introduction

In order to establish current practice and its justification, this research will first conduct a thorough literature and practice evaluation of the ballast specifications utilized by Ethiopian railways and the applicable codes. From Ethio-Djibouti railway line field data will be obtained on the ballast specification (particle size, shape and angularity), level of fouling and maintenance history & routine for Bike-Dewele sites, age and level of use. Laboratory experiments employing readily available and relevant test types and analysis procedures will be used to supplement this. Using the data, connections between ballast specification, degradation/fouling, and maintenance requirements will be found. Similarly, a review of deteriorating ballast improvements will be conducted.

3.2 Field Investigation

To better understand the problem and the course of ballast degradation, a field investigation is a visual inspection of the ballasted track and its attributes, such as vegetation growth, surface fines, shoulder ballast missing, cobles on the main track, and more degraded ballast sections.

3.3 Samples and sampling procedures

3.3.1 Sampling according to AASHTO R 90

The sampling was done at railway track sections from different locations whereby three points were selected randomly (around rail seat, under the sleeper, and between sleepers) in each location. From every position on the three points, full-depth increments of roughly equal size were obtained. The increments from the three points were combined to form a single sample for the specified location. I'll collect used spades and sample bags at each place.

3.3.2 Reducing Samples to Test Size according to AASHTO R 76

Method B, which is quartering, is chosen for the study due to its convenience of use and the sensitivity of the material (sample) to breakage when compared to other methods. The field samples were reduced to an adequate size for testing in accordance with AASHTO R 76-16.

3.4 Material Testing

3.4.1 Gradation (Sieve Analysis) according to ASTM C117 and C136

For track strength, deformation, degradation, stability, and drainage, ballast gradation is essential. Since the ballast's physical characteristics play a major role in its effective field performance. Ballast size distribution can indicate the degree of ballast breakage or degradation and has a significant impact on the way the track deforms. A higher level of uniformity of ballast aggregates leads to a higher elastic stiffness and lower breakage. However, the density and angle of internal friction decline with higher levels of particle uniformity. Ballasts with broad gradation contain fewer voids, thereby offering higher strength than uniformly graded ballasts. All ballast requirements, on the other hand, require uniform gradation to ensure proper drainage which can also reduce breakage by protecting the ballast from moisture. Ballast that is uniformly graded settles faster and is also more prone to breaking than ballast that is well graded [29].

The sample sizes were chosen based on the Nominal Maximum Size of Aggregate, which is depicted in Table 4. In this study, 35 kg were chosen as a test sample and dried at 110 ± 5° C for 24 hours before being cooled to room temperature. The material finer than 0.075mm was removed according to ASTM C117, and the material larger than 0.075mm was measured, according to ASTM C136 by choosing sieve sizes in accordance with specification requirements [28] and [30]. The material retained in each sieve was recorded and expressed in percentage. The percentage of material passing in each sieve was calculated and recorded.

Gradation (Sieve analysis) test

Table 4: Test sample sizes for aggregate gradation test

Sieve size (mm)	Sample size (g)
125	300,000
100	150,000
90	100,000
75	60,000
63	35,000
50	20,000
37.5	15,000

25.0	10,000
19.0	5000
12.5	2000
9.5	1000
6.3	1000
4.75	500

3.4.2 Los Angeles Abrasion Test according to AASHTO T 96

The Los Angeles Abrasion test is used to test durability and strength properties of ballast, with the evaluation method of mass loss rate named LAA loss (%), and it is a vital quantity evaluation of ballast. LAA test can be applied to the study of ballast attrition, for it could create dynamic impacts. It is suggested that it is too good to be true that such a simple test can separate in all aspects good performing ballast materials from the poor performance ones in a reliable way [31].

The LAA test measures the degradation of a coarse aggregate sample that is placed in a rotating drum with steel spheres. As the drum rotates the aggregate degrades by abrasion and impact with other aggregate particles and the steel spheres (called the "charge"). Once the test is complete, the calculated mass of aggregate that has broken apart into smaller sizes is expressed as a percentage of the total mass of aggregate. Therefore, lower LAA values indicate aggregate that is tougher and more resistant to abrasion.

The test sample size was chosen according to the grading of the test sample as shown in Table 5. For this project, 10kg sample and 12 steel balls of 500g each were placed in an abrasion machine drum rotating with 30-33rpm to provide 1000 revolutions. The materials are removed from the drum after the specified revolution and sieved on Sieve #12 (1.7mm standard sieve size). The Los Angeles Abrasion Value is calculated as the percentage of material passing Sieve #12:

$$\text{Los Angeles Abrasion Value} = \frac{(\text{Original Weight} - \text{Weight Retained on \#12}) \times 100}{\text{Original Weight}}$$

Los Angeles Abrasion test

Table 5: Grading of Test Samples

Sieve Sizes		Mass of Indicated Sizes (g)						
Passing	Retained	A	B	C	D	1	2	3
76.2 mm (3 in)	63.5 mm (2.5 in)	-	-	-	-	2500 ± 50	-	-
63.5 mm (2.5 in)	50.8 mm (2 in)	-	-	-	-	2500 ± 50	-	-
50.8 mm (2 in)	37.5 mm (1.5 in)	-	-	-	-	5000 ± 50	5000 ± 50 is	-
37.5 mm (1.5 in)	25.0 mm (1.0 in)	1250 ± 25	-	-	-	-	5000 ± 25	5000 ± 25
25.0 mm (1.0 in)	19.0 mm (3/4 in)	1250 ± 25	-	-	-	-	-	5000 ± 25
19.0 mm (3/4 in)	12.5 mm (1/2 in)	1250 ± 10	2500 ± 10	-	-	-	-	-
12.5 mm (1/2 in)	9.5 mm (3/8 in)	1250 ± 10	2500 ± 10	-	-	-	-	-
9.5 mm (3/8 in)	6.3 mm (1/4 in)	-	-	2500 ± 10	-	-	-	-
6.3 mm (1/4 in)	4.75 mm (#4)	-	-	2500 ± 10	-	-	-	-
4.75 mm (#4)	2.36 mm (#8)	-	-	-	5000 ± 10	-	-	-
Total		5000 ± 25	5000 ± 20	5000 ± 20	5000 ± 10	10000 ± 100	10000 ± 75	10000 ± 50

Table 6: Number of abrasive charges for above samples

Abrasive Charges	**No. of Revolutions**	**No. of Spheres**	**Weight of Charges (g)**
A	500	12	5000 ± 25
B	500	11	4584 ± 25
C	500	8	3320 ± 20
D	500	6	2500 ± 25
1	1000	12	5000 ± 25
2	1000	12	5000 ± 25
3	1000	12	5000 ± 5

3.4.3 Flakiness Index According to BS 812:1989

The study on particle shape shows that flaky or elongated particles at a limited percentage could increase the shear strength of ballast bed, and reduce the settlement for the lower rate of settlement accumulation. However, it was also reported that flaky or elongated particles would lead to increased particle degradation and higher deformation.

The misshape of ballast aggregate was assessed according to BS812:1989 for Flaky particles. The size of the test sample was chosen according to Table 7. The flakiness index of an aggregate sample is found by separating the flaky particles and expressing their mass as a percentage of the mass of the sample tested in Table 8. The test does not apply to material passing a 63.0 mm BS test sieve or retained on a 63.0 mm BS test sieve. The portions of mass passing and retained in sieves are shown in Table 8 were recorded as M1 and gauged with flakiness gauge. The mass of material passing the slots of the flakiness gauge are recorded as M2.

The value of the flakiness index is calculated from the expression:-

$$\textit{Flakiness Index (FI)} = (M2 / M1) \times 100$$

Where:
M1 = total mass of material passing sieve size 50mm and retained on sieve size 63mm.
M2 = total mass of material passed through flakiness gauge.

Flakiness index test

Table 7: Minimum mass of test portion

Nominal Size of Material (mm)	Minimum Mass of Test Portion After Rejection of Oversize and undersize particles (kg)
50	35
40	15
28	5
20	2
14	1
10	0.5

Table 8: Data for Determination of Flakiness Index

Aggregate Size Fraction		Width of Slot in thickness gauge or special sieves (mm)	Minimum mass for subdivision (kg)
BS Test Sieve Size			
100% Passing	100% Retained		
50.0	37.5	26.3±0.3	35
37.5	28.0	19.7±0.3	15
28.0	20.0	14.4±0.15	5
20.0	14.0	10.2±0.15	2
14.0	10.0	7.2±0.1	1
10.0	6.30	4.9±0.1	0.5

3.4.4 Elongation Index According to BS812:1990

The elongation index is found by separating the elongated particles and expressing their mass as a percentage of the mass of the sample tested. The misshape of ballast aggregate was assessed according to BS812:1990 for elongated particles. The size of the test sample was chosen according to Table 9. This test does not apply to material passing a 63.0 mm test sieve or retained on a 50.0 mm test. The portions of mass passing and retained in sieves were recorded as M1 and gauged with an Elongation gauge. The mass of material retained on the gap between the pins of the Elongation gauge was recorded as M2.

The value of the elongation index is calculated from the expression:

$$\textbf{\textit{Elongation Index (EI)}} = (M2/ M1) \times 100$$

Where:
M2 = total mass of material passed through sieve size of 50mm and retained on sieve size of 6.3mm.
M1 = total mass of material retained on elongation gauge.

Table 9: Data for Determination of Elongation Index

Aggregate Size Fraction		The gap between pins of the length gauge (mm)	Minimum mass for subdivision (kg)
Test Sieve Size			
100% Passing	100% Retained		
50.0	37.5	78.7±0.3	35
37.5	28.0	59±0.3	15
28.0	20.0	43.2±0.3	5
20.0	14.0	30.6±0.3	2
14.0	10.0	21.6±0.2	1
10.0	6.30	14.7±0.2	0.5

3.4.5 Fouling Index test According to Waters and Silegs' recommendation

The fouling index commonly used by practitioners was indeed a good indicator of fouling conditions, especially when all voids created by larger particles were filled by fine materials as FI values approached 40 [29]. So calculating the fouling index can show the extent of fouling and degradation of ballast. FI is the summation of the percentage by weight of ballast material passing the 4.75mm (#4) sieve and the percentage passing the 0.075mm (#200) sieve. The resultant% classifications based on FI are presented in the following table.

Table 10: The extent of ballast fouling as a function of computed FI values

% Finer Than 0.075 mm	Fouling Index (FI)	Adjudged Fouling Extent
-	<1	Clean
-	1-9.99	Reasonably clean
25-35	10-19.99	Moderately Fouled
40-50	20-39.99	Fouled
>50	>40	Highly Fouled

The value of the fouling index is calculated from the expression:

$$\textit{Fouling index (FI)} = P_4 + P_{200}$$

Where:

P_4= Percentage of material passing through the 4.75mm (No.4) sieve

P_{200}= Percentage of material passing through the 0.075mm (No. 200) sieve

4. RESULTS AND DISCUSSIONS

4.1 Field Investigation

Through visual inspection, the inquiry into the field's ballast deterioration found certain spots with vegetation growth, surface fines, missing shoulder and crib ballast, cobles on the main track, and other damaged ballast portions.

