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Performance Evaluation of ELASTOTRACK Polyurethane Stabilized Railroad Ballasts

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A Thesis in Railway Civil Engineering

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Advisor's Name

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled '**Performance Evaluation of ELASTOTRACK Polyurethane Stabilized Railroad Ballasts**' presented by **Bereket Halefom**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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DECLARATION

I certify that research work titled "Performance Evaluation of ELASTOTRACK Polyurethane Stabilized Railroad Ballast" is my own work. The work has not been presented elsewhere for assessment and award of any Degree/Diploma. Where material has been used from other sources it has been properly acknowledged / referred.

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Name	Signature	Date

ABSTRACT

Ballast, the primary loading area in ballasted railroad substructure, is crucial for the structural support and maintaining of drainage capability. So preserving and enhancing its performance is not only important but also necessary to prolong the life of railroad tracks. Though many enhancement measures were recommended by researches over years, this thesis focuses on stabilizing of ballasts with ELASTOTRACK polyurethane. ELASTOTRACK polyurethane is a liquid and solventless two components, isocyanate and resin, cross-linked rigid compact polyurethane which is sprayed on ballast stones and used to coat them to increase the rigidity of ballasts for the purpose of arresting permanent deformation of ballast layer as well as preventing infiltration of fouling.

In this thesis, an application using ELASTOTRACK polyurethane particle bonding technology for stabilizing ballast is evaluated. The results of the tests show that the average UCS strength of the EPSB specimens (3.16MPa) is greater than that of clean ballast (1.35MPa) under a confining pressure of 90KPa, which is 57.3% greater. And the EPSB specimen with full confinement during EP injection had cumulative plastic stain, ε_P, of 0.145% or 92.5% less than clean ballast (1.94%) over many loading cycles. From evaluation of the elastic deformational behavior of EPSB, the compressive moduli (i.e., Young's and Resilient Modulus) of EPSB are typically less than clean ballast. As ballast elastic modulus is reduced from 200MPa to 90MPa in the test, effect on full track modulus had been analyzed using FEM ABAQUS and results of the model shows that track modulus was ranged from 30.27-28.94MN/m/m (± 4.4%). Therefore, the EPSB integration modeled was found to have an inconsequential effect on track elastic response compared to other key components in the track. Accordingly the LCC of tracks with ELASTOTRACK polyurethane stabilization have economic advantage of about 43,079EUR/km than clean ballast which increases the benefits expected from rail transport projects. Use of EPSB stemming from this research presented can serve as an economically feasible/favorable performance improvement approach. Thus, EP stabilization is an applicable tool for maintaining track geometry thereby reducing maintenance cycles associated with plastic deformation of the ballast layer.

Key Words: Ballast stabilization and performance, Compressive strength, plastic deformation, EPSB, Track modeling, Track modulus.

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NOTATIONS

ERC	Ethiopia Railway Corporation
EP	Elastotrack Polyurethane
EPSB	Elastotrack Polyurethane Stabilized Ballasts
σ_C	Compressive strength
δ_P	Plastic deformation
δ_E	Elastic deformation
M_R	Resilient modulus
Smax	Flexural modulus
σt	Flexural stress
εt	Flexural strain
U	Track Modulus
P_c	Confining pressure
E	Elastic modulus
UCS	Unconfined Compressive Strength
AIV	Aggregate Impact Value
LAA	Los Angeles Abrasion
MDA	Micro-Deval Attrition

α	Integrated dynamic load factor
PSFB	Polyurethane Stabilized Fouled ballast
RPF	Rigid Polyurethane Foam
PSB	Polyurethane Stabilized Ballast
FEA	Finite Element Analysis
S	Shear strength
σ	Normal stress on the failure plane
Ø	Friction angle
C	Cohesion
ε_P	Plastic Strain
σd	Deviatoric Stress
ρ_{PSB}	Density of Polyurethane Stabilized Ballast
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASTM	American Standard Testing Methods
σ_b	Maximum stress at the top surface of the ballast
FEM	Finite Element Modeling
CAE	Complete ABAQUS Environment
2D	Two Dimensional

ρ	Density
h	Depth
v	Poison's ratio
P	The vertical track load;
Y	Deflection
I	Moment of inertia of the rail cross section
Ps	Static wheel load
MGT	Million Gross Tone
LCC	Life Cycle Cost.

