



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
AFRICAN RAILWAY CENTER OF EXCELLENCY

**IMPROVEMENT OF BALLAST MATERIAL WITH ADDITION OF WASTE
TIRE RUBBER**

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Improvement of ballast material with addition of waste tire rubber

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Chair Person	Signature	Date

UNDERTAKING

I certify that research work titled “**Improvement of ballast material with addition of waste tire rubber**” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Aregawi Gebru

Abstract

Railway ballasted track is the most common form of construction used in railway transportation due to a number of reasons. But a lot of problems are associated with a ballasted track. The excessive deformations and degradations of the ballast, unacceptable differential settlement of track, liquefaction of underlying soft subgrade soils etc. are some of them. The traffic flow of rail is increasing every year, due to increased goods and passenger traffic. This in turn, has led to a more rapid degradation of the railway track and high maintenance cost. Degradation will affect the comfort and safety of the traffic also. Under good track conditions, where there is supportive sub ballast and a stable subgrade, ballast is the main source of induced track settlement. To improve ballast material with addition of waste tire rubber physical strength and shear strength tests were performed. The effect of ballast flying was also studied and it safe velocities have been found within the limits of the considered ranges of rubber percentages used in the research. Researches have been carried out to develop new materials with the aim of increasing the service life of the track. This thesis identifies the use of waste tire rubber as an elastic aggregate, and analyses its effect on strength, degradation and settlement characteristics of ballast.

Keywords: Physical test, ballast material, waste tire rubber, ballast flying, PFC^{3D} 5.0

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LIST OF SYMBOLS

- A: Retained ballast weight
- A.s.g: Apparent specific gravity
- A.C.V: Aggregate Crushing Value
- B:Weight of ballast flakiness
- B.s.g: Bulk specific gravity
- B.s.g.ssd: Bulk specific gravity of saturated surface dry basis
- B.M: Ballast material
- C: Cohesion
- D: Weight of ballast elongated
- g: The unit of gram.
- K.g: The unit of Kilo gram
- K.H.E.S: Koysha hydroelectric site.
- kN: Kilo newton.
- kPa: Kilo Pascal.
- L: Length of the shear box.
- L.A.A: Los Angeles Abrasion value
- m: Unit of meter.
- mm: Unit of millimeter.
- S.g: Specific gravity.
- T.S: Test standard
- W.A: Water absorption
- W.T: Waste tire rubber.
- W: Width of the shear box.
- ϕ : Friction angle
- %:Percentage

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The railway track is composed of different layers of materials; the steel rails are laid on concrete sleepers that transmit the stress to the ballast layer which is the main bearing stratum. Below the ballast, compacted sub-ballast or capping layer placed above the formation soil. The purpose of this railway track structure is to provide a stable, safe and efficient guided platform for the train wheels to run at various speeds with different axle loads. In order to achieve these objectives, the vertical and lateral alignments of track must be maintained and each component of the structure must perform its desired functions satisfactorily under various axle loads, speeds, environmental and operational conditions. Track structures are exposed to cyclic loads so that the components of the rail track performance should be determined based on their fatigue life and better inspection and maintenance procedure could be set [1].

The ballast behavior is affected by different factors like particle characteristics, aggregate characteristics, loading characteristics and particle degradation property. To study these behaviors, different kinds of tests are usually performed, like the Los Angeles tests, shape tests, gradation and unit weight tests. There are also other shear strength tests like direct shear and triaxial shear tests [1].

Ballast is a uniformly graded aggregate that provides support to track superstructure. It is the uppermost support system for the static and dynamic loads applied by passing trains. Understanding the compressibility, shear strength, and stiffness of ballast is important for assessing the support and distribution of the train loads. If the ballast particles degrade due to the applied static and dynamic loads, ballast fouling can occur causing a decrease in shear strength and stiffness and an increase in compressibility. The particle degradation is usually caused by fouling, particle breakage, and/or abrasion. The primary function of the ballast layer is to provide a stable and uniform foundation and to reduce the loading effect to a level that can be accepted by the subgrade. Traditional railway foundations are now overloaded to an increasing demand for heavier and faster trains that have accelerated the deterioration of track substructure and increased maintenance costs [2]. The cost of a single, uneventful derailment is in the order of several millions dollars, but when the derailment is a major one involving hazardous goods in an urban area, the consequences can cost several hundreds of millions of dollars and at times, involve human

loss. These dramatic events are often associated with the loss of cross level, track profile and track alignment due to the effect of vibrations imposed on the track elements by complex dynamic loads. Field experience shows that the in-situ conditions and the engineering behavior of ballast are also important aspects governing the stability and performance of a given railway track structure [2].

Worldwide, the level of funding invested in railway maintenance is substantial, and a considerable proportion of this is related to geotechnical problems of substructure layers, including the ballast layer. The railway authorities in U.S.A. spent tens of millions of dollars annually for ballast and related maintenance costs. Another large railway system of the world, the Canadian railroads, has reported expenditure of about 1 billion dollars per year on the procurement, distribution, and rehabilitation of ballast representing up to approximately 40 percent of their track replacement and upkeep cost. The fast train lines are facing even higher maintenance costs [2].

Rubber is one of the essential materials in human life which can be seen from the use of goods by the community to carry out their activities such as sandals, rubber bands, and vehicle tires which are all made of rubber. However, the problem that cannot be avoided is waste material from un-used rubber which is difficult to recycle and the increasing number of scrap rubber which can have a negative impact on the environment. The increase of rubber wastes has become a thoughtful environmental problem particularly in the form of used tires due to the industrial life and population growth. Recycling process of the used tires and rubber made materials is the main problem which is associated with the complex structure and composition of rubber materials [15].

Therefore, the use of scrap rubber from motorized vehicle tires as added material in the ballast layer is also a solution to reduce the use of ballast material which is expected to be scarce in the future, the use of scrap rubber also serves to increase the durability of railroad structures because it can reduce material degradation in the long term. In addition, in previous studies, the optimal rubber content used as elastic material in the ballast layer was 10% [14, 15].

1.2 STATEMENT OF THE PROBLEM

In railway engineering, ballast plays a crucial part in transmitting and distributing the wheel load to the rail track foundation as well as supporting the rails and sleepers. Railway ballast is highly susceptible to vibration transmitted by passing trains as well as the breakage of the ballast materials by the load coming from train. There were observed problem concerning breakage of ballast material in Addis Ababa Light rail

transit line and environmental impact due to burning of waste tire from different research studies. To avoid the problems waste tire rubber was proposed as possible solution in replacement of the ballast material in railway truck line. There was toxic substance removed from the waste tire rubber and it pollutes both water and soil. To solve the mentioned problem the study improves ballast material with addition of waste tire rubber to avoid the breakage of the ballasts, the social, environmental problem and to recycle the waste tire as railway ballast material.

1.3 RESEARCH OBJECTIVES

The general objective of the research work concerns the improvement of ballast material with addition of waste tire rubber.

The specific objectives of this research work are:

- To determine properties of ballast material.
- To check up the waste tire rubber is suitable to use as partial replacement of natural ballast material.
- To improve degradation of ballast material with addition of waste tire rubber.
- To improve breakage of ballast material with addition of waste tire rubber.
- To check the possibility of ballast flying with and without waste tire rubber.

1.4 SCOPE OF THE RESEARCH

The study mainly focused on the improvement of ballast material with addition of waste tire rubber. The material sample for test was taken from the Koysha Project quarry site and the material sample is composed of two mineral components namely; abrashiya and basalt. The amount of ballast material used for one sample has a total weight of 88.89kg including 3% and 5% weight of waste tire rubber. The total samples used for the shear tests were nine samples (3 samples for 100% ballast, 3 samples for 97% ballast and 3% waste tire rubber and 3 samples for 95% ballast and 5% waste tire rubber). The challenges in this study involved no shear strength test machine around Addis Ababa University as well as in the railway line sites of Ethiopia, shear strength test machine only found in the Koysha hydroelectric Power site which is very far from Addis Ababa city and in the site it difficult to get accommodation and the geotechnical laboratory in site have many day to day activities. So due to the above mentioned challenges the study restricted only to nine samples of shear strength tests.

1.5 RESEARCH QUESTION

This research proposes more specifically to address the following research problems;

- What is the suitable laboratory methods used to improve long term degradation of ballast with addition of waste tire rubber?
- Why is necessary to replace partially natural ballast material with waste tire rubber?

1.6 SIGNIFICANCE OF STUDY

The significance of this study is to improve long term degradation of ballast with addition of waste tire rubber in reducing the breakage of ballast as well as reducing the environmental problems raised due to burning of waste tire in the environment by replacing some percentage of ballast material with waste tire rubber. Hence the application of the study is best in reducing the scarcity of ballast material and also helps in recycle the waste material to avoid contamination of water and soil which are very dangerous for health of the society. To overcome the mentioned problems it is mandatory to improve long term degradation of ballast with addition of waste tire rubber.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Railway transportation plays a great role in the growing economy of the world. Its huge carrying capacity with very low cost makes it preferable transportation mode. The speed of the rail is also getting very high which is becoming comparable with the airway speed. Railway is known by its limited use of space, reliability and safety, high degree of automation and management and its low environmental impact. Rail track network forms an essential part of the transportation system of a country and plays a vital role in its economy. It is responsible for transporting freight and bulk commodities between major cities, ports and numerous mineral and agricultural industries, apart from carrying passengers in busy urban networks. In recent years, the continual competition with road, air and water transport in terms of speed, carrying capacity and cost have substantially increased the frequency and axle load of the trains with faster operational speeds [1, 2].

The railway track is composed of different layers of materials; the steel rails are laid on concrete sleepers that transmit the stress to the ballast layer which is the main load bearing stratum. Below the ballast compacted sub- ballast or capping layer placed above the formation soil. The purpose of this railway track structure is to provide a stable, safe and efficient guided platform for the train wheels to run at various speeds with different axle loads. In order to achieve these objectives, the vertical and lateral alignments of track must be maintained and each component of the structure must perform its desired functions satisfactorily under various axle loads, speeds, environmental and operational conditions [3].

2.2. Ballast

Ballast has many functions. The most important functions are to retain track position, reduce the sleeper bearing pressure for the underlying materials, store fouling materials, provide drainage for water falling on to the track, and rearrange during maintenance to restore track geometry. Thus, ballast materials are required to be hard, durable, and angular, free from dust and dirt, and have relatively large voids. Past experience of ballast field performance has shown that the progressive breakdown of ballast materials, such as that caused by traffic load and maintenance tamping, and the intrusion of external materials such as wagon spillage and infiltration of underlying materials into the ballast results in major track deterioration.

The response of fouled ballast is highly dependent on the types of fouling materials, the quantity of fouling materials and water content [9, 10].

2.2.1 Ballast Properties

i. Effect of Particle Shape on Ballast Functions

Particle shape influences not only the physical state of the assembly (grain structure and porosity) but also the particle interactions (inter particle friction and contact force). In the past, various attempts have been made to characterize the particle shape of railway ballast. However, due to the complexity and irregularity of the shape of particle, universally accepted effective parameters on shape characteristic have not been established so far. In the railway industry, different shape characteristics (i.e. flakiness, elongation, sphericity, angularity and surface texture) are used [9, 10].

A. Flakiness or Flatness

A flat particle is defined as one in which the ratio of thickness to width of its circumscribing rectangular prism is less than a specified value. This ratio is called the flakiness ratio of a particle P and can be expressed as:

$$P = \frac{a}{b} * (0 < p < 1.0) \dots\dots\dots$$

Where a = thickness of the particle, b = width of the particle.

From the ballast maintenance point of view, increasing the percentage of the flaky particles could increase the ballast degradation rate and the degree of fouling and thus will increase the ballast maintenance work. Furthermore, better particle interlocking due to the existence of a substantial portion of flaky particles in a ballast sample will make the ballast maintenance work more difficult. So, it is reasonable to assume that the ballast maintenance work increases with the percentage of the flaky particles in a ballast.

B. Surface texture

Surface texture is believed to have an important effect on ballast performance. A rough particle surface is critical to form a high inter-particle friction force, which will increase the shear strength of the ballast and the track stability. On the contrary, a smooth surface will create a low inter-particle friction force which will result in an easy rearrangement of particles and cause more ballast-related track deformation. To quantify the ballast particle Surface texture, a visual estimate of particle surface roughness is recommended. Particle surface roughness is divided into four group categories in the visual method. They are rough, medium rough, medium smooth and smooth.

C. Angularity or roundness

Angularity is a measure of the sharpness of the edges and corners of an individual particle. Roundness defined as the ratio of the average radius of curvature of the corners and edges of a particle to the radius of the maximum inscribed circle. Ballast fouling capacity and drainage ability mainly depend on the ballast voids ratio. Because angular ballast can produce better particle interlocking, it generally has looser initial and final particle skeletons than rounded ballast. Therefore, angular ballast usually has a relatively larger voids ratio than does rounded ballast, which means that an angular ballast has a better ballast fouling resistance capacity and drainage ability. However, from the ballast maintenance point of view, angular ballast may need more ballast maintenance work because it is easily degraded and deformed under the repeated loading of trains. Moreover, better particle interlocking could make the ballast maintenance more difficult.

2.2.2 Function of Ballast

Some of the functions of ballast are the following [9]:

- Providing a stable load-bearing platform and support the sleepers uniformly.
- Transmitting high imposed stress at the sleeper/ballast interface to the subgrade layer at a reduced and acceptable stress level.
- Providing sufficient permeability for drainage.
- Providing minimal plastic deformation to the track structure during typical maintenance cycles.
- Facilitating maintenance operations.
- Providing required degree of elasticity and dynamic resiliency for the entire track.
- Providing acceptable stability to the sleepers against vertical, longitudinal and lateral forces generated by typical train speeds.
- Providing adequate resistance against crushing, attrition, bio-chemical and mechanical degradation and weathering.
- Inhibiting weed growth by reducing fouling.
- Providing adequate electrical resistance.

2.2.3 Ballast size

Provided that ballast is good quality durable angular stone, its most important parameter is its size and gradation. Ballast size should be chosen such that it supports the track superstructure, allows for drainage of water, and also lends itself to maintenance for correcting track geometry faults [6, 11].