Figure 10 displays a portion where the crib and shoulder ballast are absent, which can also affect the stability and drainage of the track, may happen longitudinal movement of the sleepers, shoulder ballast missing may happen track buckling, and vegetation growth between and beyond sleepers. Figure 11 depicts a stretch where the ballast bed has been contaminated with dirt, mud, and other animal wastes. If individuals are allowed to cross the main track, this risk could reduce lateral stability, which increases the likelihood of accidents, loss of life, and damage to property, decrease drainage capacity and reducing ballast and track structure stability, Decrease movement of particles through the ballast, and Vegetation growth over the rail track. Figure 12 shows cobles on the main track, which can become attached to the axles and endanger passing trains and derailment, or even endanger the lives of passengers and railroad workers. Figure 13 demonstrates the heavy crushing and extensive surface particles in the ballast which can become ballast fouling occurs, cause errors in track geometry, and reduce the ballast's capacity for drainage.

Figure 10: Missing crib and shoulder ballast and vegetation at K392+100 (Bike)

Figure 11: Fouled ballast around level crossing at K459+200 (Dire Dawa)

Figure 12: Cobble on main track at K470+300

Figure 13: Surface fines and high degraded ballast at K663+500 (Dewele)

4.2 Material Testing

4.2.1 Ballast Gradation (Sieve analysis)

Samples were taken from ten different places according to the methodology part of the test, and the findings of the sieve analyses to look at ballast degradation are displayed in Table 11 and Figures 15–16. Figure 14's PSD curves for the as-built and design limitations allow us to conclude that the built ballast bed complies with the required grading. The normal ballast grade is found between 16mm and 63mm, according to the curve PSD. According to the results of the design and as-built tests, the size of the ballast should range from 35.5 to 63 mm for 60–75 percent of the time, with more than 97 percent passing through a 63 mm sieve.

Figures 15 and 16 show the PSD curve shifting over the as-built maximum value and below the as-built lowest value, respectively. The coefficients of curvature and uniformity were calculated to estimate the impact of ballast degradation, as shown in Table 12 and Figure 17.

Table 11: Summary of sieve analysis test

% passing														
Sieve size	Location										Design upper limit	As-built upper limit	Design lower limit	As-built lower limit
	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000				
63	100.00	100.00	100.00	100.00	100.00	82.26	91.57	97.12	100.00	97.40	100.00	100.00	97.00	99.00
56	76.49	88.25	85.51	88.71	86.00	47.74	60.01	71.28	91.25	68.82	97.00	96.00	92.00	92.00
45	46.37	55.20	60.07	71.55	65.84	30.01	33.92	36.13	60.02	37.27	75.00	79.00	55.00	56.00
35.5	25.73	26.12	38.92	42.97	33.84	15.64	13.86	7.09	33.22	8.38	40.00	38.00	25.00	25.00
25	16.45	15.69	26.14	30.89	22.39	11.38	7.15	4.24	20.43	4.07	15.00	13.00	5.00	5.00
16	1.60	4.00	2.14	1.85	1.93	1.71	2.69	1.68	1.86	1.44	5.00	2.00	0.00	0.00

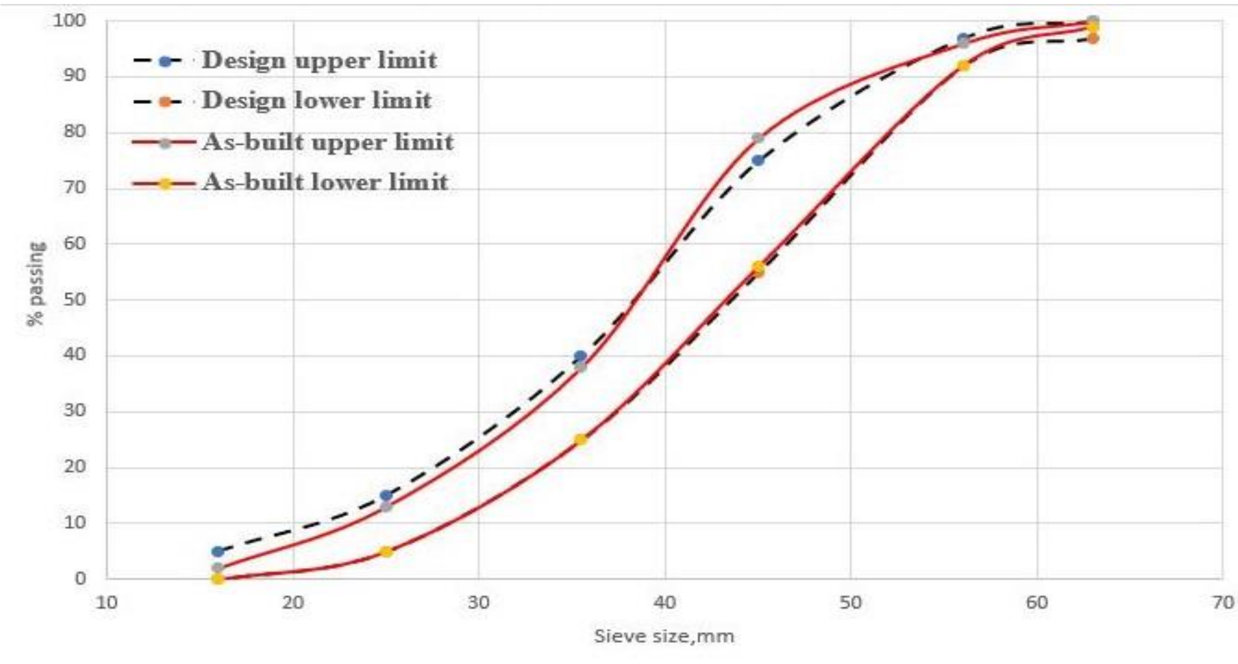

Figure 14: PSD curves for design compared with as-built.

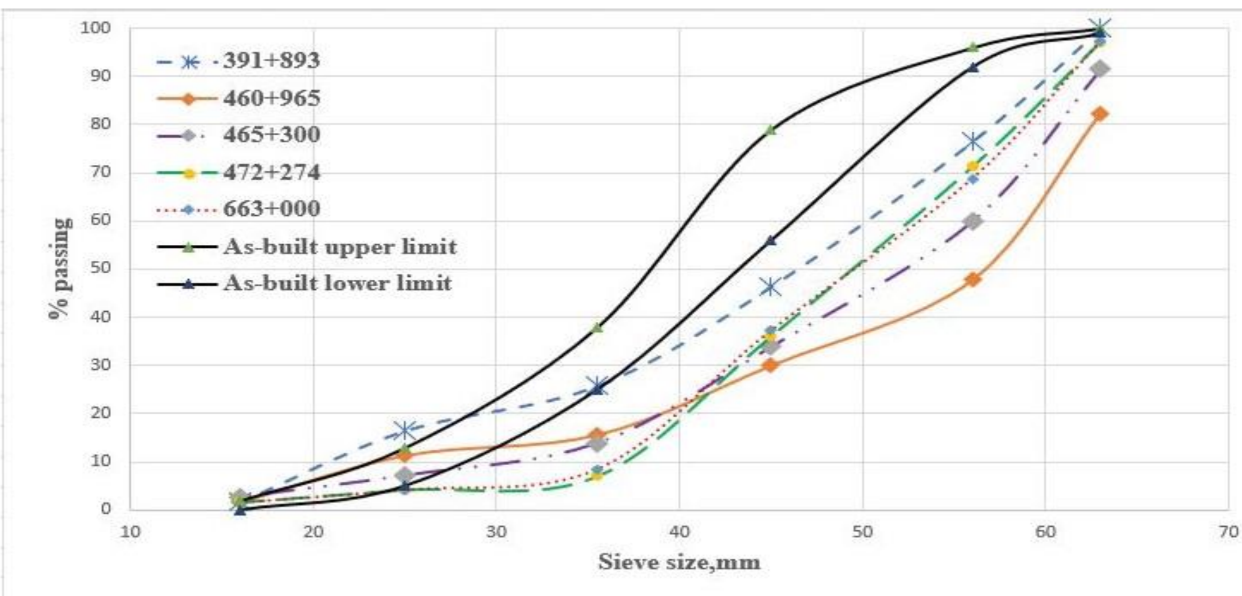

Figure 15: PSD curves with percentage passing below the as-built lower limit value.

The current ballast grading, as shown in Figure 15, indicates that boulder particle size is larger than the as-built data. This shows that either the as-built test results are inaccurate or the ballast has been maintained using materials that do not comply with the intended requirement.

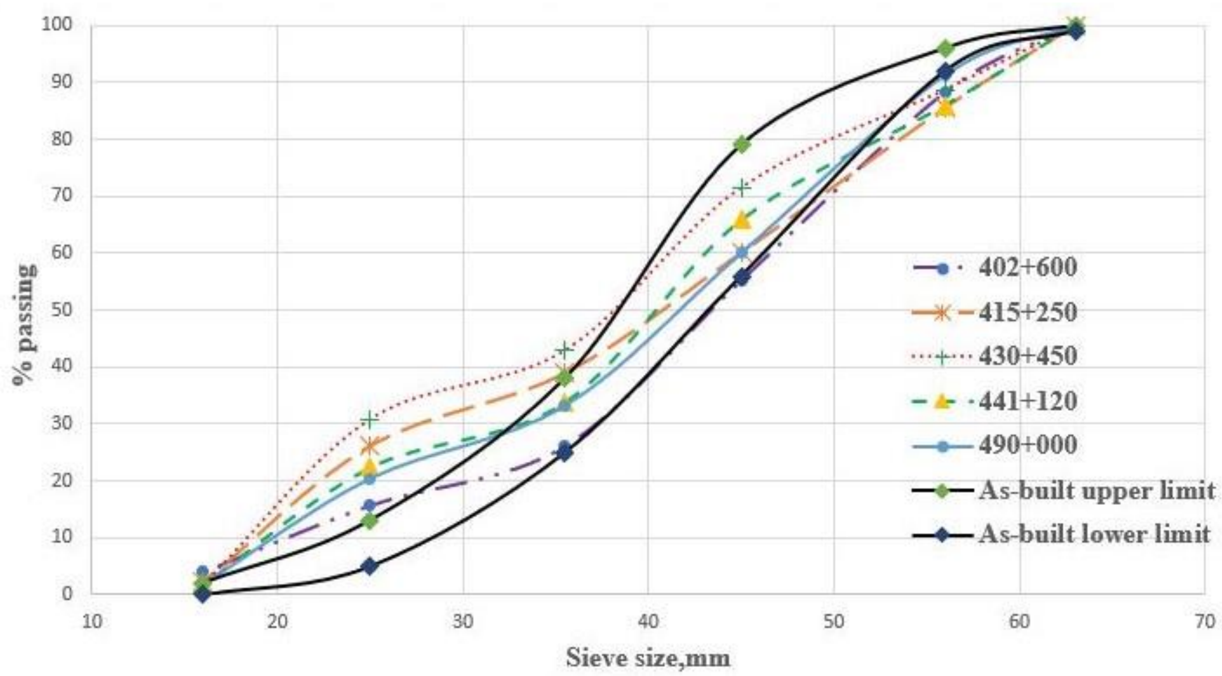

Figure 16: PSD curves with percentage passing above the as-built upper limit value.