CHAPTER 1 INTRODUCTION

1.1 Back Ground

One consequence of the globalization of the economy and the increasing integration of the international economies is a considerable growth in the entire transport sector. And railroad transport sector 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. Furthermore, during this time developing countries like Ethiopia are suffering from traffic congestion and in addition the problem is now begins threatening economic competitiveness. Greater economic development cannot take place in the current transport scenario unless ambitious measures are taken. To address this issue Ethiopian Government was set objectives to construct new railroad corridors throughout the whole country in its transformation plans. And until 2008E.C the length of railroad ballasted tracks under construction reaches around 2000km including Addis Ababa LRT project.

Railroad as seen today are not a result of some instantaneous development but it is the result of combination of ideas which have been around for a few hundred years. In railroad transport, there is an ongoing demand for performance increase, which is driven by the need to keep a competitive edge against other means of transportation, such as aircrafts, cars and ships. This calls for high technical and economical requirements, as embodied by the quest for higher train velocities, larger transport capacity, and lower energy consumption during transport, greater traveler comfort, better safety levels, lower maintenance costs and strong environmental consciousness. Developed countries like, United States of America and European countries, had done extensive researches on the improvement of railroad track difficulties for better performance and economic advantage to accommodate the increasing needs for speed, traffic volume and huge tonnage. Among all difficulties they encountered, failure due to mechanical behavior of ballasts in ballasted track imparts extreme maintenance and renewal over time.

Ballasted track forms the track bed upon which railroad sleepers are laid. Ballasted rail tracks are widely used throughout the world due to its ability for stability, flexibility, distributing loads from super structure to wide area of sub grade, resiliency to the repeated wheel loads, ease of track maintenance, ease of line re-routing, better energy absorbing properties and reduced construction costs when compared to concrete slab-track; although a ballast track's life cycle costs are likely to be higher when compared to concrete track. In fact, in the past projects where mainly assessed on the basis of investment costs, whereas today the principle of life cycle costing is strongly emerging (Esveld, 2001).

Ballast layer is constructed with uniformly graded coarse aggregates. Main functions of ballast layer are distribution of train loads from superstructure to subgrade and supplying required water drainage for track. Former is crucial for supporting relatively weak subgrade. Latter is critical to prevent any track instability. However, with repeated loading, ballast breaks and rearranges into a more graded continuum that retains more water, a process termed as 'fouling'. Track superstructure (i.e., rails, sleepers, and fastening system) typically has much longer lifecycle than the substructure (i.e., ballast, sub ballast, and sub grade); however, the superstructure lifecycle is dependent upon substructure conditions which needs periodic maintenance due to its deformation and degradation associated with particle breakage and foul (Huang 2004). If the irregularities are not corrected, dynamic loads applied from trains commonly increase to a level to cause further deteriorations which finally leading derailment (Selig and Waters, 1994). Continuous development measures had been taken to improve the performance of ballasts over years, such as; underlying hot mix asphalt under ballast layer, laying over geo-synthetic materials and stabilizing by mixing with polyurethane XiTRACK polymer.

The main conceptual intention in this thesis is to inspire Ethiopian Railway Corporation (ERC) look over mechanical property of polyurethane ELASTOTRACK polymer stabilized ballasts for better performance of its tracks and reduction of maintenance cost over span life.