The choice for ballast gradation is generally similar in all countries with some local variations. But it is interesting to note the difference in the French and the British ballast specifications. Current practice on British rail is to use single size stone with majority of ballast of size 30mm to 50mm. Ballast on French rail is a well graded ballast with stone sizes ranging from 63mm maximum to 15mm minimum with the majority of particles in the size range from 20mm to 40mm. French ballast is of a broader gradation with major proportion of particles being smaller than 40mm. This is significantly different from what is used on British rail.

Selig concludes that effects of particle size on strength of ballast is unclear [7] but tests seems to suggest that strength of ballast is more for a broader gradation than a uniform gradation and some research suggests that broadly graded ballast of smaller size is stronger than uniformly graded ballast of larger size, although results are inconclusive. It was observed that ballast compression (cumulative plastic strain) was higher for a uniformly graded.

2.2.4 Track components and functions

Track components are grouped into two main components: The superstructure and substructure. The superstructure refers to the top part of the track that is the rails, the fastening system and the sleepers, while the substructure refers to the lower part of the track: that is the ballast, the sub-ballast and the subgrade [25].

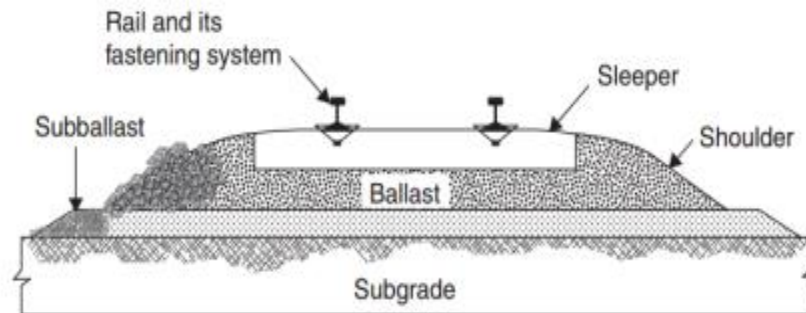


Figure 2.1: Track components [3, 25]

- I. **Rails:** A longitudinal steel members which are in contact with the train wheels. Placed on equally spaced sleepers, and are the critical components in guiding the rolling stocks. The function of the rails is to guide the train and transfer concentrated wheel loads to the sleepers. Thus, rails must have sufficient stiffness to distribute wheel loads over sleepers and limit deflection between the supports. Rail defects and discontinuities, such as joints, can cause large

impact loads, which have detrimental effects on the track components. This is the most expensive material in the track.

- II. **Sleepers:** are the transverse members of the track that are laid to support the rails. The main functions of sleepers are to distribute the wheels transferred by the rail and fastening system to the supporting ballast and restrain rail movement by anchorage of the superstructure in the ballast.
- III. **Fastenings system:** are the set of parts and materials used for joining rails together as well as ensuring the rail-sleeper connections. The purpose of providing fittings and fastenings in railway tracks is to hold the rails in their proper position in order to ensure the smooth running of trains.
- IV. **Ballast:** is the crushed granular material placed as the top layer of the substructure, in the cribs between the sleepers, and in the shoulders beyond the sleeper ends down to the bottom of the ballast layer. Traditionally, good ballast materials are granular, crushed, hard stones and rocks, uniformly graded, free of dust and dirt, not prone to cementing action. However, due to the lack of universal agreement on the specifications for ballast materials, availability and economic considerations have been the main factors considered in the selection of ballast materials. Thus, a wide range of ballast materials can be found, such as granite, basalt, limestone, slag and gravel. One of the main functions of ballast is to retain track position by resisting vertical, lateral and longitudinal forces applied to the sleepers. Ballast also provides resiliency and energy absorption for the track, which in turn reduces the stresses in the underlying materials to acceptable levels. Large voids are required in the ballast for storage of fouling materials and drainage of water falling onto the track. Ballast also needs to have the ability to rearrange during maintenance level correction and alignment operations.
- V. **Sub-ballast:** is composed of well-graded crushed rock or sand gravel mixtures. Sits between the ballast and the subgrade material. Transmits and distributes stress from the ballast layer to the subgrade over a larger area to reduce the magnitude of resultant stress.
- VI. **Subgrade:** is the foundation for the track structure. It can be existing natural soil or placed soil. The main function of the subgrade is to provide a stable foundation for the track structure. Thus, excessive settlement in the subgrade should be avoided.

2.2.5 Forces exerted on ballast

Different types of loads are imposed on the ballast. The main load is the vertical loads that come from the train load, which is a combination of a static load and a dynamic component superimposed on the static load. The static load is the dead weight of the train and superstructure, while the dynamic component, which is known as the dynamic increment, depends on the train speed and the track condition. During maintenance there is also tamping force which has been found to cause significant damage to ballast. There are also lateral and longitudinal forces on the ballast layer. The lateral force is the force that acts parallel to

the long axis of the sleepers. The principal sources of this type of force are lateral wheel force and buckling reaction force. The longitudinal force is the force that acts parallel to rails. The sources of this force are locomotive traction force including force required to accelerate the train, braking force from the locomotive cars and thermal expansion and contraction of rails.

2.3 Ballast Degradation

Degradation or deterioration is the reduction of the original quality due to various influences. By far the most significant factor contributing to the deterioration is the dynamic load. The dynamic load is directly related to the axle load and track geometry [27].

The main processes of track deterioration are:

- Wear
- Fatigue and
- Settlement.

2.3.1 Driving Forces of Degradation

In some cases, the track can degrade without any traffic (e.g. the soil may settle due to weight of the embankment, especially in the early years after construction). In most cases running trains is the driving force of deterioration.

A railway track is designed to distribute the load from trains down to the soil/ground. This distribution through super and substructure depends on original tracks design and current track condition. Stiffness of different components in the track structure, as well as the resulting track stiffness will partly determine how the loads are distributed.

The static, quasi static and dynamic forces are all important for track degradation. Some aspect determining forces and thereby influence degradation is listed:

Table 1: Parameters influencing track degradation [27]

Subsystem	Characteristics	Influence of the Subsystem
Vehicle	<ul style="list-style-type: none"> • Speed • Axle load • Unsprang mass • Suspension • Wheel profile • Axle spacing etc. 	<ul style="list-style-type: none"> • Static • Quasi-static and • Dynamic forces
	<ul style="list-style-type: none"> • Wheel (current condition such as wheel flat and wheel corrugation). 	<ul style="list-style-type: none"> • Dynamic force

Track	<ul style="list-style-type: none"> • Track design geometry (Curves etc.) 	<ul style="list-style-type: none"> • Static • Quasi-static forces
	<ul style="list-style-type: none"> • Track geometry quality 	<ul style="list-style-type: none"> • Dynamic forces
	<ul style="list-style-type: none"> • Corrugation 	<ul style="list-style-type: none"> • High-frequency forces
	<ul style="list-style-type: none"> • Rail imperfections such as joints or poor welds. 	<ul style="list-style-type: none"> • Impact forces

2.3.2 Ballast Settlement

The long-term behavior of the railroad track, including the ballast behavior and the damage mechanisms underlying the ballast settlement, is stated that there do not exist any generally accepted damage and settlement equations, and hardly any material equations for the ballast itself. Only different suggestions to describe the ballast settlement from a phenomenological point of view are available; the settlement then being a function of number of loading cycles and/or magnitude of the loading.

Railway track will settle as a result of permanent deformation in the ballast and underlying soil. After having been used some time, the track will not be so straight and at so good level as it was when it was new. The settlement is caused by the repeated traffic loading and the severity of the settlement depends on the quality and the behavior of the ballast, the sub-ballast and the subgrade.

Ballast settlement occurs in two major phases:

- Directly after tamping, when the track position has been adjusted to a straight level, the settlement is relatively fast until the gaps between the ballast particles have been reduced and the ballast is consolidated.
- The second phase of settlement is slower and there is a more or less linear relationship between settlement and time (or load).

The second phase of settlement is caused by several basic mechanisms of ballast and subgrade behavior:

- Movement of ballast and subgrade particles away from under the sleepers. This causes the sleepers to sink into the ballast and subgrade.
- Volume reduction caused by abrasive wear. A particle may diminish in volume due to a abrasive wear at points in contact with other particles, i.e. originally cornered stones become rounded, thus occupying less space.
- Sub-ballast and/or subgrade penetration into ballast voids. This causes the ballast to sink into the sub-ballast and subgrade and the track level will change accordingly.
- Volume reduction caused by particle breakdown from train loading or environmental factors; i.e. ballast particles may fracture (divide into two or more pieces) due to the loading.

- Inelastic recovery on unloading. Due to micro-slip between ballast particles at loading, all deformations will not be fully recovered upon unloading the track. In this case the permanent deformation is a function of both stress history and stress state.

2.4 Ballast Flying

Ballast flying is defined as the projection of ballast particles from its resting position as the train pass over the track structure. Ballast particles become airborne by overcoming gravity and friction (interlocking) forces from neighboring particles. This phenomenon occurs when a combination of mechanical and aerodynamic forces, generated by passage of the train, cause ballast particles to overcome gravity. It is a complex interaction of different forces that cause the ballast flying to happen. This complexity arises from train aerodynamics, train dynamic load, track structure and the physical property of ballast. Since 1980's, ballast flying become a known problem for high speed train due to aerodynamic force of the train. Different researchers tried to explain the concept of ballast flying and its causes that lead to the initiation and final projection of the ballast. Full scale experiment on the actual filled; wind tunnel test simulation and numerical test have revealed the major causes of ballast flying [12].

2.4.1 Mechanism of Ballast Flying

Based on an extensive literature review and observations, found that ballast fouling was caused through five primary modes. These sources of ballast fouling are as follows [27, 28].

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

Table 2: Source of ballast fouling [28]

Category	Source of ballast fouling	Amount (% by weight)
Ballast breakdown	<ul style="list-style-type: none"> • From handling (at quarry, from dumping, transportation), Tamping traffic damage (repeated loading, vibration). • Chemical weathering, thermal stress (desert) freezing of water in particles. 	76
Ballast surface infiltration	<ul style="list-style-type: none"> • Delivered with ballast • Dropped from trains 	

Improvement of ballast material with addition of waste tire rubber

	<ul style="list-style-type: none"> • Wind blown • Water borne • Splashing from adjacent wet spots 	7
Sleeper wear	<ul style="list-style-type: none"> • Sleeper-ballast interaction 	1
Underlying granular layer infiltration	<ul style="list-style-type: none"> • Old track bed breakdown • Sub –ballast particle migration from inadequate gradation. 	13
Subgrade infiltration	<ul style="list-style-type: none"> • Infiltration from subgrade into ballast 	3

Analysis of the data and modeling suggest that neither mechanical forces nor aerodynamic forces in isolation are likely to be sufficient to initiate ballast flight under that the conditions investigated, but that the phenomenon could arise from a combination of the two effects. The probabilistic occurrence of a ballast flight event is modeled as a combination of two sub events the displacement of ballast particles and the ballast flight given the displacement. The likelihood of ballast displacement is affected by the atmospheric conditions and ground conditions, while atmospheric, track, ground and aerodynamics forces contribute to the likelihood of ballast flight given a ballast displacement [5, 6].

The risk of ballast flying can be expressed by the following expression:

$$R_{fb} = P_d * P_{fb/d} * C \dots\dots\dots [2.1]$$

Where:

R_{fb} – Ballast flying risk

P_d – The probability that a ballast particle will displace from its rest position

$P_{fb/d}$ - The conditional probability that a ballast particle will flying given the displacement

C- The consequence from the event of flying ballast

G.Q. Jing [8] gave the detailed descriptions about the ballast flying mechanism using the following simple mechanics model to explain the main parameters.

Herein, the ballast particles are analyzed and characterized by the mg , F_I , F_w , F_a & a_r .

Where:

mg - is gravity force by mass,

F_i –is ballast particle interlock force,

F_w – is wind force resulted by high speed train acted on ballast effective surface (A_e), and

a_r - is ballast acceleration due to ballast bed vibration,

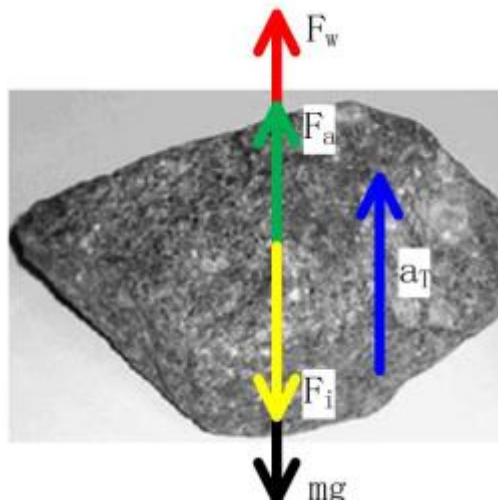


Figure 2.2: Forces acting on ballast [5, 6]

Based on d'Alembert principle, the equation for ballast particle balance is

$$F_w + F_a = mg + ma_r + F_i \dots\dots\dots[2.2]$$

Setting $F_i = 0$

$$ma_r = F_w - mg + F_a$$

$$ma_r = F_w - mg + ma = F_w - m(g-a) \dots\dots\dots[2.3]$$

Where a is ballast particle vertical acceleration caused by sleeper induced dynamic responses. Based on aerodynamics, the ballast particle force can be calculated by:

$$F_w = \int_0^A \int_{v1}^{v2} f(A) f(v) dA dv \dots\dots\dots[2.4]$$

Here:

A- Wind loads effective area of ballast particle, and

v_1, v_2 – the points where the ballast particle interaction beginning and ending wind speed.

Due to wind speed calculation complexity, we usually take the wind pressure coefficient α , and then equation [2.4] becomes:

$$F_W = \alpha \int_0^A f(A) dA \dots\dots\dots [2.5]$$

Substituting equation [2.5] into equation [2.2]

$$m a_r = \alpha \int_0^A f(A) dA - m(g - a) \dots\dots\dots [2.6]$$

$$a_r = \frac{\alpha \int_0^A f(A) dA}{m} - (g - a) \dots\dots\dots [2.7]$$

$$\frac{\alpha \int_0^A f(A) dA}{m} \dots\dots\dots [2.8]$$

a_r – indicates the particular ballast particle state of balance,

If $a_r < 0$ it indicates the ballast particles are stable and free of ballast flying,

$a_r = 0$ it indicates the ballast particles are in the critical state of stability, the train speed is a critical speed,

$a_r > 0$ it indicates the possibility of ballast flying phenomena,

$(g - a)$ – It is a constant value for ballast particles under certain train and track conditions which depends on ballast particle position, density and shape.