The current ballast grading, as shown in Figure 16, indicates that the particle size is reducing in comparison to as-built data. This proves that the ballast has been losing its broad grading and cracking at these locations. There is substantial ballast degradation in these spots.

Table 12: Coefficient of uniformity (C_u) and Coefficient of curvature (C_c)

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
C_u	2.41	2.31	2.52	2.31	2.31	2.41	1.81	1.43	2.27	1.51
C_c	1.35	1.43	0.93	0.84	1.33	1.41	1.10	0.98	1.33	0.95

Where:

$C_u = D_{60} / D_{10}$

$C_c = D_{30}^2 / D_{60} * D_{10}$

The coefficient of uniformity of the present ballast is compared to the designed standard, and the results are found to be within the designed range (between 1 and 3) for all ten places, suggesting that the grading of the ballast material still complies with the designed requirement. Additionally, the material is degrading from its initial values if the current ballast coefficient of curvature is less than 1 in 4 locations, which may be seen by the material being inside a constrained range of gradation.

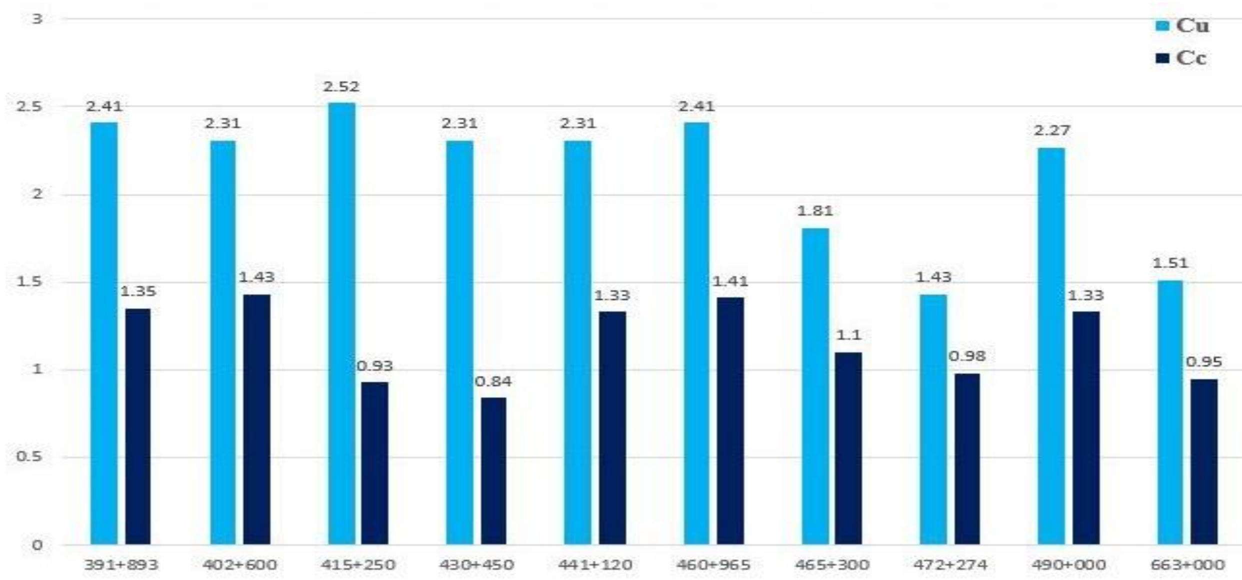

Figure 17: Coefficient of uniformity (C_u) and Coefficient of Curvature (C_c)

The test findings displayed in Figures 15–16 reveal that the gradations of ballast aggregates from each location differ from the construction-related as-built limits. While some gradations fall below the as-built minimum limitations, others exceed the as-built maximum limits. As the degradation continued, a greater percentage of ballast passed through the standard sieves, exceeding the maximum design limit where the degradation was severe. Any ballast maintenance should keep the gradations within the bounds if done appropriately. The existing gradation in situ, the gradation curve is below the lower limits implies that the gradation is shifting to a broader range due to additional materials beyond the recommended design lower limits. As a result of the degradation and improper maintenance of ballast material, as well as the addition of incorrect proportions, the ballast layer functions are compromised.

4.2.2 Los Angeles Abrasion test (LAA)

The findings of dry laboratory tests carried out in compliance with AASHTO-T 96 protocols to ascertain the mechanical characteristics of ballast based on samples gathered at various locations. Ballasts at positions 465+300 and 415+250, or 24 percent and 13 percent, respectively, contain the maximum and minimum LAAVs. Table 13 includes a list of the mechanical characteristics of the ballast at the chosen sites as well as the American Standard Test Method's suggested limitations. Every LAA number falls below the ASTM maximum value of 30%. As a result, it is widely recognized that the contemporary ballast is abrasion resistant.

Table 13: Summary of LAA Values of selected locations and Recommendations

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
LAA %	18	17	13	21	19	14	24	16	15	21
Recommendations Max 30% ASTM-C535-C131										

4.2.3 Flakiness Index test

The definition of a flaky particle is one with a thickness to width ratio of less than 0.6, and the flakiness index is the percentage of flaky particles per weight that pass through the flakiness gauge. The maximum (37%) and minimum (10%) FI values for ballast are found at sites K430+450 and K663+000. The recommended FI values, according to the design specification, are 50%; hence, the ballast form parameters at the chosen locations are within the recommended ranges.

Table 14: Summary of FI Values of selected locations and Recommendations

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
FI (%)	31	25	36	37	19	12	14	12	23	10
Recommendations <50%										

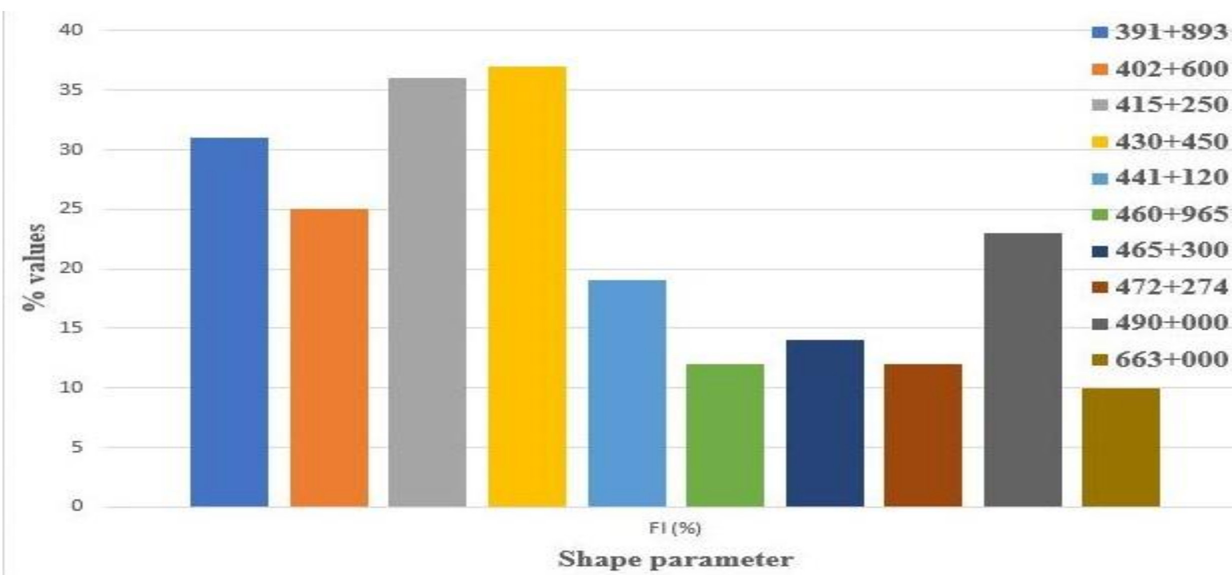

Figure 18: A Clustered Bar Chart showing the FI values of the ballast at different locations

4.2.4 Elongation Index test

Another form characteristic of ballast material, elongation impacts how well particles interlock and how resilient the ballast bed is. Aggregates are defined as having a length (largest dimension) greater than 1.8 times their mean sieve size in accordance with British Standard BS 812-105.2:1990. The highest (46%) and lowest (15%) EI values are found in the ballast at coordinates K415+250 and K472+274. The recommended FI values, according to the design specification, are 50%; hence, the ballast form parameters at the chosen locations are within the recommended ranges.

Table 15: Summary of EI Values of selected locations and Recommendations

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
EI (%)	38	40	46	38	32	19	16	15	33	18
Recommendations <50%										

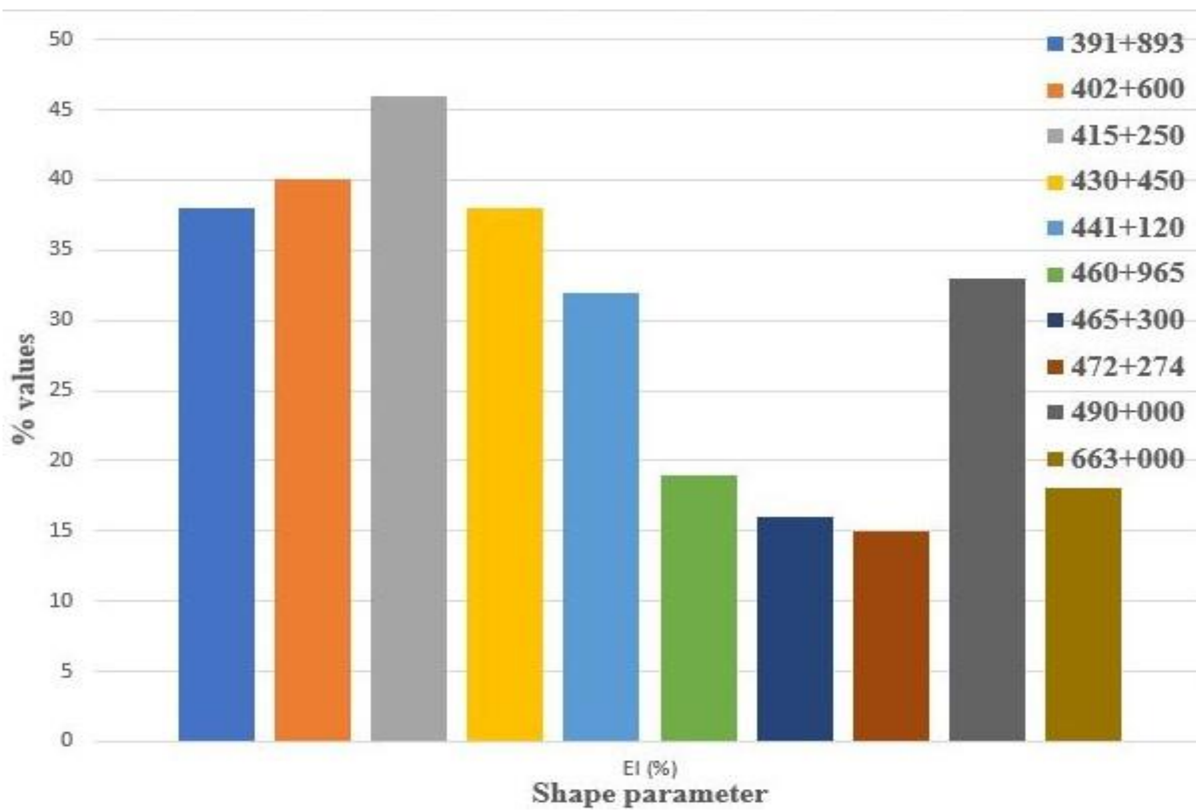

Figure 19: A Clustered Bar Chart showing the EI values of the ballast at different locations