1.2 Motivation and Statement of the Problem

Considerable evidence suggests that, ballast is the main cause of uniform and non-uniform settlement of ballasted railroad track, provided the subgrade is adequately specified. The requirement of a good track is that the sleepers are firmly supported by the ballast bed but over a period of time uneven settlement of the ballast will cause voids to form under the sleepers leading to unacceptable ride quality of track. Voids below sleepers can lead to major track defects and in worst cases can be the cause of vehicle derailment (Ball, 2003). The vast majority of railroads across the world are constructed using ballast, a material that develops strong non-linearity under shear forces. Stress reversals generate hysteresis and cyclic mobility in the stress-strain loops and hence plastic strains develop resulting in ballast degradation and associated plastic deformation which eventually leads to track misalignments and train derailment (Indraratna *et al*., 2005). This problem stems from poor intention given to understanding of complex ballast breakage mechanisms that includes plastic deformation and particle breakage under a large and number of load cycles, typically a few millions. This limited understanding of giving little attention results in requiring frequent remedial measures and costly maintenance putting the economic benefits of the country from the investment in danger.

Under the stabilization of ballasts with polyurethane ELASTOTRACK polymer the performance of the ballasted railroad track will be improved. This paper will focus on the evaluation of the mechanical behavior improvement of ballasts with polyurethane stabilization through laboratory testing and software model analysis. The evaluation was done by selecting basic infrastructural, operational and experimental parameters and performing laboratory tests by providing beam specimen, to evaluate the unconfined compressive strength and plastic deformation of ballasts under static and dynamic loading.

1.3 Scope of the Study

This study is bounded to ballasted single track railroad with any type of passenger and freight trains running with speed less than or equal to 200km/hr. This is a general investigation on the comparative performance of ballasts with and without polyurethane ELASTOTRACK polymer in response to important infrastructural and operational variants for new and long term planning of railroads construction projects instead of evaluating fixed infrastructure. The initial demanders from the output of this stabilization are the critical railroad elemental assets such as, bolted rail joints, rail intersections and track transitions which was known and faced with frequent and costly maintenance measure in the life of railway history. In general this thesis primarily focuses on evaluating improvements of ballast track performance through stabilization with ELASTOTRACK polyurethane in minimizing ballast breakage, controlling track settlement, reducing plastic deformation and enhancing lateral stability under static and dynamic loading.

1.4 Objective of the Study

To meet the growing demand for rail travel, the railroad industry needs to significantly increase the performance of existing tracks and design new tracks accordingly, without increasing maintenance costs or downtime. The primary purpose of this thesis is therefore to investigate new methods that are available to provide increased track substructure performance under load using laboratory experiments backed up by computer modeling. This method enables strategic ballast stabilization with polyurethane, which is a pre-surgical prevention tool to enhance strength and performance of problematic infrastructure elements. The specific objectives of this research presented herein, are: (1) Perform testing for evaluating the mechanistic behavior of railroad ballast infrastructure materials stabilized with ELASTOTRACK polyurethane. (2) Describe mechanisms controlling behavior of ballast materials. (3) Perform track modeling using finite element analysis tools, ABAQUS software, for studying full track mechanistic response to ELASTOTRACK polyurethane injections. (4) Analyze and compare the life cycle cost of railroad ballasted track with and without polyurethane stabilization of ballasts.

1.5 Significance of the Study

Ethiopia is at the infant stage of constructing railroad infrastructures. Even though, the country had facing financial difficulties for the investment cost of railroad projects (Ethiopian railway corporation project financing directorate), the advantage of implementing modern and improved way of railroad technologies for its new railroad infrastructures would have incredible solution to minimize maintenance costs. This paper would have significant findings particularly to Ethiopian Railway Corporation (ERC). Some of the findings of this study are displayed below: Improving ballast performance and preserving track geometry thereby enhancing rail capacity and rider-comfort. Thus, it would have great merits for the planning and designing of new railroad construction; Reducing particle breakage and fines intrusion, thus mitigating fouling generation, in order to arrest permanent deformation. And this impact would inform ERC to consider wastage on maintenance cost of ballasts; and providing a cost and time-effective construction technology which minimizes tedious maintenance work. The research would provide relevant knowledge and information on ballast improvement for cost-benefit analysis of railroad projects.