$\frac{\alpha \int_0^A f(A) dA}{m}$ – It is related with the wind load effective area, the ballast particle mass, ballast shape, ballast density, ballast size.

α - Wind pressure coefficient

The volume of ballast can be calculated with the integral of surface area multiplied with the thickness of the ballast.

$$M = \alpha \int_{x_1}^{x_2} A(z) dz \dots\dots\dots [2.9]$$

Where;

ρ is density of ballast particle

$$a_r = \frac{\alpha f(A)}{\rho \int_{x_1}^{x_2} A(z) dz} (g - a) \dots\dots\dots [2.10]$$

$$a_r = \frac{\alpha}{\rho \int_{x_1}^{x_2} dz} (g - a) \dots\dots\dots [2.11]$$

Equation [2.11] shows the relationship between wind effects and vibration of ballast.

2.5 Compositions of Tire

The raw materials used in tires are synthetic and natural rubber, nylon, polyester cord, carbon black, sulphur, oil resin and other chemicals. These constituents provide the tire with a good strength to ensure adequate road holding properties under all conditions [Islam, et al. 2010].

The components of tire manufactured by different manufacturers are very similar. Basically, tires are made of rubber (60-65wt. %), carbon black (25-35wt. %), fillers (3wt. %) and accelerators [Islam, et al. 2010].

Rubber is the main component in tires. Both natural and artificial rubbers are used for tire manufacturing. Fillers such as carbon black, carbon chalk are added to impart color to tires. Some reinforcing materials like steel, rayon and nylon are added to provide support and strength to the tire components [24].

Table 3: Compositions of waste tires [24]

Components	Percentage (%)
Rubber	38%
Filler (carbon black, silica, carbon chalk)	30%
Reinforcing material (steel and nylon)	16%
Plasticizers (oil and resins)	10%
Vulcanization agent (sulphur, zincoxide, various chemicals)	4%
Antioxidants to counter ozone effect and material fatigue	1%
Miscellaneous	1%

2.6 Problems of Waste Tires

Waste tires known as End-of-Life-Tires, un recycled tire waste is an enormous global problems because of their non-bio-degradability, their flammability and their chemical composition that leads to leaching of toxic substances into the ground on dumping and hazardous fumes on incineration.

Lifespan of tires depends on a combination of factors including a driver's habits, tire design, climate, road conditions, and service of the tire. These conditions can loss quality and worn out before life time.

Used tires also referred to as waste tires can be defined as tires that have expired as a result of exceeding their production life span or are no longer safe for usage due to defects, such as degradation of its physical composition/structure from use and cannot be retreaded. It is one of the most challenging hazardous solid wastes facing modern society, particularly in developing countries.

The environmental challenges come from the property of tires themselves. Tires are designed to be abrasive, load carrying and indestructible made to high quality standards. These distinctive properties that ensure safe travel and long service life make scrap tire disposal a difficult task. Rubber, the major component of tire, is non-biodegradable material. In addition to being unpleasant, tire piles are breeding grounds for mosquitoes and rats, and they are susceptible to fire hazards. Un controlled open-air burning of tires release potentially hazardous chemicals that affect the ground, surface of water and air.

Degrading of scrap tires in the nature is difficult for many years. There are studies and available literature on pyrolysis of waste vehicle tires. Scrap tire disposing methods like landfill, reusing and burning can create serious hazards, especially in terms of human and environmental health. Thus, waste tire is required to keep under control without damaging the environment [23].

2.7 Waste Tire Recycling Methods

There are different methods for treatment of waste tire. Some common waste tire treatment.

2.7.1 Common Waste Tire Recycling Methods

- I. **Reuse**, mechanical processing: Shredding (civil and co-combustion, granulation/crumbing., road building, sport surfaces, and as shoemaking: soles, heels and straps of sandals can be made from tire materials.
- II. **Retreading of used tires:** Retreading of used tires is the most preferable way of making use of old tires. But scrap tires retreated without any loss in quality and can retreated one time.
- III. **Open burning** to separate the steel from the other components and burning as fuel.

2.7.2 Thermal Valorization

Reclamation is the process of recovering useful materials from the waste. Waste tires are shredded into fines and are mixed with some reclaiming agents to yield reclaimed tires. Nonetheless, it is reported that

only 5% of the total waste tires is reclaimed. There are three main technologies in thermal valorization that are gasification, combustion and pyrolysis.

i. Gasification Process Method

Gasification is a thermal process, that it allows converting carbonaceous materials, such as organic waste or biomass into carbon monoxide and hydrogen with a controlled amount of oxygen and or steam. The resulting gas mixture, also called synthesis gas or gas, is a full able to power gas turbines or fuel cells,. In gasification, the impetus is given to convert waste tire into more gaseous products. The gasifying agent can be air, O₂, steam, CO₂ or any mixture of these. The quality and the proportion of gaseous product yield largely depend on the gasifying agent.

ii. Combustion Process Method

Combustion or burning is a high-temperature exothermic chemical reaction between a fuel and an oxidant, usually atmospheric oxygen that produces oxidized, often gaseous products, in a mixture termed as smoke. Combustion in a fire produces a flame, and the heat produced can make combustion self-sustaining. Combustion is often a complicated sequence of elementary radical reactions. Solids fuels, such as wood and coal, first undergo endothermic pyrolysis to produce gaseous fuels whose combustion then supplies the heat required to produce more of them. Combustion is often hot enough that incandescent light in the form of either glowing or a flame is produced. A simple example can be seen in the combustion of hydrogen and oxygen into water vapor, a reaction commonly used to fuel rocket engines. This reaction releases of heat and reduces the enthalpy accordingly at constant temperature and pressure.

iii. Pyrolysis Process Method

Pyrolysis is an endothermic process, an environmentally attractive method for the treatment of tire wastes. Pyrolysis of tires involves the thermal degradation of the rubber of the tire at temperature (300°C-700°C) and an oxygen-free environment to decompose solid tire wastes chemically in to char, oil, and gas, thus producing minimum emissions of nitrogen oxide and sulfur oxide compared to incineration, the most common process in the industry.

In the pyrolysis process, the organic volatile matter of tires is decomposed to low molecular weight products, liquid or gases. The inorganic components and the non-volatile carbon black remain as a solid residue which is relatively unaltered, and therefore can be recycled in worthwhile applications.

There are many classifications of pyrolysis types depending on the operating conditions, such as the heating rate, temperature, and the pyrolysis time. In general, pyrolysis is classified as either fast or slows.

- a. **Slow pyrolysis:** this type of pyrolysis, as the name suggests, considers a slow thermal decomposition at low temperatures. It is characterized by low heating rates, relatively long solid and vapor residence times, and sometimes by low temperature. Longer residence times result in leading secondary conversion of primary products, yielding more coke, tar, as well as

thermally-stable products. This fact is why slow pyrolysis is sometimes referred to as carbonization.

- b. **Fast pyrolysis:** Fast pyrolysis indicates a rapid thermal decomposition characterized by higher heating rates. This process usually requires a feedstock with small particle sizes and specially-designed devices to allow quick removal of the vapors released. Fast pyrolysis is recognized as an effective conversion route for the production of liquid fuels, chemicals and derived products with higher yield (usually around 50-60 wt. % for rubber feedstock).

2.8 Shear Strength Rockfill

The shear strength of rockfill is its resistance to deformation by continuous shear displacement of the rockfill particles upon the action of shear stress. When the maximum shear stress is reached, the rockfill is regarded to have failed. The failure conditions of a rockfill may be expressed in terms of limiting shear stress, called shear strength, or as a function of principal stresses. The shear strength of granular soil is frequently characterized by ϕ and C . Friction angle is the measure of the resistance of the particles to shear force when normal stress on the shear plane is not zero.

2.8.1 Factors Controlling the Shear Strength of Rockfill

The angle of internal friction is a function of the following parameters [2.11]:

- Particle shape and roughness of grain surface (friction angle typically increases with increasing angularity and surface roughness).
- Grain quality
- Grain size (friction angle increases or decreases with increase in grain size).
- Grain size distribution (friction angle typically increases with decreasing coefficient of uniformity, C_u).
- Specific gravity.
- State of compaction or packing (friction angle typically increases with increasing density or decreasing void ratio).
- Applied stress level (friction angle decreases with increasing confining stress, resulting in a curved strength envelope passing through the origin instead of the classical straight line).
- Degree of saturation.

A. Confining pressure /Normal stress

The effect of confining pressure in tri-axial tests or normal load in the case of direct shear tests on shear strength and behavior of materials have been studied for many years.

B. Maximum Particle Size

There is no common agreement on the effect of particle size on the shear strength after evaluating the literature on this topic. Different views are presented with some indicating that the shear strength decreases with increasing particle size [16]. While some have opposite views indicating that an increase in the particle size increases the load per particle, and hence crushing begins at a smaller confining stress, and causes a reduction in the friction angle for materials compacted to the same density with geometrically similar grading, the smaller the elements are, the higher the friction angle of the material [13, 15].

C. Density

It is generally accepted that the shear strength of ballast increases with a higher relative density. The effect of relative density on the friction angle can be explained by the phenomenon of interlocking the denser the ballast; the greater the interlocking, and so the greater the value of friction angle. The dense ballast specimens show a marked curvature on the stress-strain curve, with a distinct drop in the friction angle while the loose ballast specimens shows minimal curvature and drop in friction because the loose require less dilation as particle have more freedom to move or rotate during shearing [14,16].

D. Effect of Gradation

A number of researchers investigated the gradation effect on the shear strength by varying the coefficient of uniformity (C_u) of ballasts. A better graded ballast has a larger friction angle compared to uniform ballast due to a better interlocking and less particle breakage in the former, the less breakage arising from the fact that in a well graded ballast there are more interparticle contacts and the load per contact is thus less than in a uniform ballast. The impact of type of grading on the friction angle is about 2 to 3 degrees [17].

2.9 Shear Strength Testing

A. Direct Shear Box Test

Direct shear testing, introduced by Coulomb in 1776, has long been used to estimate the shear strength parameters. Many alternative testing machines have been developed since then.

Direct shear testing has many advantages over alternative test methods [13, 14] including:

- The sample can be made to shear in a prescribed plane or zone;
- If appropriate sample dimensions are used, the shear deformation is approximately plane strain, and deformation occurs mostly by simple shear, which is often the design assumption of earth structures;
- The test sample required can be relatively small or very large;
- The structure of the apparatus and the testing method are simple.

Disadvantages of the direct shear test include changes in the area of the shear surface during shearing, and uncertainty in interpretation of the results due to non-uniformity of the stresses and strains that occur across the shear surface, and throughout the sample thickness.

B. Triaxial Compression Test

The triaxial test offers one of the best ways to determine the shear strength of granular materials in the laboratory. The specimen is usually subjected to a constant all-around confining pressure (σ_3) simulating the lateral stress caused by the overburden pressure. In tri-axial test, the top and sides of the specimen are assumed not to be subjected shear stress. Since these planes do not have shear stresses, by definition, they are principal planes [23].

2.10 Summary of Previous Studies on Ballast and waste tire rubber materials

2.10.1 Evaluation of shear strength parameters of rail track ballast

The ballasted rail tracks are the most preferred by the railway authority due to low initial investment and it continues using crushed rock as rail track ballast. Regardless of the frequent usage of these aggregates as track ballast in Sri Lanka, their shear strength characteristics have not been scientifically measured or used in design. Selig and Waters [22] investigated shear strength properties of fresh and fouled rail track ballast in Sri Lanka using a large-scale direct shear device, which accommodates actual size ballast particles. The shear stress-strain and dilation behavior of fresh and fouled ballast were obtained and the internal friction angle was estimated. The results obtained the friction angle vary from 65° to 58° for fresh ballast and 62° to 54° for fouled ballast depending on the applied normal stress. Finally the shear strength of fresh ballast was higher than that of fouled ballast.

2.10.2 Enhanced shear resistance of rail tracks with ballast-rubber composites

Siti Farhanah [23] describes the exploratory work on ballast-rubber composites to enhance the shear resistance of rail tracks and identify the effects of ballast exposure to the weathering and oil contamination. The rubber elements were sourced from tire inner tubes commonly used for motorcycles, cut and shaped accordingly to produce strips, shreds and circular patches respectively and were arranged in various pre-determined configurations within the ballast layer. The direct shear test results indicated that rubber inclusion could effectively improve the shear resistance of ballasts to various degrees, though the

configurations clearly played an important role in the improvement observed. The shear resistance did not rise dramatically with the rubber reinforcement. This susceptible shear strain plots indicate ductile behavior on the aggregates-rubber composites. This is evident by the linear rise of shear stress with strain up to approximately 10% for the control samples (CS) until it reaches a constant value. In addition, the friction angle for all configurations (dry, acid, oil) was in the ranged 87° - 88° with the critical specific volume, V_{crit} was 2.160. The inclusion of rubber elements apparently prevented the dilation of the granular material when approaching the shear failure and the reducing the settlement [23].

2.10.3 Shredded tires as a construction material

Megan [24] investigated the application of the shreds as a horizontal drain, a ravine crossing, lightweight backfill, and in a road embankment requires the engineering properties of the shredded tire material. The engineering properties of the shredded tires associated with these applications have been investigated by a number of researchers. This research conducted in dependent direct shear tests on tire shreds in large-size shear machines. The sizes of the materials they tested varied from 38mm to 1400mm. Using peak shear stress or, stress at a horizontal displacement equal to 10% or 9% of the length of the shear box if no peak stress is observed, as a failure criterion, the shear strength parameters were obtained. The friction angles obtained from these studies ranged from 19° to 38° with zero or a small cohesion intercept up to 11.5kPa.



Figure 2.3: sample use of waste tire for road construction and building [24]

2.11 PFC3D for simulation of ballast flying

PFC3D is chosen to explain the major model parameters used in DEM which are [21, 27]:

1. Element shape, size, and gradation
2. Parameters describing contact between two elements. Element shape, size and gradation.