4.2.5 Fouling Index test

Ballast fouling happens gradually and is impacted by a variety of causes. Ballast breakdown and degradation are to be expected when there is no contamination from the environment or operations, and they may initially increase stability by keeping the ballast particles in situ. According to Selig and Waters,

$$\textbf{\textit{Fouling index (FI)}} = P_4 + P_{200}$$

Where:

P_4= Percentage of material passing through the 4.75mm (No.4) sieve

P_{200}= Percentage of material passing through the 0.075mm (No. 200) sieve

In order to conduct the test, 35000g of ballast is sieved through sieves #4 and #200, respectively, for each of the ten locations where ballast samples were taken. The percentage passes of each sieve are then added. Therefore, the fouling state of the ballast is very low, meaning that the FI is found below 2% in all sites and the ballasts are classed as clean in 6 places and reasonably clean in 4 locations, in accordance with the classification criteria of the Fouling Index that Waters and Selig proposed. We can assume that ballast fracture or deterioration is negligible based on these FI statistics.

Table 16: Summary of FI Test results

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
FI (%)	1.14	0.66	0.75	1.53	0.40	0.74	1.21	0.49	1.01	0.68
Category	Reasonably clean	Clean	Clean	Reasonably clean	Clean	Clean	Reasonably clean	Clean	Reasonably clean	Clean

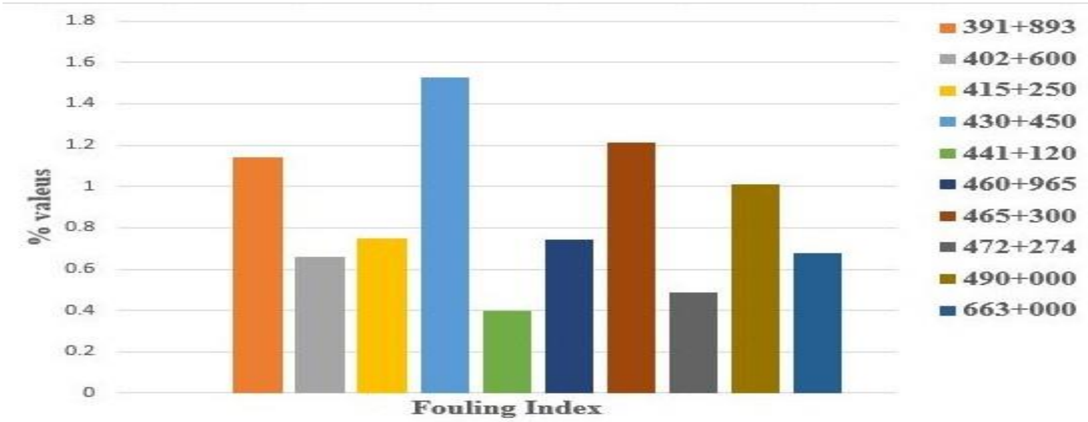

Figure 20: A Clustered Bar Chart showing the FI values of the ballast at different locations

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Regarding ballast degradation along the Ethio-Djibouti Railway Line's Bike-Dewele segment, the following conclusions have been reached:

Within five years of operation, there is significant deterioration of ballast, as shown by the PSD curves shifting above the as-built maximum values of 40-115 percent. Improper ballast aggregate addition has been found, as indicated by PSD curves dropping below the as-built minimum value of 41-180 percent. The ballast is within the intended Cu and Cc limits, as shown by the coefficients of uniformity and curvature, but it is losing its broad grading and uniformity in both cases. The majorities of ballast aggregates throughout the Bike-Dewele stretch are broadly graded and fall within as-built data, while others are even more broadly graded than as-built data.

The resistance of the present ballast to abrasion is between 76 and 87%. However, due to a lack of data on the As-Built values for the abrasion tests, an adequate judgment regarding whether these results varied from the initial values or not could be drawn. Additionally, when the values are compared to the recommendations in various standards, it can be concluded that the ballast is still capable of carrying the imposed loads.

The shape property (flakiness and elongation) index tests show that particle shape has been rapidly changing (highest FI value is 37% and highest EI value is 46%) and the material is deteriorating. Even if these values are high after five years, it's fortunate that they haven't reached their maximum, and it's predicted that they would drop with time because ballast can break easily during years of service.

According to the fouling index test, the amount of fine materials in the ballast is minimal, which suggests that the ballast is clean or moderately clean. This shows that the material is not severely contaminated with fines from other external sources, even though the large particles are breaking and the specified grading's arrangement is changed at the majority of places. While conducting a field investigation, I discovered that several portions of the ballast were highly fouled, but that sampling was not permitted.

According to a field assessment and the results of laboratory tests, the quality of current ballast material on the Bike-Dewele railway line has degraded somewhat in some location and severe degraded in other place over the course of the last five years of operation. Therefore, the current ballast needs maintenance and replacement.

Last but not least, the results of the tests for sieve analysis, LAA, flakiness and elongation index, and fouling index show that the lines are maintained regularly by the tamping method; however, if the tamping procedure is regularly interrupted, the ballast is severely degraded and the track settlement is distorted.

5.2 Recommendations

The investigation of the degradation of the railway line between Bike and Dewele yielded the following recommendations:

- The study advises that the investigations be repeated using a full-scale triaxial test to model an in-situ ballast degradation trend to assess its carrying capacity.
- To keep the ballast grading within the acceptable standard, maintenance should be carried out in accordance with regular grading results and necessary sizes.
- The maintenance materials must be created and tested in accordance with the established standards.
- To prevent fines for foot stepping and animal wastes, it is advised that pedestrians have adequate crossings, such as overpasses.
- It is recommended to combine sieve analysis with digitalized equipment, such as Ground Penetration Radar (GPR), when testing for ballast fouling.

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APPENDIX I

Laboratory Test Result:

1. **Sieve analysis results**

Note: The weight of the washed and dried ballast for all sieve tests is 35000g.

Location: 391+893 (Bike)

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	0.00	0.00	0.00	100.00	100.00
56	8220.51	23.51	23.51	76.49	76.49
45	10537.30	30.12	53.63	46.37	46.37
35.5	7224.18	20.64	74.27	25.73	25.73
25	3246.11	9.28	83.55	16.45	16.45
16	5228.40	14.94	98.40	1.60	1.60
pan	543.50	1.52	100.00	0.00	1.60

Location: 402+600

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	0.00	0.00	0.00	100.00	100.00
56	4113.54	11.75	11.75	88.25	88.25
45	11568.35	33.05	44.80	55.20	55.20
35.5	10177.40	29.08	73.88	26.12	26.12
25	3650.30	10.43	84.31	15.69	15.69
16	4090.03	11.69	96.00	4.00	4.00
pan	1400.38	4.00	100.00	0.00	4.00

Location: 415+250

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	0.00	0.00	0.00	100.00	100.00
56	5070.10	14.49	14.49	85.51	85.51
45	8904.32	25.44	39.93	60.07	60.07
35.5	7403.20	21.15	61.08	38.92	38.92
25	4473.86	12.78	73.86	26.14	26.14
16	8401.25	24.00	97.86	2.14	2.14
pan	747.26	2.14	100.00	0.00	2.14

Location: 430+450

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	0.00	0.00	0.00	100.00	100.00
56	3950.19	11.29	11.29	88.71	88.71
45	6007.60	17.16	28.45	71.55	71.55
35.5	10001.25	28.58	57.03	42.97	42.97
25	4227.83	12.08	69.11	30.89	30.89
16	10164.77	29.04	98.15	1.85	1.85
pan	648.35	1.85	100.00	0.00	1.85

Location: 441+120

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	0.00	0.00	0.00	100.00	100.00
56	4900.69	14.00	14.00	86.00	86.00
45	7057.10	20.16	34.16	65.84	65.84
35.5	11201.20	32.00	66.16	33.84	33.84
25	4007.88	11.45	77.61	22.39	22.39
16	7160.45	20.46	98.07	1.93	1.93
pan	672.67	1.93	100.00	0.00	1.93

Location: 460+965 (Dire Dawa)

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	6208.55	17.74	17.74	82.26	82.26
56	12080.87	34.52	52.26	47.74	47.74
45	6204.70	17.73	69.99	30.01	30.01
35.5	5030.72	14.37	84.36	15.64	15.64
25	1491.43	4.26	88.62	11.38	11.38
16	3384.68	9.67	98.29	1.71	1.71
pan	599.04	1.71	100.00	0.00	1.71

Location: 465+300

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	2950.56	8.43	8.43	91.57	91.57
56	11047.15	31.56	39.99	60.01	60.01
45	9132.53	26.09	66.08	33.92	33.92
35.5	7021.93	20.06	86.14	13.86	13.86
25	2349.43	6.71	92.85	7.15	7.15
16	1560.89	4.46	97.31	2.69	2.69
pan	937.51	2.69	100.00	0.00	2.69

Location: 472+274

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	1009.53	2.88	2.88	97.12	97.12
56	9045.10	25.84	28.72	71.28	71.28
45	12303.24	35.15	63.87	36.13	36.13
35.5	10164.42	29.04	92.91	7.09	7.09
25	995.72	2.85	95.76	4.24	4.24
16	894.46	2.56	98.32	1.68	1.68
pan	587.53	1.68	100.00	0.00	1.68

Location: 490+000

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	0.00	0.00	0.00	100.00	100.00
56	3063.17	8.75	8.75	91.25	91.25
45	10931.25	31.23	39.98	60.02	60.02
35.5	9380.20	26.80	66.78	33.22	33.22
25	4476.86	12.79	79.57	20.43	20.43
16	6500.16	18.57	98.14	1.86	1.86
pan	648.35	1.86	100.00	0.00	1.86

Location: 663+000 (Dewele)

Sieve size (mm)	Weight retained (g)	% retained	Cumulative % retained	% passing	Cumulative % passing
63	909.41	2.60	2.60	97.40	97.40
56	10004.32	28.58	31.18	68.82	68.82
45	11043.44	31.55	62.73	37.27	37.27
35.5	10110.51	28.89	91.62	8.38	8.38
25	1509.31	4.31	95.93	4.07	4.07
16	919.55	2.63	98.56	1.44	1.44
pan	503.44	1.44	100.00	0.00	1.44

Summary of sieve analysis test:-

% passing										
Sieve size	Location									
	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
63	100.00	100.00	100.00	100.00	100.00	82.26	91.57	97.12	100.00	97.40
56	76.49	88.25	85.51	88.71	86.00	47.74	60.01	71.28	91.25	68.82
45	46.37	55.20	60.07	71.55	65.84	30.01	33.92	36.13	60.02	37.27
35.5	25.73	26.12	38.92	42.97	33.84	15.64	13.86	7.09	33.22	8.38
25	16.45	15.69	26.14	30.89	22.39	11.38	7.15	4.24	20.43	4.07
16	1.60	4.00	2.14	1.85	1.93	1.71	2.69	1.68	1.86	1.44

D_{10}, D_{30} and D_{60} Values:

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
D_{10}	21.15	20.71	18.20	18.01	19.20	24.70	31.25	36.50	19.82	35.75
D_{30}	38.00	37.30	27.60	25.00	33.60	45.00	44.02	43.21	34.50	42.50
D_{60}	50.45	47.00	45.00	41.40	44.13	58.69	56.21	52.30	45.00	53.20

2. Los Angeles Abrasion Test Value

Grade 2	Location	Weight of Sample (g)	Weight Retained on sieve #12 (1.7mm)	LAA %
	391+893	10000	8157.23	18.43
	402+600	10000	8270.12	17.31
	415+250	10000	8656.09	13.44
No. revolution 1000	430+450	10000	7879.57	21.20
	441+120	10000	8068.24	19.32
	460+965	10000	8575.21	14.23
Weight of 12 steel balls 6000g	465+300	10000	7589.35	24.11
	472+274	10000	8402.76	15.97
	490+000	10000	8511.37	14.89
	663+000	10000	7936.27	20.64

Summary of LAA test:-

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
LAA %	18	17	13	21	19	14	24	16	15	21
									Min.	13
									Max.	24

3. Flakiness Index Test Value

Location: 391+893 (Bike)

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.0	37.5	26.3 ± 0.3	6747.40	1870.03	7.79
37.5	28.0	19.7 ± 0.3	9235.43	3650.13	15.20
28.0	20.0	14.4 ± 0.15	8025.55	1900.32	7.92
20.0	14.0	10.2 ± 0.15	0.00	0.00	-
14.0	10.0	7.2 ± 0.1	0.00	0.00	-
10.0	6.30	4.9 ± 0.1	0.00	0.00	-
Total			24008.38	7420.48	30.91

Location: 402+600

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	4250.56	874.76	3.41
37.50	28.00	19.7 ± 0.3	11674.08	2453.54	9.53
28.00	20.00	14.4 ± 0.15	9832.45	3002.22	11.66
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			25757.09	6330.52	24.58

Location: 415+250

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	5832.16	3417.33	14.72
37.50	28.00	19.7 ± 0.3	8372.04	2863.65	12.33
28.00	20.00	14.4 ± 0.15	9012.46	2019.07	8.70
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			23216.66	8300.05	35.75

Location: 430+450

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	9821.29	4501.75	19.68
37.50	28.00	19.7 ± 0.3	8374.43	2906.16	12.71
28.00	20.00	14.4 ± 0.15	4673.84	1023.67	4.48
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			22869.56	8431.58	36.87

Location: 441+120

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	7008.43	1041.05	4.59
37.50	28.00	19.7 ± 0.3	11089.02	2361.26	10.40
28.00	20.00	14.4 ± 0.15	4608.11	849.74	3.74
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			22705.56	4252.05	18.73

Location: 460+965 (Dire Dawa)

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	6720.13	833.32	3.65
37.50	28.00	19.7 ± 0.3	8634.56	1046.42	4.59
28.00	20.00	14.4 ± 0.15	7453.03	883.74	3.87
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			22807.72	2763.48	12.12

Location: 465+300

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	8021.43	842.21	2.95
37.50	28.00	19.7 ± 0.3	10765.76	1874.33	6.56
28.00	20.00	14.4 ± 0.15	9802.27	1278.47	4.47
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			28589.46	3995.01	13.97

Location: 472+274

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	3422.36	246.73	0.97
37.50	28.00	19.7 ± 0.3	11743.06	1945.27	7.67
28.00	20.00	14.4 ± 0.15	10207.34	728.23	2.87
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			25372.76	2920.23	11.51

Location: 490+000

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	8467.60	1879.43	7.15
37.50	28.00	19.7 ± 0.3	10188.37	3175.15	12.07
28.00	20.00	14.4 ± 0.15	7645.10	924.07	3.51
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			26301.07	5978.65	22.73

Location: 663+000 (Dewele)

BS Test Sieve Size (mm)		Width of Slot in thickness gauge or special sieves (mm)	Weight retained on sieve (g)	Weight passing on flakiness gauge (g)	% passing on flakiness gauge (%)
100% passing	100% retained				
50.00	37.50	26.3 ± 0.3	4311.53	172.23	0.68
37.50	28.00	19.7 ± 0.3	10633.76	1674.05	6.63
28.00	20.00	14.4 ± 0.15	10305.01	644.79	2.55
20.00	14.00	10.2 ± 0.15	0.00	0.00	-
14.00	10.00	7.2 ± 0.1	0.00	0.00	-
10.00	6.30	4.9 ± 0.1	0.00	0.00	-
Total			25250.03	2491.07	9.87

Summary of Flakiness index test:-

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
FI (%)	31	25	36	37	19	12	14	12	23	10
									Min.	10
									Max.	37
									Standard	<50

4. **Elongation Index Test Value**

Location: 391+893 (Bike)

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	6747.40	2467.45	10.28
37.50	28.00	59±0.3	9235.43	4460.38	18.58
28.00	20.00	43.2±0.3	8025.55	2304.06	9.60
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			24008.38	9231.89	38.45

Location: 402+600

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	4250.56	1874.76	7.29
37.50	28.00	59±0.3	11674.08	4453.54	17.29
28.00	20.00	43.2±0.3	9832.45	4002.22	15.54
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			25757.09	10303.52	40.00

Location: 415+250

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	5832.16	4417.33	19.03
37.50	28.00	59±0.3	8372.04	3463.65	14.92
28.00	20.00	43.2±0.3	9012.46	2819.07	12.14
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			23216.66	10700.05	46.09

Location: 430+450

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	9821.29	4701.13	20.56
37.50	28.00	59±0.3	8374.43	3006.22	13.15
28.00	20.00	43.2±0.3	4673.84	1023.37	4.47
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			22869.56	8730.72	38.18

Location: 441+120

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	7008.43	2041.05	8.99
37.50	28.00	59±0.3	11089.02	3361.26	14.80
28.00	20.00	43.2±0.3	4608.11	1849.74	8.15
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			22705.56	7252.05	31.94

Location: 460+965 (Dire Dawa)

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	6720.13	1722.08	7.55
37.50	28.00	59±0.3	8634.56	1145.47	5.02
28.00	20.00	43.2±0.3	7453.03	1356.11	5.95
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			22807.72	4223.66	18.52

Location: 465+300

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	8021.43	1025.60	3.59
37.50	28.00	59±0.3	10765.76	2100.08	7.35
28.00	20.00	43.2±0.3	9802.27	1305.13	4.57
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			28589.46	4430.81	15.51

Location: 472+274

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	3422.36	946.34	3.73
37.50	28.00	59±0.3	11743.06	1879.53	7.41
28.00	20.00	43.2±0.3	10207.34	1002.78	3.95
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			25372.76	3828.65	15.09

Location: 490+000

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	8467.60	2647.34	10.07
37.50	28.00	59±0.3	10188.37	4509.17	17.14
28.00	20.00	43.2±0.3	7645.10	1391.05	5.29
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			26301.07	8547.56	32.51

Location: 663+000 (Dewele)

BS Test Sieve Size (mm)		The gap between pins of the length gauge (mm)	Weight retained on sieve (g)	Weight passing on Elongation gauge (g)	% passing on Elongation gauge (%)
100% passing	100% retained				
50.00	37.50	78.7±0.3	4311.53	1206.65	4.78
37.50	28.00	59±0.3	10633.76	2319.17	9.18
28.00	20.00	43.2±0.3	10305.01	1021.12	4.04
20.00	14.00	30.6±0.3	0.00	0.00	-
14.00	10.00	21.6±0.2	0.00	0.00	-
10.00	6.30	14.7±0.2	0.00	0.00	-
Total			25250.03	4546.95	18.00

Summary of Elongation index test:-

Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
EI (%)	38	40	46	38	32	19	16	15	33	18
									Min.	15
									Max.	46
									Standard	<50