As shown in Fig 2.4 contacts between two elements in PFC3D consists of three parts:

- Normal spring which control the relationship between normal contact and the relative displacement perpendicular to the common plane.
- Shear spring which controls the relationship between incremental shear contact force and the movement parallel to the common plane.
- The surface friction angle which acts as a frictional slider and supplies friction angle between two elements in contact.

Two types of bonds are typically used in PFC3D the contact bond and the parallel bond. In the contact bond model, elastic spring with constant normal and shear stiffness's, k_n and k_s act at the contact points between particles, thus allowing only forces to be transmitted. In the parallel bond model, the moment induced by particle rotation is resisted by a set of elastic springs uniformly distributed over a finite-sized section lying on the contact plane and centered at the contact point.

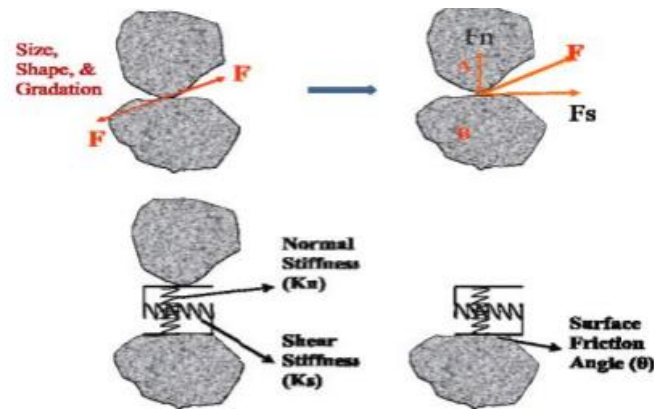


Figure 2.4: Diagram of surface friction angle, normal and shear stiffness [21, 27]

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

This chapter begins with the description of the type of materials used in this study. A detailed description of the test program and procedure are presented in the following sections.

3.2 Materials Used

The materials tested in this study are Track Ballast and Waste tire rubber. Track Ballast forms the track upon which railroad ties (sleepers) are laid. It is packed between, below, and around the ties. It is used to bear the load from the railroad ties, to facilitate drainage of water, and also to keep down vegetation that might interfere with the track structure. Waste tire rubber a tire that is no longer mounted on a vehicle and no longer suitable for use as a vehicle tire due to wear, damage, or deviation from the manufacturer's original specifications. The ballast material was obtained from Koysha hydroelectric power crushing plant site and the waste tire rubber was also obtained from Addis Ababa unique place near to tekle-haymot church.

3.3 Equipment used

Equipment's for the laboratory tests were list as follow:

- Stainless Steel Test Sieves
- LOS ANGELES Abrasion Machine
- Compressive Testing Machine
- Electronic Precision Balances
- Thermometer
- Shear test machine

3.4. Sample Preparation

Sieving

In this study, the maximum particle size used was 50mm. The specimen length to maximum particle size ratio is 12 and respects the requirement of having a ratio greater than 6. Seven sieves were used to separate

the ballast material into six categories. Then it was flushed with water to remove dust and oven dried. The material was weighed following the selected grain size distribution curve of the test material.

Preparation of Specimens

The sample was prepared as follows:

1. For a single test, two boxes with dimensions of 300mm*300mm*300mm were used for casting the loose ballast sample.
2. For single sample the total weights of ballast and waste tire rubber in the two boxes were 88.89kg.
3. The total weight of waste tire used for 6 samples were 21.33kg.
4. The total weight of ballast used for 9 samples were 778.68kg.
5. Then place the required weight of ballast and waste tire rubber in the boxes and add some amount of mixture of cement and water as grouting into the boxes to create bondage between ballast materials.
6. Keep the casting of the ballast material for two days.

3.5 Laboratory Tests for Physical Properties of Ballast

The method of selection of ballast has been based on the physical testing of representative specimens to ensure that materials are of the suitable rock type with no inherent planes of weakness such as foliation and cleavage (petrographic analysis). The following tests are recommended to judge the suitability of the ballast material for a railway track.

- Aggregate Abrasion Value
- Flakiness Index test
- Specific gravity and water absorption test
- Particle size distribution
- Particle Shape
- Aggregate Crushing value
- Aggregate Impact value

3.5.1 Aggregate Abrasion Value

To check for aggregate abrasion, a test sample of 10kg of clean ballast conforming to the following grading is taken:

Passing the 50mm sieves and retained on the 40mm square mesh sieve: 5000g passing the 40mm and retained on the 25mm square mesh sieve: 5000g sample, along with the abrasive charge, is placed in the Los Angeles machine, which is rotated at a speed of 30-33 rpm for 1000 revolutions. The sample is sieved and material coarser than the 1.7 mm sieve is washed, dried, and weighed. The difference between the original weight (A) and the final weight of the sample (B) is expressed as a percentage of the original weight of the test sample.

There are three types of ballast:

Type A: Used sieve sizes were 37.5mm, 25mm, 19mm, 12.5mm, and 9.5mm in which the sample of ballast used for tests were retained in four sieves. So the weight of individual samples used for test was 2500g (2.5kg) totally 10kg.

Type B: Used sieve sizes were 19mm, 12.5mm, and 9.5mm in which the sample of ballast used for tests were retained in four sieves. So the weight of individual samples used for test was (5 Kg) totally 10kg.

Type C: Used sieve sizes were 9.5mm, 6.3mm, and 4.75mm in which the sample of ballast used for tests were retained in four sieves. So the weight of individual samples used for test was (5 Kg) totally 10kg.

3.5.2 Flakiness Index test

The flakiness index of an aggregate is the percentage by weight of the particles with a least dimension (thickness) less than three-fifths of their mean dimension. The test is not applicable to sizes smaller than 6.3 mm. Track ballast sample of sufficient quantity is taken to provide a minimum of 200 pieces, which is weighed (weight A). The sample consisting of aggregates is sieved as per the prescribed procedure in a series of sieves. The flaky material is separated and weighed (weight B). The flakiness index is then determined by the total weight of the material passing the various sieves, expressed as a percentage of the total weight of the sample gauged

3.5.3 Specific gravity and Water Absorption Test

A sample consisting of at least 2000 g of aggregate is washed thoroughly to remove finer particles and dust. The whole material is then drained, placed in a wire basket, and immersed in distilled water at a temperature between 22°C and 32°C. The sample is shaken, jolted, and dried as per specific procedure. The sample is finally placed in an oven in a shallow tray at a temperature of 100°C to 110°C. It is then removed from the oven, cooled in the container, and weighed (weight C).

3.5.4 Particle size distribution

The particle size distribution, 'grading', is a fundamental property for all construction aggregates and often defines the product. Grading is usually carried out by sieve analysis. The sample is passed through a sieve stack (wet or dry) and the weight proportion retained on each sieve is determined. Aggregate should be clean (free of clay, silt and dust) to ensure effective binding of cement or bitumen.

3.5.5 Particle shape

The shape of aggregate particles is a product of the rock type, depositional environment and quarrying and production process. For example, hard, tough or brittle rocks will often generate more flakes, whereas softer rocks produce more fines. Angular, cuboidal aggregate is usually preferred. Flat, flaky or long, thin particles will not interlock well and result in weak road stone or concrete products. Also, poorly-shaped aggregate has a high surface area and has a high demand for binder.

Aggregate shape is determined using petrographic analysis and can be classified as: rounded, cuboidal, irregular, angular, flaky, or elongated. Flakiness and elongation are the key measures of poor particle shape. The 'flakiness' of an aggregate is measured as the weight proportion passing a specially designed slotted sieve. A limit of 35% flaky particles is imposed for general purpose construction aggregate whereas a stricter limit of 25% flaky particles is imposed for wearing course road stone.

3.5.6 Aggregate crushing value

This is the measurement of the resistance of aggregate to crushing by compressive force. A test specimen (20-50mm) is compressed (up to 400 kN) and the proportion of material passing 2.36mm is the ACV (mean value of two tests). An ACV greater than 35% indicates that aggregate is too weak for most construction uses. A variation is the Ten per Cent Fines Value (TFV) which is expressed as the load required producing 10% fines. TFV ranges from 10kN (very weak rock) to greater than 400 kN (very strong rock).

3.6 Shear strength tests

Assessments of the stability of embankment, bearing capacity, lateral and longitudinal resistance are required shear strength of parameters of ballast. Proper understanding of the shear strength properties of the ballast, which forms the major part of the track substructure, is important. Shear strength of ballast derives from two sources (Cohesion between particles and frictional resistance between particles). Most commonly used laboratory devices available to estimate the shear strength parameters of ballasts are:

- Direct shear test: this test conduct to investigate the shear behavior of different ballast specimens as it is the most efficient method to study the shear behavior of granular material.
- Tri-axial shear test: is a common method to measure the mechanical properties of many deformable solids, especially soil and rock, and other granular materials or powders.

3.6.1. Shear test equipments

The shear test included different equipment for evaluation of properties of ballast material with and without of waste tire rubber. Among the parts of the shear machine the following are the crucial for determination shear strength parameters.

- Frame
- Sliding plate
- Base
- Clump
- Displacement gauge
- Load cell, Jack spacer and Shear test machine.

3.6.2. Shear test procedures

The procedure to take in account in this test listed as following:

- ✓ Adjust all equipments in place before putting the materials for test.
- ✓ Properly level the frame at the center position in relation to the length of the test sample.
- ✓ Confine the test material sample with allowable confining pressure given by pressing the load cell up to the material become ready for applying the shear pressure.
- ✓ After putting the material in the shear machine then start the shear test of the ballast material and also the ballast material in addition of waste tire rubber.
- ✓ Then record the important data's in the prepared paper sheet of shear test with in one minute time interval:
 - Confining load.
 - Shear load.
 - Deformations (in the left and right direction of the gauge).
- ✓ Shear load, confining load, vertical displacement were continually recorded during testing. Confining pressures of 50kPa, 150kPa and 250kPa were used in the tests.

CHAPTER 4

ANALYSIS RESULT AND DICUSSION

4.1 Physical Test Analysis Results for Ballast material waste tire rubber

Physical test are the fundamental tests usually used to determine the properties of the material in accordance with the allowable range in the standards. After conducting the basic physical properties of ballast with and without waste tire in the laboratory the results are presented in table 4.1.

Table 4.4: Summary of physical properties of ballast material only

Properties	Test values
Aggregate Crushing Value	22.65%
Water Absorption	1.10%
Apparent specific gravity	2.96
Bulk specific gravity	2.89
Bulk specific gravity of saturated surface dry basis	2.91
Flakiness Index Value	20.85%
Elongation Index Value	21.04%
Aggregate Impact Value	19.55%
Los Angeles Abrasion Value	22.27%

4.2 Analysis results of ballast material with 5% and 3% waste tire rubber

The basic formulas used to determine the shear strength parameters are listed below:

- **Normal stress:** The ratio of confining load, and Area of shear surface. The condition of normal stress occurs when a loaded member is in tension or compression.

$$\text{Normal stress} = \frac{\text{Confinig load}}{\text{Area of shear surface}}$$

- **Peak shear stress:** The maximum value of the shear stress or the maximum value of the ratio of shear load to the area of shear surface.

$$\text{Peak shear stress} = \frac{\text{Peak shear load}}{\text{Area of shear surface}}$$

- **Peak friction angle:** It is the angle measured between the normal force and peak shear force, which is attained when failure just occurs in response to a shearing stress. Its tangent is the coefficient of sliding friction.

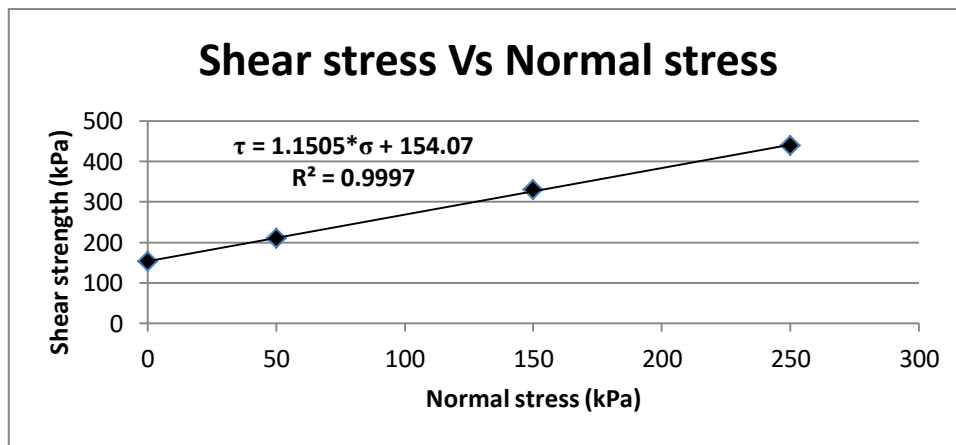
$$\text{Peak friction angle} = \frac{\text{Change in peak shear stress}}{\text{Change in Normal stress}} \text{ or slope of peak shear stress and normal stress.}$$

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- Peak Cohesion:** The cohesion intercept results from a linear approximation of a segment of nonlinear shear strength against normal stress relationship. However, a mobilized strength equal to or less than the peak strength is used to define the factor of safety. In simple word cohesion is defined as Intercept of Peak shear stress and normal stress.

Case 1: Peak values of 100% Ballast material

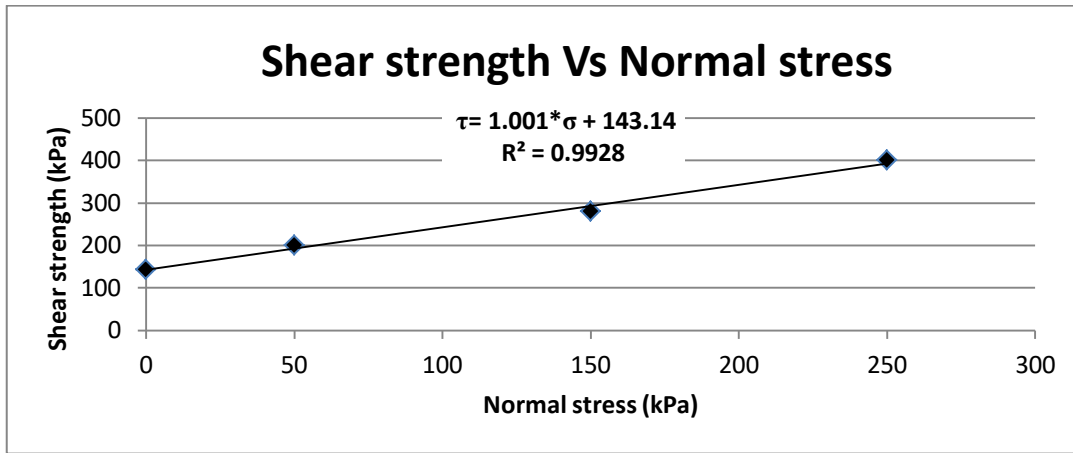
The analysis results of 100% ballast material from laboratory shear tests were peak shear load, normal load, and area of shear surface, left displacement, right displacement, peak shear stress, and peak normal stress. The output parameters from the analysis of laboratory results in the Microsoft excel sheet Peak friction angle and Peak cohesion yielded as the following in table below. And the graph of the shear stress and normal stress also showed below.