5. <u>Fouling Index Test Value</u>

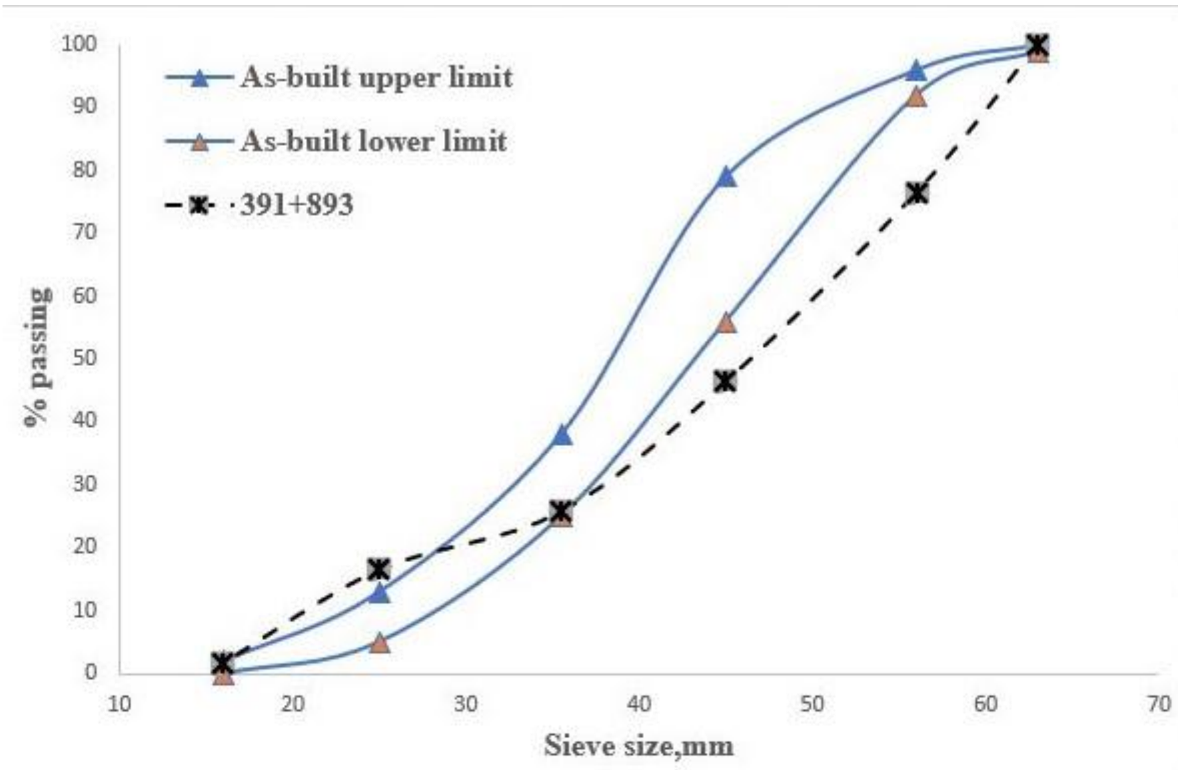
Location	Weight of Sample (g)	Passing on sieve #4 (g)	Passing on sieve #200 (g)	% Passing on sieve #4	% Passing on sieve #200	Fouling index (%)
391+893	35000	367.03	124.12	1.05	0.36	1.41
402+600	35000	134.45	96.72	0.38	0.28	0.66
415+250	35000	206.33	57.00	0.59	0.16	0.75
430+450	35000	403.26	132.45	1.15	0.38	1.53
441+120	35000	89.67	49.06	0.26	0.14	0.40
460+965	35000	176.37	84.03	0.50	0.24	0.74
465+300	35000	315.33	107.82	0.90	0.31	1.21
472+274	35000	97.03	73.00	0.28	0.21	0.49
490+000	35000	243.67	113.08	0.69	0.32	1.01
663+000	35000	153.46	83.27	0.44	0.24	0.68

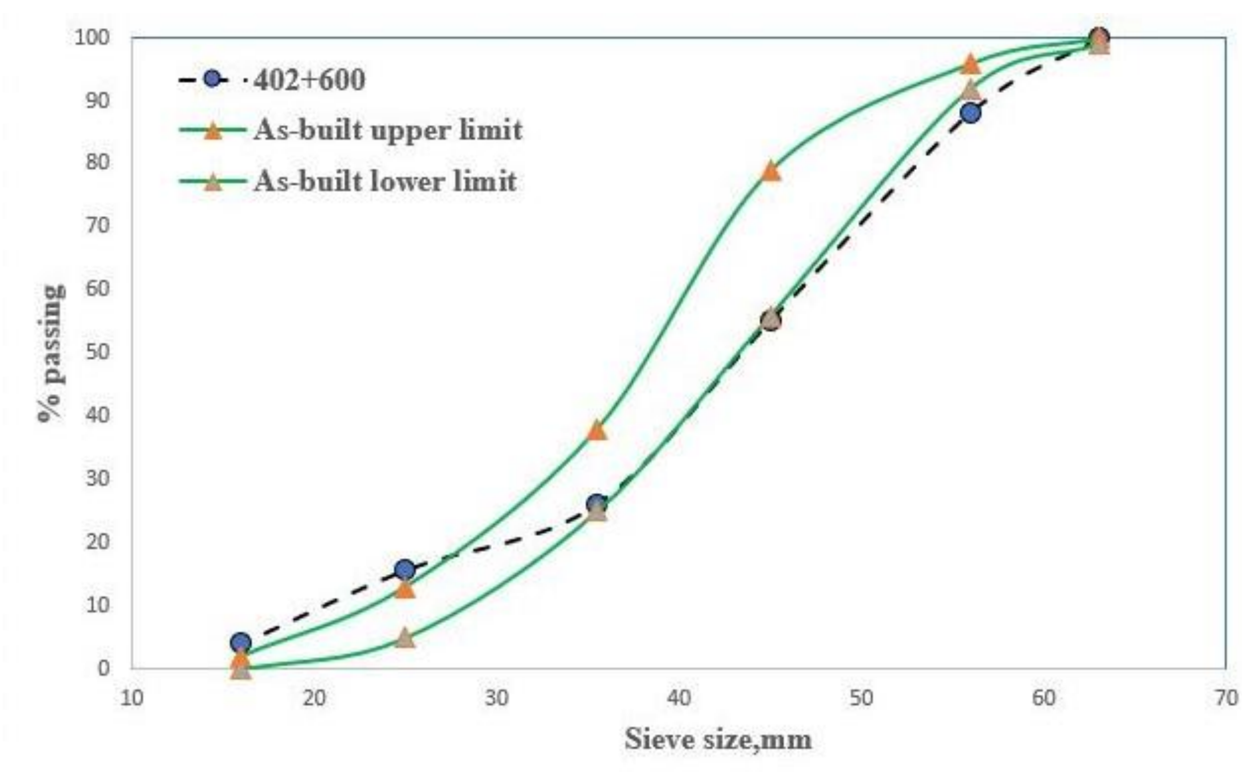
Summary of Fouling index test:-

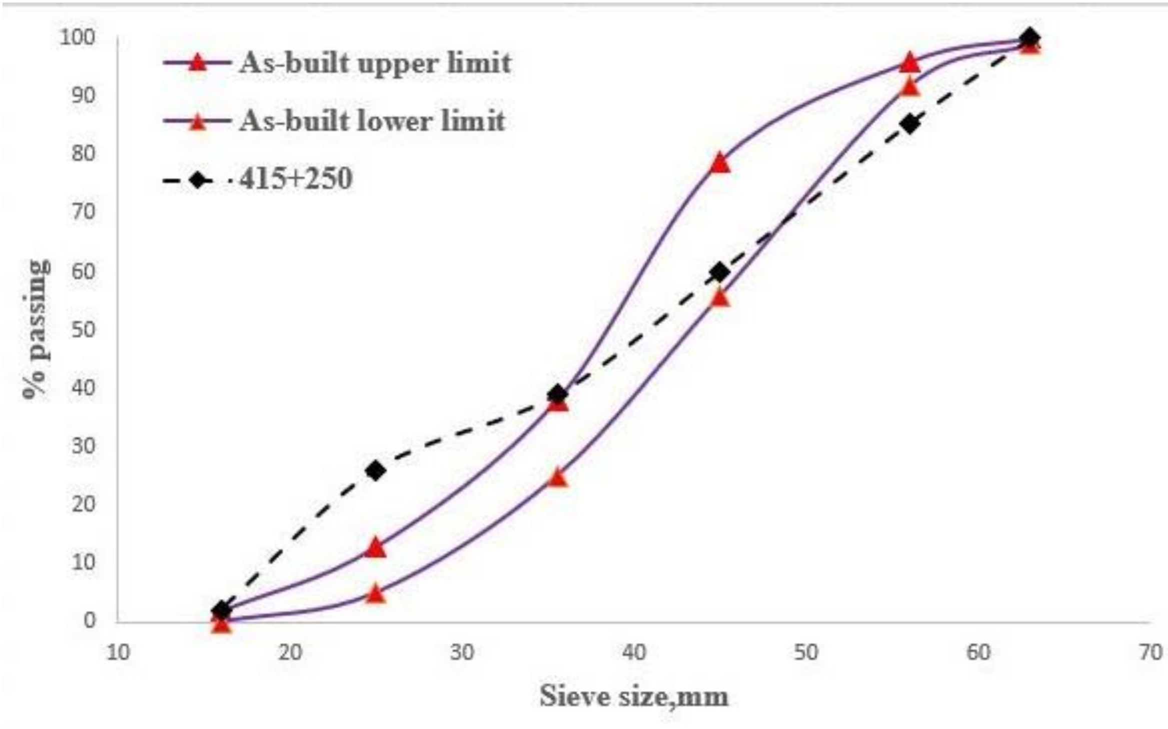
Location	391+893	402+600	415+250	430+450	441+120	460+965	465+300	472+274	490+000	663+000
FI (%)	1.14	0.66	0.75	1.53	0.40	0.74	1.21	0.49	1.01	0.68
Category	Reasonably clean	Clean	Clean	Reasonably clean	Clean	Clean	Reasonably clean	Clean	Reasonably clean	Clean

APPENDIX II

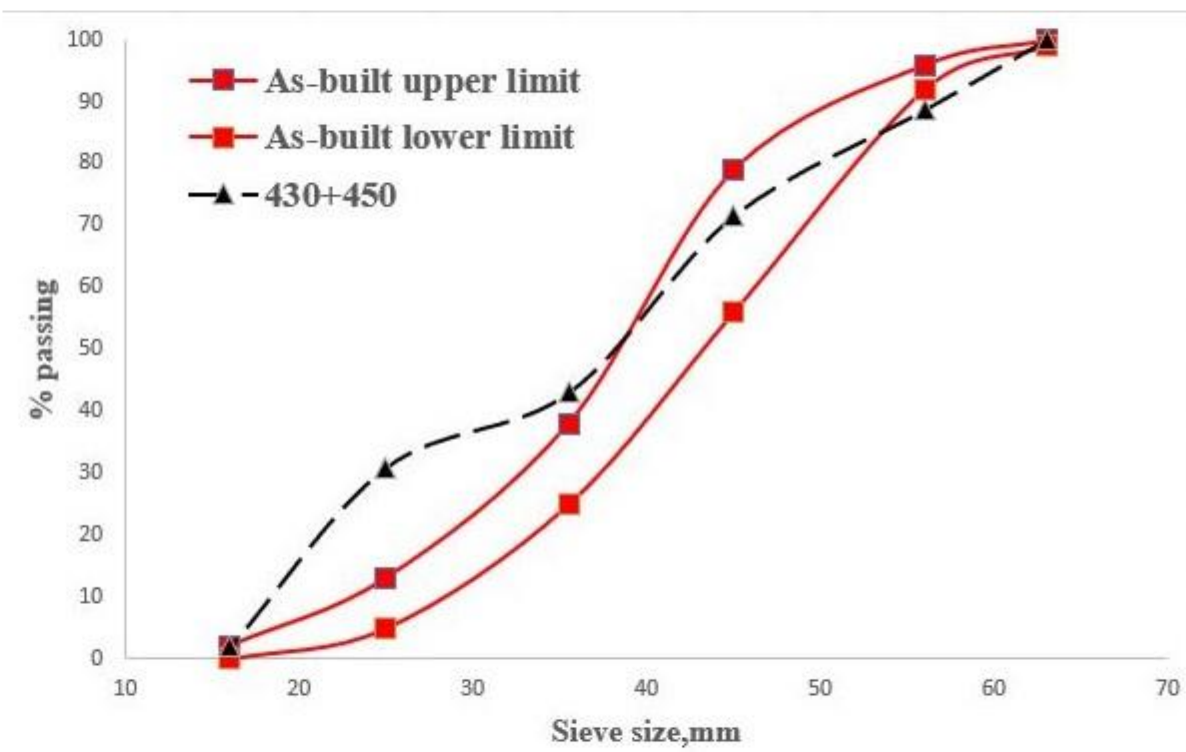
<u>Particle size distribution curve of each location:</u>