Shear stress (kPa)	Normal stress (kPa)	Friction Angle (Degree)	Cohesion (kPa)
440	250	49.0	154
330	150		
210	50		

Case 2: Peak values of 97% Ballast material and 3% Waste tire rubber

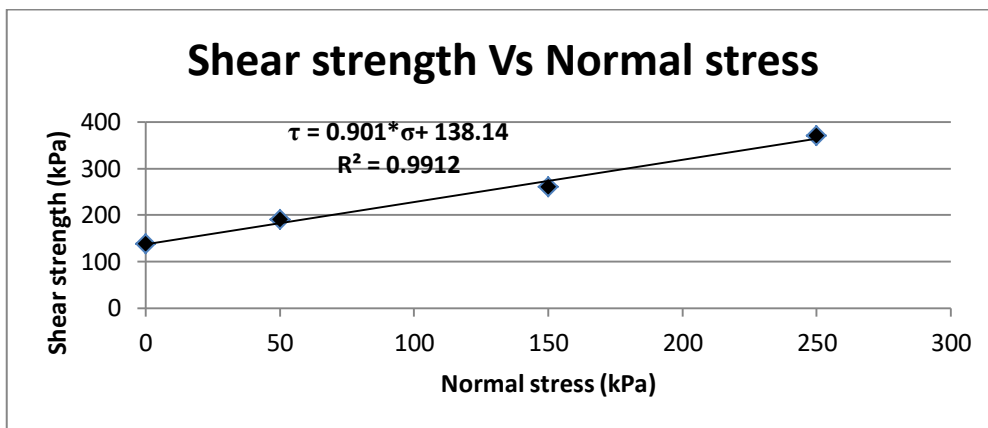
The analysis results of 97% ballast material and 3% Waste tire rubber from laboratory shear tests were peak shear load, peak normal load, area of shear surface, left displacement, right displacement, peak shear stress, and peak normal stress. The output parameters using the laboratory data worked out by the help of Microsoft excel given in the following table.



Shear strength (kPa)	Normal stress (kPa)	Friction Angle (Degree)	Cohesion (kPa)
400	250	45.0	143
280	150		
200	50		

Case 3: Peak values of 95% Ballast material and 5% Waste tire rubber

The analysis results of 95% ballast material and 5% Waste tire rubber from laboratory shear tests were peak shear load, peak normal load, area of shear surface, left displacement, right displacement, peak shear stress, and peak normal stress. The output parameters using the laboratory data worked out by the help of Microsoft excel given in the following table



Shear strength (kPa)	Normal stress (kPa)	Friction angle (Degree)	Cohesion (kPa)
370	250	42	138
260	150		
190	50		

4.3 Effect of waste tire on ballast flying with the help of PFC 3D software

In order to simplify the calculation process, discrete element method usually uses the following assumptions:

1. All particles considered rigid bodies and the geometry of particles will not change under the extrusion force between particles. The deformation of particle system is the summation of deformations in contact points of all particles.
2. The contacts between particles happen at a tiny small area, i.e. contact at point;
3. The contact behavior of particles is soft contact can be determined by force displacement law. Compared with the size of particles, the overlap between particles is small and it is also much smaller than the translation and rotation of particles.
4. The interaction only happens at contacts between particles and the time step should be small enough to make sure that each particle only force effect on its contacted particles and will not affect other particles.
5. The values of speed and acceleration are constant in each specific time step and single rigid particle motion is predicted by Newton's second law of motion.
6. Time step chosen is so small that, during a single time step, disturbances cannot propagate from any particle further than its immediate neighbors. Then at all times, the forces acting on any particle are determined exclusively by its interaction with the particles with which it is in contact.

Limitation of discrete element method

- Can only use spherical particle to model ballast aggregates as default.
- Particle rotation becomes dominant in contact between particles due to the spherical shape.
- Calculation time is relatively long.

4.3.1 The ballast gradation Modeling

A. Numerical Model

Sieve analysis is a technique commonly used to measure the gradation in particle size of a granular material. The test usually consists of shaking aggregate in sieves with progressively smaller mesh sizes. There are two standards used for comparison of the experimental results [25, 26].

Upper boundary		Lower boundary	
Sieve size (mm)	% passing	sieve size (mm)	% passing
16	5	16	0
25	15	25	5
35.5	40	35.5	25
45	75	45	55
56	97	56	92
63	100	63	97
70	100	70	100

B. Experimental model

The experimental test results of ballast material from Koyeha project site. The experimental test results compared with upper and lower boundary by the help of PFC ^{3D}5.0 software to know whether it's within the range given by different research studies according to the diameter of the sieve size.

Trial one: Experimental test results		Trial two: Experimental test results	
Sieve size (mm)	% passing	Sieve size (mm)	% passing
16	0	16	0
25	9.2	25	14.0
35.5	34.4	35.5	38.7
45	67.1	45	74.0
56	96.0	56	96.0
63	100	63	99.0
70	100	70	100

C. The outputs from the modeling of PFC for gradation of ballast material:

The particle size distribution modeling using PFC ^{3D} 5.0 software gives the curve of the particle size gradation in Figure 4.5 for the inputs of the experimental results. From the above particle size gradation curves it can be concluded that the ballast material have well graded distribution of the ballast material, approximately the shape is “S” curve and also satisfied the specification standard give to the gradation of ballast aggregate material.

I. The particle size distribution of the two experimental results with the help of PFC ^{3D}

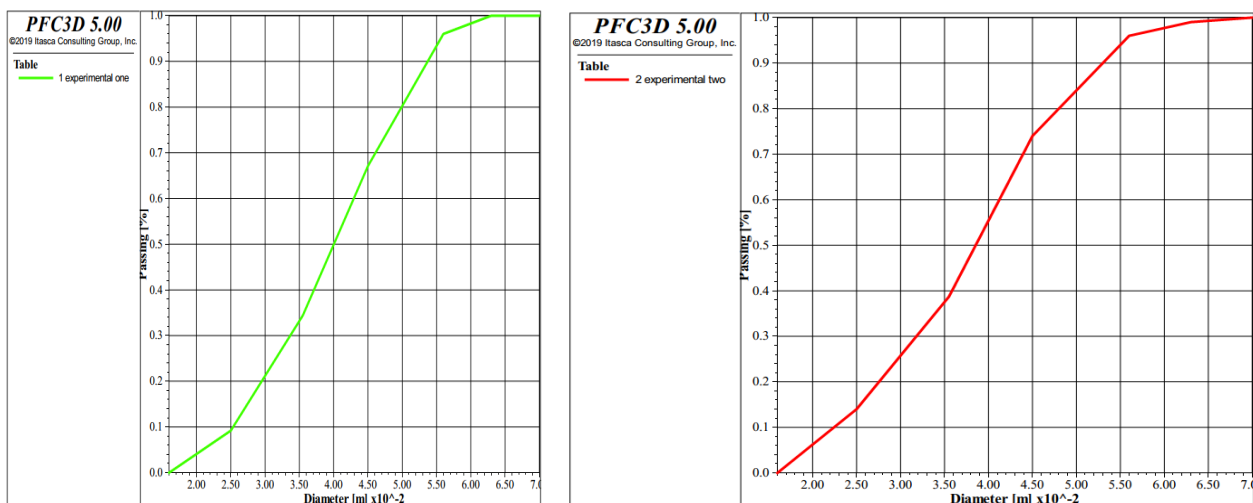


Figure 4.5: Particle gradation curve for experimental one and two

II. The particle size distribution curve comparison of the two experimental results with upper and lower boundary with the help of PFC^{3D}

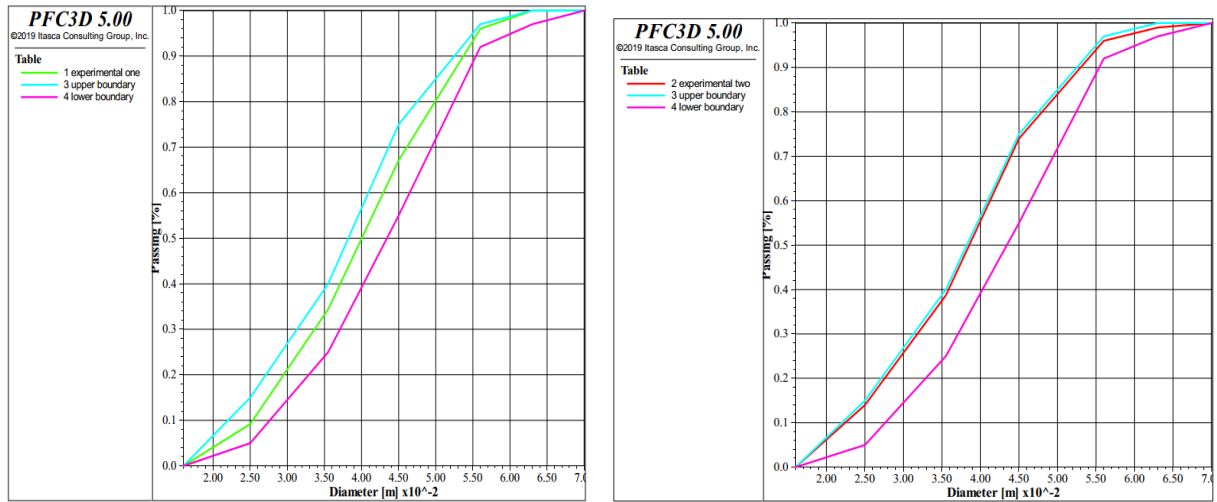


Figure 4.6: Comparison of particle gradation experimental one and two with upper and lower boundary

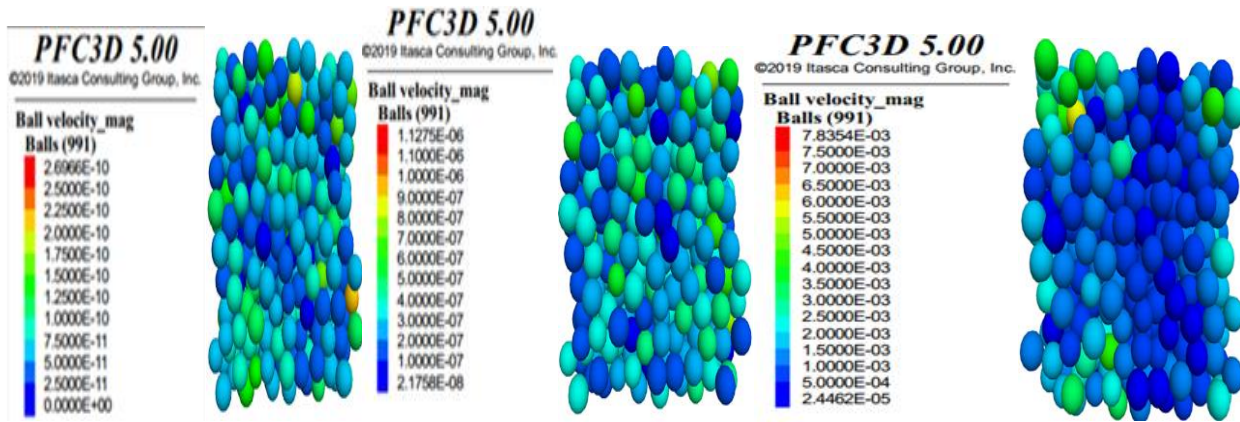
4.3.2 DEM input for ballast gradation modeling

From the above sieve analysis results can be used as the basis to plot the size distribution of the sample that has been generated as code for DEM [26]. The value of the mechanical parameters of ballast adopted for DEM simulation obtained from laboratory test results.

Table 4.5: Mechanical parameters of ballast adopted for DEM simulation

Parameters	Ballast	Waste tire rubber
Particle density (kg/m^3)	1500	650
Coefficient of friction (μ)	0.855, 0.785, 0.733	0-0.12
Radius of particles (mm)	16-63	5-10
Size of particles (mm)	20-50	10-15
Moisture content (%)	0.71	0.8-1.2
Damping	0.7	
Contact normal stiffness (N/m)	$1.0 \cdot 10^8$	
Contact shear stiffness (N/m)	$1.0 \cdot 10^8$	
Number of aggregate used	991	

4.3.3 The results found with the help of PFC 3D ballast flying



- a. 100% ballast material b. 95% ballast material and 5% of waste tire c. 93% ballast and 7% of waste tire

Figure 7: Ball velocity for the three cases of ballast with waste tire rubber

From the modeling results:

Case I: For 100% of ballast material: The maximum vibrational velocity from the Particle Flow Code is 2.6966×10^{-10} m/s.

Case II: For 95% ballast material and 5% of waste tire rubber: The maximum vibrational velocity from the PFC ^{3D} 5.0 was 1.1275×10^{-6} m/s.