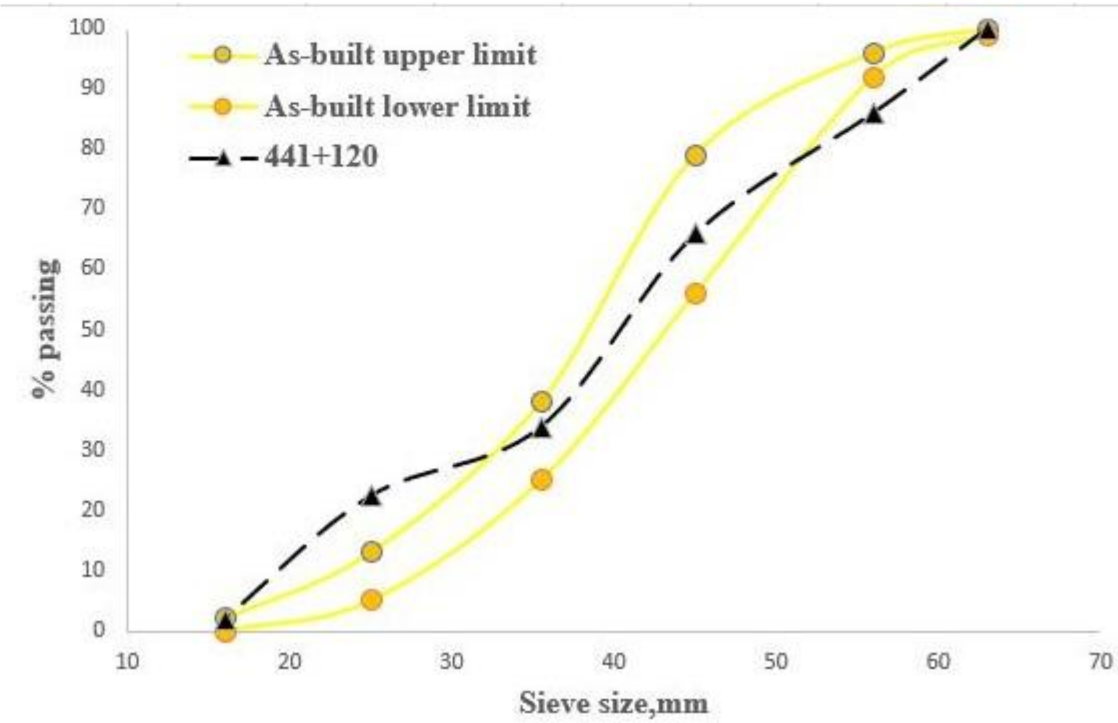


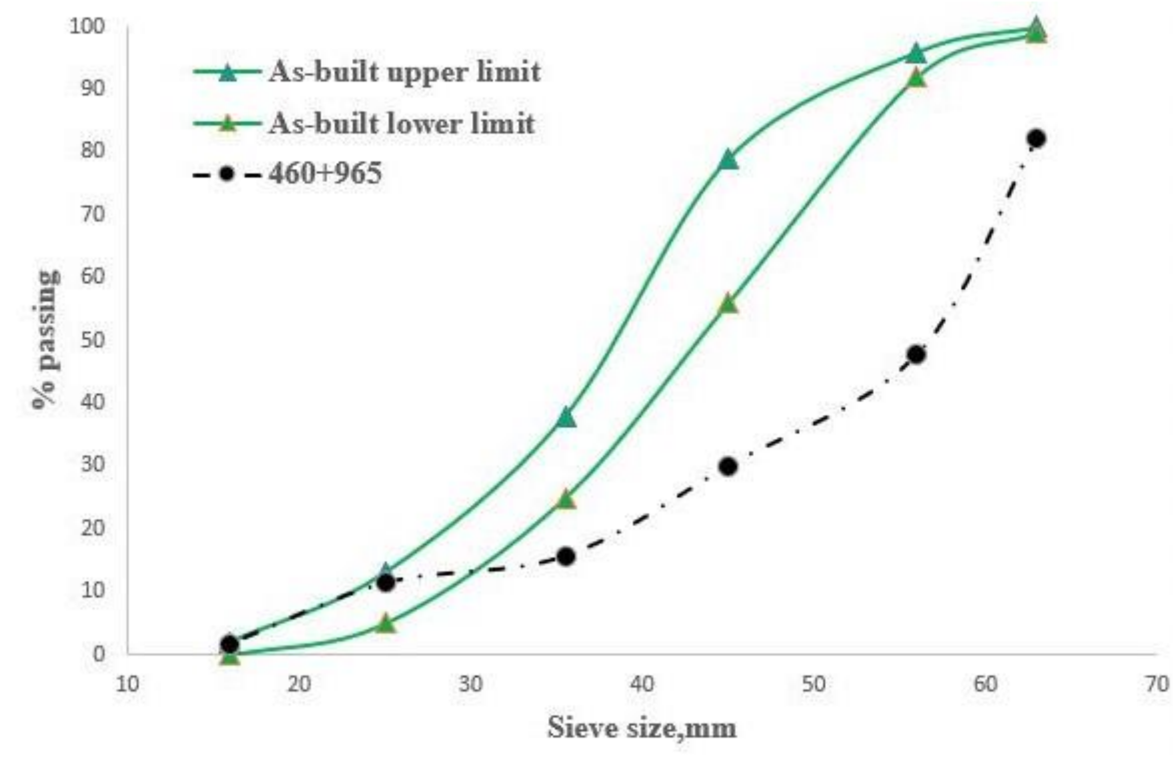


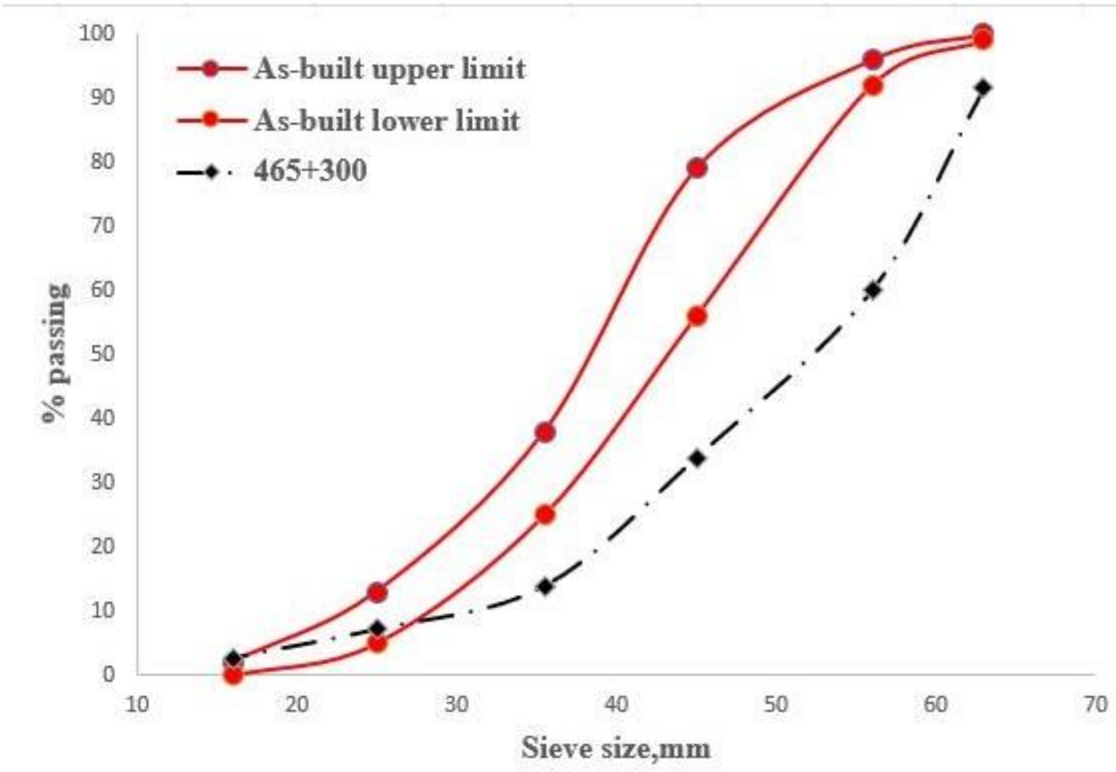
As-built upper limit
As-built lower limit
415+250
% passing
Sieve size,mm



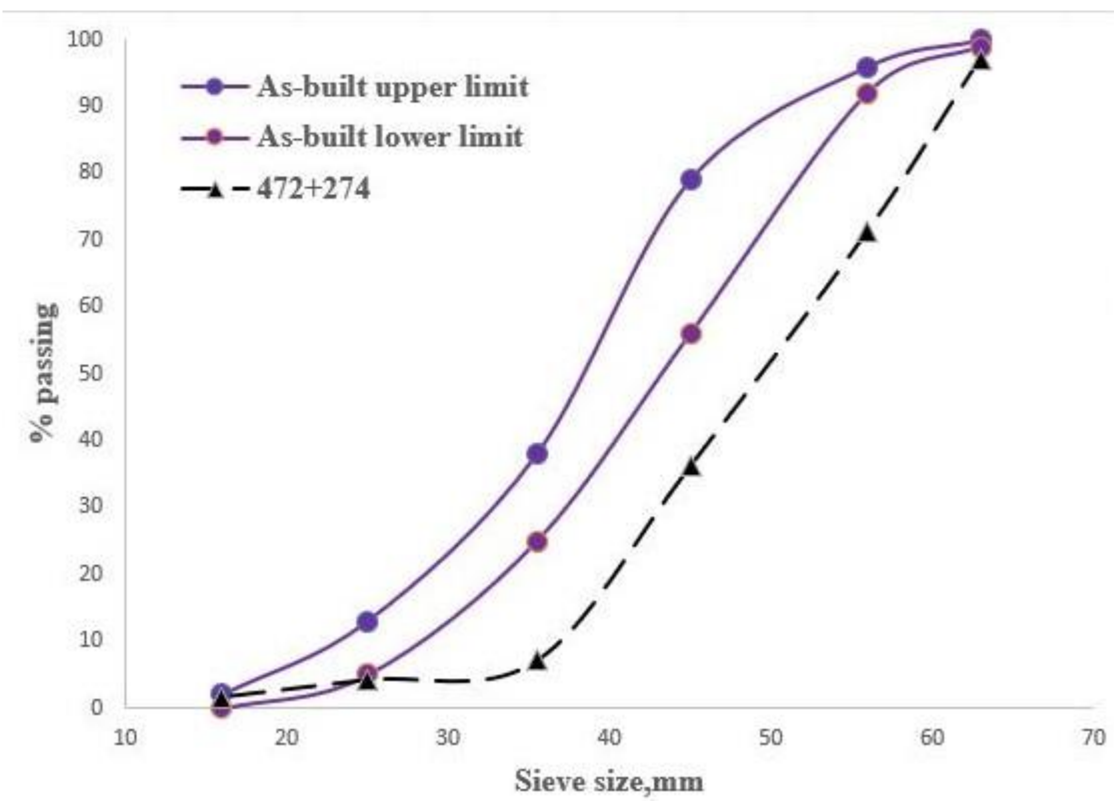
As-built upper limit
As-built lower limit
430+450
% passing
Sieve size,mm


As-built upper limit
As-built lower limit
441+120
% passing
Sieve size,mm

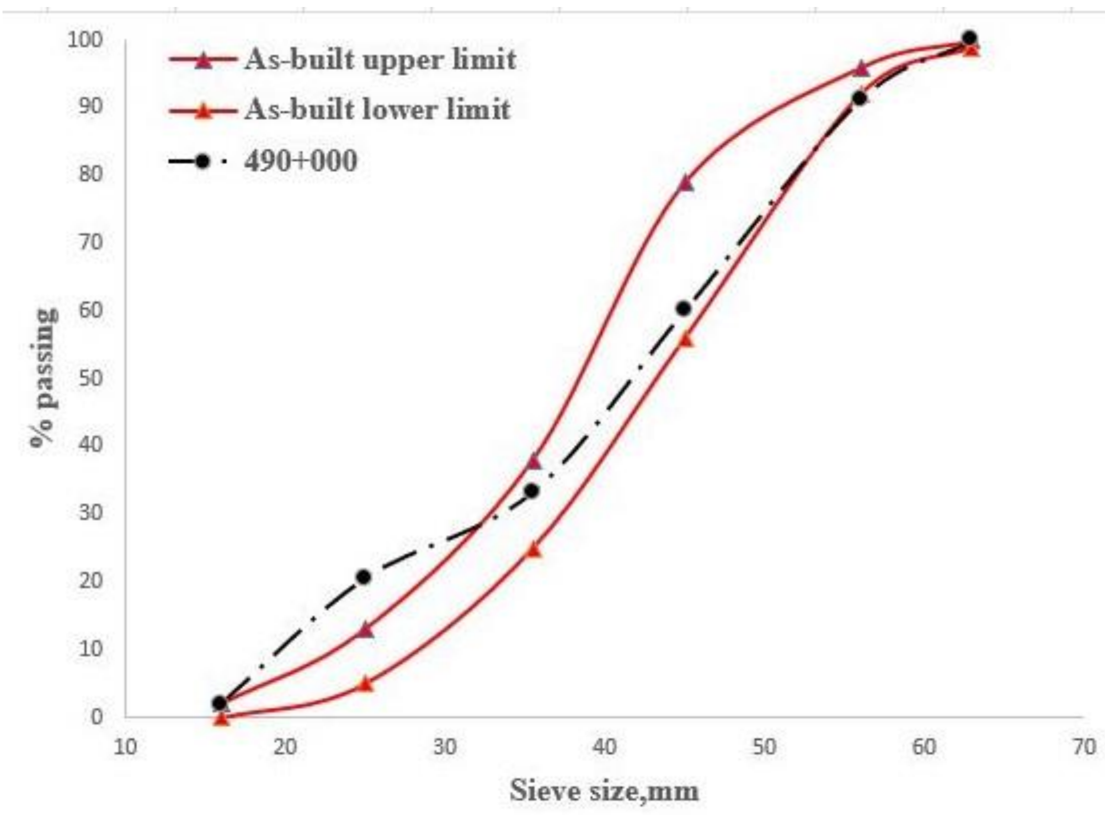

As-built upper limit
As-built lower limit
460+965
% passing
Sieve size,mm



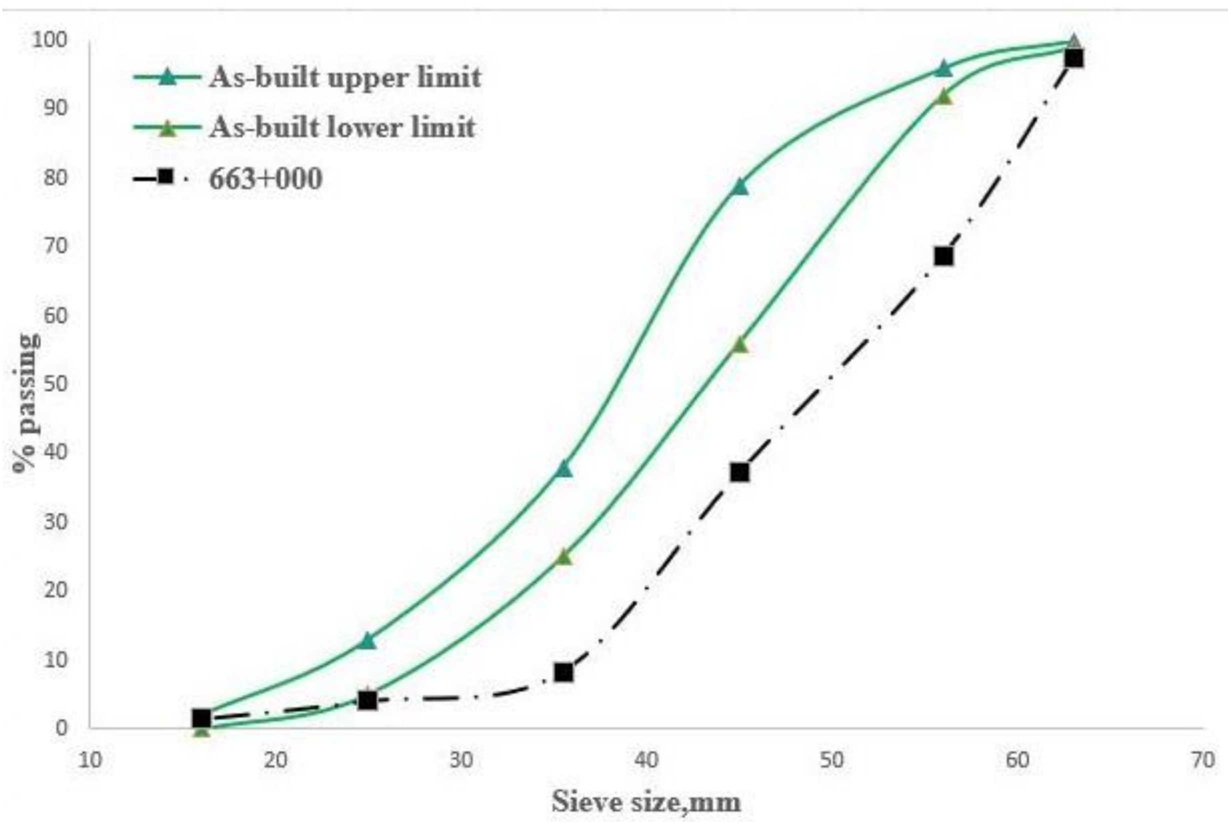
As-built upper limit
As-built lower limit
465+300
% passing
Sieve size,mm



As-built upper limit
As-built lower limit
472+274
% passing
Sieve size,mm



As-built upper limit
As-built lower limit
490+000
% passing
Sieve size,mm



As-built upper limit
As-built lower limit
663+000
% passing
Sieve size,mm

APPENDIX III

Test Procedures:

1. **Gradation (Sieve Analysis) test:**

The gradation test, also known as sieve analysis, is a common method used to determine the particle size distribution of ballast materials. This test helps in evaluating the quality and suitability of the ballast for railway track construction.

i. Prepared ballast samples
ii. Washed and dried the ballast
iii. Take note of each sieve and the pan weight at the bottom that will be used in the analysis.
iv. Keep a record of the dry ballast sample's weight.
v. Assemble the sieves in increasing order of sieve numbers, making sure they're all clean. Fill the ballast sample at the top sieve and cover it with the cap.
vi. Shake the sieve stack for 10 minutes in the mechanical shaker.
vii. 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.
viii. The percentage of material passing through each sieve is calculated and
ix. Used data to create a gradation curve, which shows the distribution of particle sizes within the ballast sample.

2. **Los Angeles Abrasion test:**

The Los Angeles Abrasion Test is a widely used method to determine the durability and resistance of aggregates, including ballast, to abrasion and wear. It measures the degradation of the material caused by the action of steel balls within a rotating drum.

i. Prepared ballast samples
ii. Check the Los Angeles Abrasion Testing Machine is functional
iii. Insert 12 steel balls of 5000g placed in an abrasion machine drum rotating
iv. The drum is mounted horizontally and rotated at a speed of 30-33 revolutions per minute
v. The ballast sample is removed from the drum and sieved through a set of standard sieves
vi. The sieves are arranged in decreasing order of mesh size, with the finest sieve at the bottom
vii. The amount of material retained on each sieve is weighed and
viii. The Los Angeles Abrasion Value is calculated.

3. **Flakiness index test:**

The flakiness index test is commonly used method to assess the shape of ballast materials. It measures the percentage by weight of particles in the ballast sample that have a thickness less than 0.6 times their average particle size.

i. Prepared ballast samples
ii. Requires a set of sieves with different slot widths
iii. The set of sieves and gently shaken for a specified period of time (usually 10 minutes)
iv. The material that passes through each sieve is collected and weighed and
v. The flakiness index is calculated as the percentage by weight of particles that pass through the flakiness gauge compared to the total weight of the sample.

4. **Elongation index test:**

The elongation index test is another method used to assess the shape of ballast materials. It measures the percentage by weight of particles in the ballast sample that have a length greater than 1.8 times their average particle size.

i. Prepared ballast samples
ii. Requires a set of sieves with different slot widths
iii. The set of sieves and gently shaken for a specified period of time (usually 10 minutes)
iv. The material that passes through each sieve is collected and weighed and
v. The elongation index is calculated as the percentage by weight of particles that pass through the elongation gauge compared to the total weight of the sample.

5. **Fouling index test:**

The fouling index test is another method used to assess the quality of ballast materials. It measures the percentage by weight of ballast material passing the 4.75mm (#4) sieve and the percentage passing the 0.075mm (#200) sieve through the voids between larger particles.

i. Prepared ballast samples
ii. Requires a set of sieves with different slot widths
iii. The material that passes through each sieve is collected and weighed and
iv. The fouling index is calculated as the percentage by weight of particles that pass through the specified size sieve compared to the total weight of the sample.

APPENDIX IV

Pictures during laboratory test:

(a): Ballast sample

(b): Ballast weighting

(c): Sieve and sieve shaker


(d): Los Angeles Abrasion test

(e): Shape property test

Figure 21(a-e): Laboratory tests