Case III: For 93% ballast material and 7% of waste tire rubber: The maximum vibrational velocity from the PFC ^{3D} 5.0 was 7.8354×10^{-3} m/s

4.4 Discussion of Analysis results

4.4.1 Discussion results from the physical strength tests

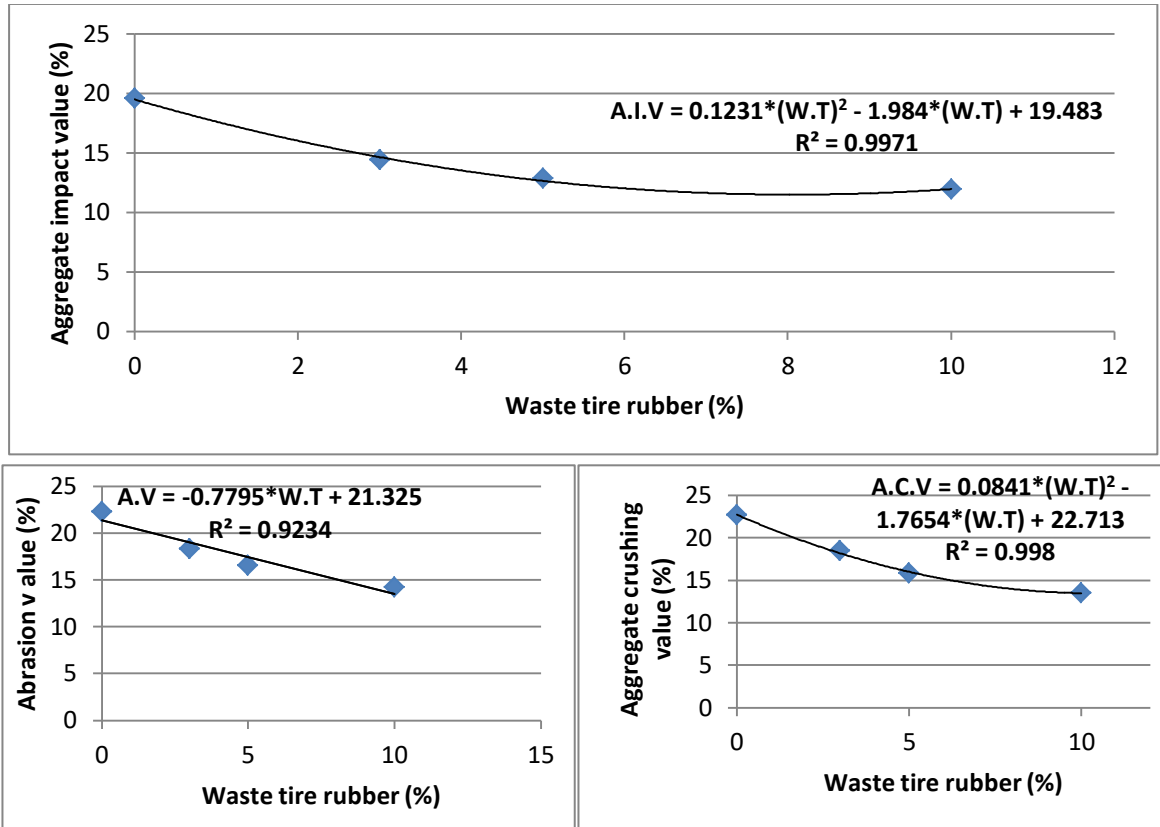


Table 4.6: Physical properties of ballast material with addition of waste tire rubber

Waste tire rubber (%)	Abrasion value (%)	Aggregate crushing value (%)	Aggregate impact value (%)
0	22.27	22.65	19.55
3	18.3	18.4	14.4
5	16.5	15.8	12.84
10	14.2	13.5	11.92

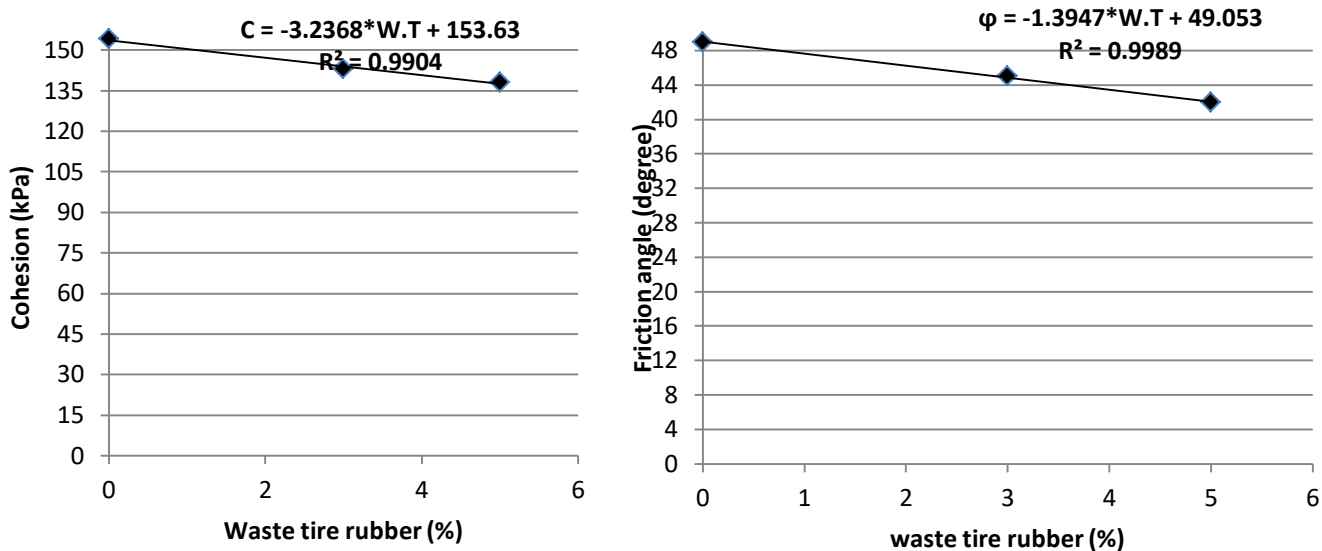
- The graph indicated that the second degree polynomial and linear relationship of the Los Angeles Abrasion and Aggregate Crushing Value with the waste tire rubber respectively. The relation shows as percentages of waste tire increased to the ballast material the percentage of both Los Angeles Abrasion and Aggregate crushing values decreased.
- Abrasion test was used to optimize the quantity of elastic aggregate to be added to the aggregate. It was found that at 8.07%, the degradation was minimum. Tests were conducted with hand without this optimum additive content. There was 9.15% reduction in the aggregate crushing value when

Improvement of ballast material with addition of waste tire rubber

tested without and with the addition of waste tire rubber. It was found that reinforced aggregate shows better resistance against crushing under gradually applied compressive load. Aggregate impact test was conducted to measure the resistance to sudden impact or shock. Reinforced ballast had shown 7.63% reduction in the aggregate impact value, which is an indication of improved toughness.

- From the three test cases the contribution of waste tire rubber was very essential to avoid degradation and breakage between the interlocking ballast materials.
- The main purpose replacement of waste tire rubber for the purpose durability enhancement to the natural ballast material because the waste tire rubber has elastic behavior.

4.4.2 Analysis results from the shear test tests



No.	Results obtained	φ (degree)
1	When 100% ballast material tested for shear strength.	49
2	When 97% ballast material and 3% of waste tire rubber tested together for shear strength.	45
3	When 95% ballast material and 5% of waste tire rubber tested together for shear strength.	42

Main ideas from shear tests:

- The difference of the peak friction angle of 100% ballast material and 97% ballast material with 3% waste tire rubber were 8.14%.
- The difference of the peak friction angle of 100% ballast material and 95% ballast material plus 5% waste tire rubber were 14.31%.
- From the above graphs of friction angle From the laboratory of shear tests when waste tire increased to the ballast material the friction angle decreased with minimum percentage of 14.3.

- Generally when compared the reduction in both mechanical shear strength parameters of ballast and ballast with waste tire have insignificance difference so the addition of waste tire rubber in ballast have advantage for reduction of ballast breakage.

4.4.3 The modeling of ballast and waste tire rubber Using PFC software

Table 7: Results of waste tire rubber and Ball velocity

Waste tire rubber (%)	Ball velocity (m/s)
0	2.6966E-10
3	1.1275E-06
5	0.0078354

The ballast material in railway track is susceptible to wind force from the train and have to ballast flying movement of ballast particle from its position to the rail as well as to the sleepers. The causes to occur ballast flying, first an initial vertical velocity of about 2.0 m/s is required to initiate flight. This is well above that indicated by the geophone measurements, but could perhaps arise from extreme differential aerodynamics pressures over the particle. Taking the second cause an initial vertical velocity of the order of that measured by the geophones 0.02 m/s is required to initiate flight [26].

- The model was done with ballast and ballast with addition of waste tire rubber. The first case is 100% ballast, the second is with 95% ballast and 5% waste tire and the third is with 97% of ballast and 7% of waste tire. In the first modeling the vibrational speed is 2.6966×10^{-10} m/s, the second one is 1.1275×10^{-6} m/s and the third one is 7.8354×10^{-3} m/s. The difference is due to their density.
- The effect of ballast flying was also studied and it safe velocities have been found within the limits of the considered ranges of rubber percentages used in the research.
- Generally, the maximum vibrational velocity is very small to occur ballast flying according to the two requirements.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- The study is focused on the analysis of the practicality of using waste tire rubber as elastic aggregate in the ballast layer with the intention of modifying its mechanical behavior and its durability. The use of waste tire rubber could reduce ballast degradation and consumption of natural aggregates. At the same time, an abundant waste source can be reused. For this reason, the influence of different percentages of waste tire rubber was studied in laboratory. Its effect on different ballast behavior was analyzed. The results can be concluded as increasing the percentage of waste tire rubber mixed with ballast leads to a reduction in the abrasion and at the optimum percentage of 10, the percentage reduction in the abrasion was around 8.07.
- There was a considerable reduction in the Crushing and impact values also. Lower crushing value indicates lower crushed fraction under load and would give a longer service life and a more economical performance. Lower impact value indicates better resistance against disintegration.
- Water absorption was found increased with the addition of waste tire rubber, but was well within the permissible limit as suggested by the standard code.
- Though incorporation of elastic solution increased ballast settlement, the ability to take load was improved by the addition of these waste tire rubber. Stiffness was also found improved, which increases the efficiency of the track. Thus application of waste tire rubber to ballast particles could be appropriate solution since it allows reduction of an abundant waste material, at the same time improving ballast behavior.
- The main purpose replacement of waste tire rubber for the purpose durability enhancement to the natural ballast material because the waste tire rubber has elastic behavior.
- The effect of ballast flying was also studied and it safe velocities have been found within the limits of the considered ranges of rubber percentages used in the research.
- This study concluded that replacement of ballast material with allowable range of waste tire rubber have advantage in reduction the abrasion, breakage of ballast material and recycle waste tire rubber which was very dangerous to the environment.

5.2 Recommendations

The suggestions for further study were listed as follows:

- In the future will expect using best technology for prototype the existing railway to evaluate the whole railway track.
- In the future further investigation with the help of discrete element method in the shear strength parameters of ballast material with other rubber materials expected in real railway track.

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Appendix A: Physical strength test Data

Table 8: Specification for ballast particle size distribution [25, 26]

Upper boundary		Lower boundary	
Sieve size (mm)	% passing	sieve size (mm)	% passing
16	5	16	0
25	15	25	5
35.5	40	35.5	25
45	75	45	55
56	97	56	92
63	100	63	97
70	100	70	100

1. Particle size distribution

Sample: One

Table 9: Results of Koysha railway site particle size distribution of ballast material

Mass of wet ballast (g)=34070				
Sieve size (mm)	Mass of dry ballast (g)	Weight of retained ballast (g)	Retained ballast (%)	Passing ballast (%)
70	22866	0	0	1.0
63	22866	0	0	1.0
56	22866	750	3.279979008	0.9620021
45	22866	7523	32.9003761	0.67099624
35.5	22866	15000	65.59958016	0.3440042
25	22866	20760	90.78981895	0.09210181
16	22866	22600	98.83670078	0.01163299
12.5	22866	22601	98.84107408	0.01158926
9.5	22866	22602	98.84544739	0.01154553
6.3	22866	22603	98.84982069	0.01150179
4.75	22866	22604	98.854194	0.01145806
2.36	22866	22605	98.85856731	0.01141433
1.18	22866	22607	98.86731392	0.01132686
0.63	22866	22608	98.87168722	0.01128313
0.315	22866	22609	98.87606053	0.01123939
0.15	22866	22700	99.27403131	0.00725969
0.075	22866	22702	99.28277792	0.00717222
0.045				
Pan		23166		

Sample: Two

Table 10: Results of Koysha hydroelectric power site particle size distribution of ballast material

Mass of wet ballast (g)=22022				
Sieve Size (mm)	Mass of dry ballast (g)	Weight of retained ballast (g)	Retained ballast (%)	Passing ballast (%)
70	21866	0	0	1.0
63	21866	100	0.457331016	0.9942669
56	21866	800	3.65864813	0.963413519
45	21866	5540	25.3361383	0.742638617
35.5	21866	13400	61.28235617	0.387176438
25	21866	18600	85.06356901	0.14336431
16	21866	20966	95.88402085	0.041159791
12.5	21866	21200	96.95417543	0.030458246
9.5	21866	21284	97.33833349	0.026616665
6.3	21866	21288	97.35662673	0.026433733
4.75	21866	21326	97.53041251	0.024695875
2.36	21866	21342	97.60358548	0.023964145
1.18	21866	21378	97.76822464	0.022317754
0.63	21866	21422	97.96945029	0.020305497
0.315	21866	21464	98.16152931	0.018384707
0.15	21866	21506	98.35360834	0.016463917
0.075	21866	21586	98.71947315	0.012805268
0.045				
Pan		24272		

2. Flakiness and Elongation test analysis results

Table 11: Flakiness index and Elongation index results of ballast material

Sample One			
Sieve size (mm)	Retained ballast weight (g)	Flakiness (g)	Elongation (g)
50-75			
37.5-50	1052	164	
28-37.5	4686	2244	1596
20-28	9112	1603	2336
14-20			
Total	A= 14850	B= 4011	D= 3932
Aggregate Size		20-50mm	
Flakiness index	B/A	27.01%	

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Elongation index	D/A	26.48%	
Sample Two			
Sieve size (mm)	Retained ballast weight (g)	Flakiness (g)	Elongation (g)
50-63	1404	492	326
28-37.5	8110	994	1120
20-28	7226	838	940
14-20			
Total	A= 19992	B= 2944	D= 3114
Aggregate Size		20-50mm	
Flakiness index	B/A	14.70%	
Elongation index	D/A	15.60%	
Test Limit < 30%			

3. Los Angeles test analysis results of 100% ballast material

Table 12: Los Angeles Abrasion value for 100% ballast Material

Weight of Ballast material (Kg)	Test Samples		
	1	2	3
Original weight of ballast sample	10	10	10
Passing weight of ballast sample with sieve size 1.7mm	2.12	2.32	2.24
Retained weight of ballast sample	7.88	7.68	7.76
Los Angeles Abrasion value (%)	21.2	23.2	22.4
Average Los Angeles Abrasion value (%)	$\left(\frac{21.2+23.2+22.4}{3}\right) = 22.27$		

4. Los Angeles test analysis results

Table 13: Los Angeles Abrasion value for ballast material and waste tire rubber

Test Samples	1	2	3
weight of ballast material (Kg)	9.7	9.5	9
weight of waste tire rubber (Kg)	0.3	0.5	1
Passing weight of ballast sieve size 1.7mm (kg)	1.83	1.65	1.42
Retained weight of ballast and waste tire rubber (kg)	8.17	8.35	8.58
Los Angeles Abrasion Value (%)	18.3	16.5	14.2

5. Specific gravity and water absorption test analysis results

Table 14: Results of Koysha project site specific gravity and water absorption results of ballast material

Aggregate size (20-50)mm		Sample	
		1	2
B	weight of saturated surface dry sample in air (g)	8069	8746
C	weight of saturated sample in water (g)	5294	5750
A	weight of oven dry sample in air (g)	8007	8690
K	Correction factor at t (degree centigrade)	1	1
a*k	Apparent Specific gravity	2.951	2.961
a-c			
B*k	Bulk specific gravity (Saturated Surface Dry Basis)	2.908	2.919
b-c			
a*k	Bulk specific gravity	2.885	2.901
b-c			
(b-a)*100	Water Absorption	0.77%	0.64%
A			
Average	A.s.g= 2.956 > 2.5		
	B.s.g= 2.893 >2.5		
	B.s.g.ssdB= 2.914>2.5		
	W.A= 0.71% T.S Limit <3%		
	T.S. Limit <3% for W.A & T.S. Limit >2.5 for s.g		
	W.A= 1.299% T.S Limit <3%		
	T.S. Limit <3% for W.A & T.S. Limit >2.5 for s.g		

6. Aggregate crushing value of 100% ballast material

Table 15: Results of Koysha project site aggregate crushing value of ballast material

Samples	1	2	3
weight of ballast material (Kg)	10	10	10
Passing weight of ballast sieve size 2.36mm (kg)	2.224	2.267	2.304
Retained weight of ballast material (kg)	7.776	7.733	7.696
Aggregate crushing Value (%)	22.24	22.67	23.04
Average crushing Value (%)	22.65		

7. Aggregate crushing value of ballast material with addition of waste tire rubber

Table 16: Results of Koysha project site aggregate crushing value of ballast material and waste tire rubber

Samples	1	2	3
weight of ballast material (Kg)	9.7	9.5	9
weight of waste tire rubber (Kg)	0.3	0.5	1
Passing weight of ballast sieve size 2.36mm (kg)	1.84	1.58	1.35
Retained weight of ballast and waste tire rubber (kg)	8.16	8.42	8.65
Aggregate crushing Value (%)	18.4	15.8	13.5

8. Aggregate impact value of 100% of ballast material

Samples	1	2	3
weight of ballast material (Kg)	50	50	50
Passing weight of ballast sieve size 2.36mm (kg)	9.45	9.67	10.2
Aggregate impact value (%)]= (w2/w1)*100	18.9	19.34	20.4
Average Aggregate Impact Value (%)	19.55		

9. Aggregate impact value of ballast material with addition of waste tire rubber

Samples	1	2	3
weight of ballast material (Kg)	48.5	47.5	45
weight of waste tire rubber (Kg)	1.5	2.5	5
Passing weight of ballast and waste tire rubber sieve size 2.36mm (kg)	7.2	6.42	5.96
Aggregate impact value (%)]= (w2/w1)*100	14.4	12.84	11.92

Appendix B: Data of shear strength parameters of 100% ballast material

Sample: One

Table 17: Results of peak shear stress & normal stress for confining load of 1660 lbs 100% ballast

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Deformation 1(mm)	Deformation 2(mm)	Area of shear (mm ²)	Normal stress (kPa)	Shear stress (kPa)
2.016	2.24	10	30	5	5	30000	67	75
2.24	2.24	10	30	5	5.02	30000	75	75
2.464	2.24	10	30	4.99	5	30000	82	75
2.688	2.24	10	30	4.98	5	30000	89.6	75
2.912	2.24	10	30	4.96	4.98	30000	97	75
3.136	2.24	10	30	4.93	4.95	30000	105	75
3.36	5.376	10	30	5.07	5.2	30000	112	179
3.584	8.288	10	30	5.07	5.2	30000	119	276
4.256	11.2	10	30	5.05	5.2	30000	142	373
4.48	14.112	10	30	5.04	5.2	30000	149	470
4.704	18.368	10	30	5	5.06	30000	157	612
4.928	22.176	10	30	4.97	5.02	30000	164	739
5.376	22.4	10	30	5.06	5.1	30000	179	747
6.272	20.16	10	30	5.07	5.12	30000	209	672
6.72	17.92	10	30	5.13	5.18	30000	224	597
7.468	15.68	10	30	5.15	5.21	30000	249	523
7.468	13.44	10	30	5.22	5.27	30000	249	448
7.468	11.2	10	30	5.23	5.28	30000	249	373
7.468	12.32	10	30	5.26	5.28	30000	249	411
7.468	12.544	10	30	5.27	5.33	30000	249	418
7.468	13.14	10	30	5.5	5.54	30000	249	438
6.72	13.14	10	30	5.94	5.62	30000	249	438
6.72	10.752	10	30	6.24	6.12	30000	224	358
7.168	10.304	10	30	6.45	6.33	30000	239	343
7.392	9.856	10	30	6.72	6.63	30000	246	329
6.72	11.2	10	30	7.46	7.57	30000	224	373
8.064	10.752	10	30			30000	269	358
7.168	10.304	10	30			30000	239	343
7.468	10.976	10	30			30000	249	366
7.468	10.976	10	30	9.42	10.56	30000	249	366
7.468	10.752	10	30			30000	249	358

Sample: Two

Table 18: Results of shear stress & normal stress for Confining load of 1000lbs of 100% ballast

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
1.792	2.24	10	30	30000	60	74.7
2.24	2.688	10	30	30000	75	89.6
2.464	3.136	10	30	30000	82	104.5
3.584	3.584	10	30	30000	119	119.5
4.48	5.376	10	30	30000	149	179.2
5.376	6.272	10	30	30000	179	209.1
4.48	4.928	10	30	30000	149	164.3
4.48	5.6	10	30	30000	149	186.7
4.48	5.824	10	30	30000	149	194.1
4.48	6.048	10	30	30000	149	201.6
6.72	5.6	10	30	30000	224	186.7
8.064	8.736	10	30	30000	269	291.2
8.96	10.752	10	30	30000	299	358.4
6.72	8.064	10	30	30000	224	268.8
6.272	7.616	10	30	30000	209	253.9
5.376	8.736	10	30	30000	179	291.2
4.928	9.184	10	30	30000	164	306.1
5.376	9.408	10	30	30000	179	313.6
6.272	10.304	10	30	30000	209	343.5
5.376	11.2	10	30	30000	179	373.3
4.48	9.856	10	30	30000	149	328.5
4.928	9.856	10	30	30000	164	328.5
9.408	11.2	10	30	30000	314	373.3
9.856	11.648	10	30	30000	329	388.3
10.304	11.2	10	30	30000	343	373.3
8.96	9.856	10	30	30000	299	328.5
4.48	6.72	10	30	30000	149	224

Improvement of ballast material with addition of waste tire rubber

Sample: Three

Table 19: Results of shear stress & normal stress for Confining load of 300lbs of 100% ballast

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Deformation 1(mm)	Deformation 2(mm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
0.448	0.896	10	30	5	5	30000	14.9	29
0.5376	0.896	10	30	4.98	5.01	30000	18	30
0.6272	0.896	10	30	5.03	5.04	30000	21	29
0.7168	1.12	10	30	5.04	5.06	30000	24	37
0.8064	1.344	10	30	5.06	5.07	30000	27	45
0.896	2.016	10	30	5.08	5.09	30000	29	67
1.0752	2.24	10	30	5.1	5.13	30000	36	75
1.12	2.464	10	30	5.13	5.15	30000	37.3	82
1.1648	2.688	10	30	5.15	5.18	30000	39	89
1.2544	2.912	10	30	5.17	5.19	30000	42	97
1.344	3.136	10	30	5.18	5.2	30000	45	104
1.4336	3.36	10	30	5.19	5.22	30000	48	112
1.4784	3.584	10	30	5.21	5.24	30000	49.3	112
1.4784	3.808	10	30	5.24	5.27	30000	49.3	127
1.4784	4.032	10	30	5.28	5.31	30000	49.3	134
1.4784	4.256	10	30	5.31	5.34	30000	49.3	142
1.344	4.48	10	30	5.43	5.48	30000	45	149
1.3888	4.704	10	30	5.51	5.55	30000	46.3	157
1.4336	4.928	10	30	5.54	5.58	30000	47.8	164
1.4784	5.152	10	30	5.58	5.61	30000	49.3	172
1.4784	6.272	10	30	6.05	6.09	30000	49.3	210
1.4784	6.272	10	30	6.08	7.01	30000	49.3	210
1.568	6.272	10	30	7.5	7.8	30000	52.3	210
1.4336	4.48	10	30	9.3	9.5	30000	47.8	149
1.4784	5.376	10	30			30000	49.3	179
1.4784	4.928	10	30			30000	49.3	164
1.4784	4.48	10	30	13.6	14.2	30000	49.3	149.3

Appendix C: Data shear strength parameters of 97% of ballast material & 3% of waste tire rubber

Sample: One

Table 20: Results of shear stress & normal stress for Confining load of 1600 lbs of Ballast with waste tire

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
2.016	2.24	10	30	30000	67.2	75
2.24	2.24	10	30	30000	74.7	75
2.464	2.24	10	30	30000	82.1	75
2.688	2.24	10	30	30000	89.6	75
2.912	2.24	10	30	30000	97.1	75
3.136	2.24	10	30	30000	104.5	75
3.36	4.48	10	30	30000	112	149
3.584	4.928	10	30	30000	119.5	164
4.256	5.824	10	30	30000	141.9	194
4.48	5.376	10	30	30000	149.3	179
4.704	5.6	10	30	30000	156.8	187
4.928	5.824	10	30	30000	164.3	194
5.152	6.272	10	30	30000	171.7	209
5.376	6.72	10	30	30000	179.2	224
5.824	7.168	10	30	30000	194.1	239
7.4682	8.512	10	30	30000	248.9	284
7.4682	8.96	10	30	30000	248.9	299
7.4682	9.408	10	30	30000	248.9	314
7.4682	9.856	10	30	30000	248.9	329
7.4682	10.752	10	30	30000	248.9	358
7.4682	12	10	30	30000	248.9	400
7.4682	11.948	10	30	30000	248.9	398
6.72	10.752	10	30	30000	224	358
7.168	10.304	10	30	30000	238.9	343
7.392	9.856	10	30	30000	246.4	329
6.72	11.2	10	30	30000	224	373
8.064	10.752	10	30	30000	268.8	358
7.168	10.304	10	30	30000	238.9	343
7.4682	10.976	10	30	30000	248.9	366
7.4682	10.976	10	30	30000	248.9	366
7.4682	10.752	10	30	30000	248.9	358

Improvement of ballast material with addition of waste tire rubber

Sample: Two

Table 21: Results of shear stress & normal stress for Confining load of 1000lbs of Ballast with Waste tire

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
1.792	2.24	10	30	30000	59.7	75
2.016	2.24	10	30	30000	67.2	75
2.464	2.688	10	30	30000	82.1	90
3.584	4.256	10	30	30000	119.5	142
4.48	5.376	10	30	30000	149.3	179
5.376	6.272	10	30	30000	179.2	209
4.48	4.928	10	30	30000	149.3	164
4.48	5.6	10	30	30000	149.3	187
4.48	5.824	10	30	30000	149.3	194
4.48	6.048	10	30	30000	149.3	202
6.72	5.6	10	30	30000	224	187
8.064	5.824	10	30	30000	268.8	194
8.96	6.048	10	30	30000	298.7	202
6.72	6.272	10	30	30000	224	209
6.272	6.496	10	30	30000	209.1	217
5.376	6.72	10	30	30000	179.2	224
4.928	6.944	10	30	30000	164.3	231
5.376	7.168	10	30	30000	179.2	239
6.272	7.392	10	30	30000	209.1	246
5.376	7.616	10	30	30000	179.2	254
4.48	8.36416	10	30	30000	149.3	279
4.48	8.36416	10	30	30000	248.9	279
9.408	11.2	10	30	30000	313.6	373
9.856	11.648	10	30	30000	328.5	388
10.304	11.2	10	30	30000	343.5	373
8.96	9.856	10	30	30000	298.7	329
4.48	6.72	10	30	30000	149.3	224

Improvement of ballast material with addition of waste tire rubber

Sample: Three

Table 22: Results of shear stress & normal stress for Confining load of 330lbs of Ballast with Waste tire

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Deformation 1(mm)	Deformation 2(mm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
0.448	0.896	10	30	5	5	30000	14.9	29.9
0.5376	0.896	10	30	4.98	5.01	30000	17.9	29.9
0.6272	0.896	10	30	5.03	5.04	30000	20.9	29.9
0.7168	1.12	10	30	5.04	5.06	30000	23.9	37.3
0.8064	1.344	10	3	5.06	5.07	30000	26.8	45
0.896	2.016	10	30	5.08	5.09	30000	29.9	67
1.0752	2.24	10	30	5.1	5.13	30000	35.8	75
1.12	2.464	10	30	5.13	5.15	30000	37.3	82
1.1648	2.688	10	30	5.15	5.18	30000	38.8	89
1.2544	2.912	10	30	5.17	5.19	30000	41.8	97
1.344	3.136	10	30	5.18	5.2	30000	44.8	104.5
1.4336	3.36	10	30	5.19	5.22	30000	47.8	112
1.4784	3.584	10	30	5.21	5.24	30000	49.3	119
1.4784	3.808	10	30	5.24	5.27	30000	49.3	127
1.4784	4.032	10	30	5.28	5.31	30000	49.3	134
1.4784	4.256	10	30	5.31	5.34	30000	49.3	142
1.344	4.48	10	30	5.43	5.48	30000	45	149
1.3888	4.704	10	30	5.51	5.55	30000	46.3	157
1.4336	4.928	10	30	5.54	5.58	30000	47.8	164
1.4784	5.152	10	30	5.58	5.61	30000	49.3	172
1.4784	5.97184	10	30	6.05	6.09	30000	49.3	199
1.4784	5.97184	10	30	6.08	7.01	30000	49.3	199
1.568	5.376	10	30	7.5	7.8	30000	52.3	179.2
1.4336	4.48	10	30	9.3	9.5	30000	47.8	149
1.4784	5.376	10	30			30000	49.3	179
1.4784	4.928	10	30			30000	49.3	164
1.4784	4.48	10	30	13.6	14.2	30000	49.3	149

Appendix D: Data shear strength parameters of 95% of ballast material & 5% of waste tire rubber

Sample one:

Table 23: Results of shear stress & normal stress for Confining load of 1660lbs of Ballast with Waste tire

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Deformation 1(mm)	Deformation 2(mm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
2.016	2.24	10	30	5	5	30000	67	70
2.24	2.24	10	30	5	5.02	30000	75	70
2.464	2.24	10	30	4.99	5	30000	82	70
2.688	2.24	10	30	4.98	5	30000	90	70
2.912	2.24	10	30	4.96	4.98	30000	97	70
3.136	2.24	10	30	4.93	4.95	30000	105	70
3.36	4.48	10	30	5.07	5.2	30000	112	150
3.584	4.928	10	30	5.07	5.2	30000	119	160
4.256	5.824	10	30	5.05	5.2	30000	142	190
4.48	5.376	10	30	5.04	5.2	30000	149	180
4.704	5.6	10	30	5	5.06	30000	157	190
4.928	5.824	10	30	4.97	5.02	30000	164	190
5.152	6.272	10	30	5.06	5.1	30000	172	210
5.376	6.72	10	30	5.07	5.12	30000	179	220
5.824	7.168	10	30	5.13	5.18	30000	194	240
7.4682	8.512	10	30	5.15	5.21	30000	249	280
7.4682	8.96	10	30	5.22	5.27	30000	249	300
7.4682	9.408	10	30	5.23	5.28	30000	249	310
7.4682	9.856	10	30	5.26	5.28	30000	249	330
7.4682	10.752	10	30	5.27	5.33	30000	249	360
7.4682	12	10	30	5.5	5.54	30000	249	400
7.4682	11.052	10	30	5.94	5.62	30000	249	370
6.72	10.752	10	30	6.24	6.12	30000	224	360
7.168	10.304	10	30	6.45	6.33	30000	239	340
7.392	9.856	10	30	6.72	6.63	30000	246	330
6.72	11.2	10	30	7.46	7.57	30000	224	370
8.064	10.752	10	30			30000	269	360
7.168	10.304	10	30			30000	239	340
7.4682	8.96	10	30			30000	249	300
7.4682	8.96	10	30	9.42	10.56	30000	249	300
7.4682	8.512	10	30			30000	249	280

Sample Two:

Table 24: Results of shear stress & normal stress for Confining load of 1000lbs of Ballast with Waste tire

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (kPa)
0.448	2.24	10	30	30000	14.9	74.7
0.896	2.24	10	30	30000	29.9	74.7
1.344	2.688	10	30	30000	44.8	89.6
1.344	4.256	10	30	30000	44.8	141.87
1.344	5.376	10	30	30000	44.8	179.2
1.344	6.272	10	30	30000	44.8	209.1
1.344	4.928	10	30	30000	44.8	164.3
1.344	5.6	10	30	30000	44.8	186.7
1.4336	5.824	10	30	30000	47.8	194.1
1.4784	6.048	10	30	30000	49.3	201.6
1.4784	5.6	10	30	30000	49.3	186.7
1.4784	5.824	10	30	30000	49.3	194.1
1.4784	6.048	10	30	30000	49.3	201.6
1.344	6.272	10	30	30000	44.8	209.1
6.272	6.496	10	30	30000	209.1	216.5
5.376	6.72	10	30	30000	179.2	224
4.928	6.944	10	30	30000	164.3	231
5.376	7.168	10	30	30000	179.2	238.9
6.272	7.392	10	30	30000	209.1	246
5.376	7.616	10	30	30000	179.2	253.9
4.48	7.76384	10	30	30000	149.3	259
4.48	7.76384	10	30	30000	149.3	259
9.408	11.2	10	30	30000	313.6	373
9.856	11.648	10	30	30000	328.5	388
10.304	11.2	10	30	30000	343.5	373
8.96	9.856	10	30	30000	298.7	328
4.48	6.72	10	30	30000	149.3	224

Improvement of ballast material with addition of waste tire rubber

Sample: Three

Table 25: Results of shear stress & normal stress for confining load of 330lbs of Ballast with Waste tire

Confining load (kN)	Shear load (kN)	Width (cm)	Length (cm)	Deformation 1(mm)	Deformation 2(mm)	Area of shear (mm^2)	Normal stress (kPa)	Shear stress (KPa)
0.448	0.896	10	30	5	5	30000	14.9	29
0.5376	0.896	10	30	4.98	5.01	30000	17.9	29
0.6272	0.896	10	30	5.03	5.04	30000	20.9	29
0.7168	1.12	10	30	5.04	5.06	30000	23.9	37.3
0.8064	1.344	10	30	5.06	5.07	30000	26.9	45
0.896	2.016	10	30	5.08	5.09	30000	29.9	67.2
1.0752	2.24	10	30	5.1	5.13	30000	35.8	75
1.12	2.464	10	30	5.13	5.15	30000	37.3	82.1
1.1648	2.688	10	30	5.15	5.18	30000	38.8	90
1.2544	2.912	10	30	5.17	5.19	30000	41.8	97
1.344	3.136	10	30	5.18	5.2	30000	44.8	104
1.4336	3.36	10	30	5.19	5.22	30000	47.8	112
1.4784	3.584	10	30	5.21	5.24	30000	49.3	119
1.4784	3.808	10	30	5.24	5.27	30000	49.3	127
1.4784	4.032	10	30	5.28	5.31	30000	49.3	134
1.4784	4.256	10	30	5.31	5.34	30000	49.3	142
1.344	4.48	10	30	5.43	5.48	30000	44.8	149
1.3888	4.704	10	30	5.51	5.55	30000	46.3	157
1.4336	4.928	10	30	5.54	5.58	30000	47.8	164
1.4784	5.152	10	30	5.58	5.61	30000	49.3	171
1.4784	5.6762	10	30	6.05	6.09	30000	49.3	189
1.4784	5.6762	10	30	6.08	7.01	30000	49.3	189
1.568	5.376	10	30	7.5	7.8	30000	52.3	179
1.4336	4.48	10	30	9.3	9.5	30000	47.8	149
1.4784	5.376	10	30			30000	49.3	179
1.4784	4.928	10	30			30000	49.3	164
1.4784	4.48	10	30	13.6	14.2	30000	49.3	149

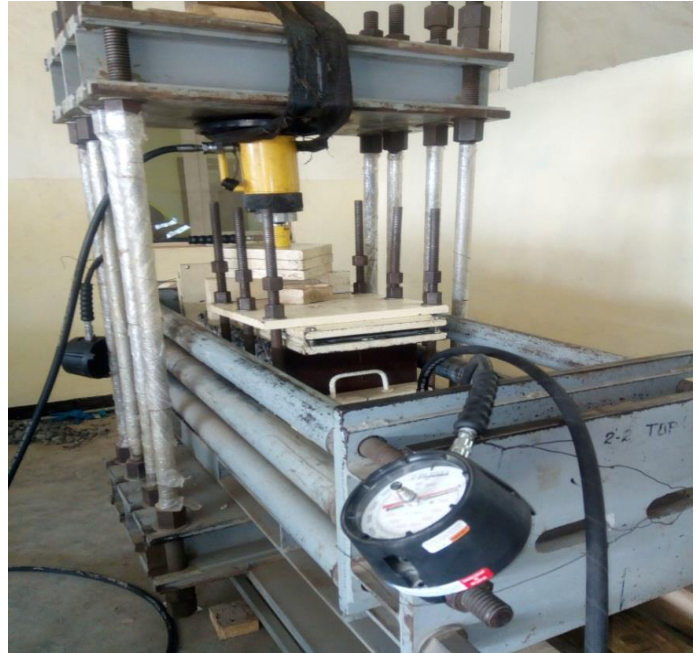
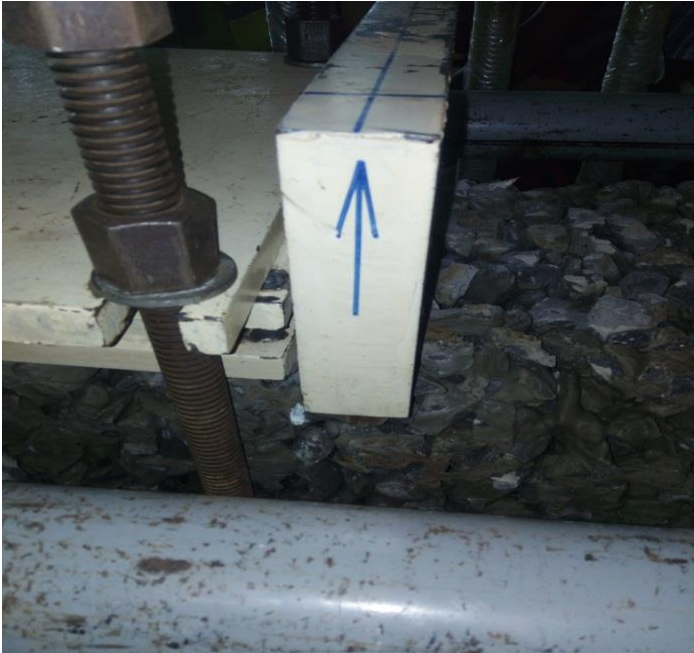
Appendix E: Pictures of the equipment used for physical strength tests of ballast material and waste tire rubber



Appendix F: Pictures of the equipment machine of shear test, test sample of ballast material and waste tire rubber.



Improvement of ballast material with addition of waste tire rubber



Appendix G: Source code of PFC 3D 5.0

1. Code for Gradation

```
;fname: gradation.p3dat
```

```
pfc3d>def gradation
```

```
Def>global exptab=table.create('experimental one')
```

```
Def>table(exptab,0.016)=0
```

```
Def>table(exptab,0.025)=0.092
```

```
Def>table(exptab,0.0355)=0.344
```

```
Def>table(exptab,0.045)=0.671
```

```
Def>table(exptab,0.056)=0.96
```

```
Def>table(exptab,0.063)=1
```

```
Def>table(exptab,0.07)=1
```

```
Def>end
```

```
pfc3d>@gradation
```

```
pfc3d>def gradation
```

```
Def>global exptab=table.create('experimental two')
```

```
Def>table(exptab,0.016)=0
```

```
Def>table(exptab,0.025)=0.14
```

```
Def>table(exptab,0.0355)=0.387
```

```
Def>table(exptab,0.045)=0.74
```

```
Def>table(exptab,0.056)=0.96
```

```
Def>table(exptab,0.063)=0.99
```

```
Def>table(exptab,0.07)=1
```

```
Def>end
```

```
pfc3d>@gradation
```

pfc3d>def gradation

Def>global exptab=table.create('upper boundary')

Def>table(exptab,0.016)=0

Def>table(exptab,0.025)=0.15

Def>table(exptab,0.0355)=0.4

Def>table(exptab,0.045)=0.75

Def>table(exptab,0.056)=0.97

Def>table(exptab,0.063)=1

Def>table(exptab,0.07)=1

Def>end

pfc3d>@gradation

pfc3d>def gradation

Def>global exptab=table.create('lower boundary')

Def>table(exptab,0.016)=0

Def>table(exptab,0.025)=0.05

Def>table(exptab,0.0355)=0.25

Def>table(exptab,0.045)=0.55

Def>table(exptab,0.056)=0.92

Def>table(exptab,0.063)=0.97

Def>table(exptab,0.07)=1

Def>end

pfc3d>@gradation

2. Code for the ballast flying:

Case one: 100% of ballast material

```
pfc3d>; setup model domain and CMAT
```

```
pfc3d>domain extent -10 10 condition periodic
```

```
pfc3d>cmat default model linear method deformability emod 1e8 kratio 1.25 property
```

```
fric 0.855
```

```
pfc3d>;generate balls
```

```
pfc3d>ball distribute radius 1.0 1.2 porosity 0.3
```

```
--- 991 balls generated - There may be huge overlaps!
```

```
pfc3d>ball attribute density 1500 damp 0.7
```

```
--- Attribute density initialized in 991 ball(s).
```

```
--- Attribute damp initialized in 991 ball(s).
```

```
pfc3d>cycle 1000 calm 100
```

Case two: 95% of ballast material and 5% of waste tire rubber

```
pfc3d>; setup model domain and CMAT
```

```
pfc3d>domain extent -10 10 condition periodic
```

```
pfc3d>cmat default model linear method deformability emod 1e8 kratio 1.25 property
```

```
fric 0.785
```

```
pfc3d>;generate balls
```

```
pfc3d>ball distribute radius 1.0 1.2 porosity 0.3
```

```
--- 991 balls generated - There may be huge overlaps!
```

```
pfc3d>ball attribute density 1458 damp 0.7
```

```
--- Attribute density initialized in 991 ball(s).
```

```
--- Attribute damp initialized in 991 ball(s).
```

```
pfc3d>cycle 1000 calm 100
```

pf3d>solve

Case Three: 97% of ballast material and 3% of waste tire rubber

pf3d>; setup model domain and CMAT

pf3d>domain extent -10 10 condition periodic

pf3d>cmat default model linear method deformability emod 1e8 kratio 1.25 property

fric 0.733

pf3d>;generate balls

pf3d>ball distribute radius 1.0 1.2 porosity 0.3

--- 991 balls generated - There may be huge overlaps!

pf3d>ball attribute density 1475 damp 0.7

--- Attribute density initialized in 991 ball(s).

--- Attribute damp initialized in 991 ball(s).

pf3d>cycle 1000 calm 100

pf3d>solve