1.6 Methodology

Literatures regarding sources and causes of railroad ballast damage and improvement measures are thoroughly studied and reviewed. Technical papers, manuals, journals and publications regarding the effect of ballast damage on the full track performance of railroads were reviewed. The data and data sources are from Chinese Railway manual (GB) which the Ethiopian Railways are designed from, American Railway Engineering and Maintenance-of-Way Association (AREMA) manual and other acknowledged publications.

First laboratory testing was done on the prepared test specimens for evaluation of unconfined compressive strength and deformational characteristics of ELASTOTRACK polyurethane stabilized ballasts. Two dimensional Finite element modeling and analysis together with some mathematical evaluations of different parameters is done for the track model developed to back up the test results and to determine the effect of ballast stabilization on the track modulus of the full track model. Finally life cycle cost analysis was performed based on the available cost of the ELASTOTRACK product and literature reviews.

1.7 Thesis Outline

This thesis is written in several units that address the implementation of the research.

Chapter-Two: A review of railroad track structure features, problems facing the rail industry and current aspects of railroad maintenance and improvements are introduced.

Chapter-Three: Development of constitutive materials and creation of specimens for mechanistic testing and analysis of EPSB. Methods developed in Chapter 3 were used to determine deformational behavior, unconfined compressive strength, and Young's modulus. The mechanical properties of clean ballast and EPSB were also compared.

Chapter-Four: A 2-dimensional model is presented using FEM to study track modulus response due to establishment of EPSB within the ballast layer. The effect on individual substructure layers and overall track response due to localized areas of differing modulus (EPSB formation) in the ballast layer is investigated. Life cycle costs based on available data were analyzed.

Chapter-Five: Conclusions and recommendations for the new track using ELASTOTRACK polyurethane developed herein are presented.

CHAPTER 2 BACKGROUND REVIEW

In this Chapter, a typical ballasted railroad track components, detail description of clean ballast property, problems facing the rail industry, several aspects of ballasted railroad maintenance and ballast layer improvement measures are introduced. An introduction into the composition and behavior of polyurethanes, uses of polyurethane in civil engineering applications, and uses and benefits of polyurethanes in rail infrastructure is also provided.

2.1 Ballasted Railroad Track Structure

Railroad track structure is a stable guide-way which serves as a safe and comfortable train transportation with appropriate vertical and horizontal alignment. To achieve this role, each component of the system performs its specific functions satisfactorily in response to the traffic loads and environmental factors imposed on the structure (Ionescu, 2004). The type of structure chosen depends not only on the expected axle loads and speeds, but also on the required service life, the type and amount of maintenance, local conditions, intended purpose and availability of basic materials. This means that the choice of track system is a technical, economic, social and political question, which has to be answered according to each individual case. The eventual aim is to arrive at minimum costs and maximum benefits throughout the life span of the track.

In ballasted railroad tracks rails are supported on sleepers, which are embedded on a compacted ballast layer mostly up to 350mm thick. A common problem with this type of track is the progressive deterioration of ballast with increasing tonnage and traffic passage (number of load cycles). The breakage of sharp corners, repeated grinding and wearing of aggregates, and crushing of weak particles under heavy and cyclic loading causes differential track settlement and unevenness of the surface. Nevertheless, the main advantages that makes ballasted track to be more preferable and widely used throughout the world are; relatively low construction cost and use of indigenous materials, ease of maintenance work (simple replacement of track components), high hydraulic conductivity of track structure (good permeability), simplicity in design and construction, good elasticity and good damping of noise and it requires less soil stabilization. Even though ballasted track are preferable as of the above advantages but through the life history of its usage implementation it has shown significant disadvantages. To list some of them, but not limited to; degradation and fouling of ballast particles, leading to large track accumulated plastic deformation and requiring frequent and massive track maintenance work and routine checks; Reduction in hydraulic conductivity due to the clogging of voids by crushed particles and infiltrated fines from the subgrade; Pumping of subgrade clay and silt size particles to the top of ballast layer particularly in areas of saturated and soft subgrade; Emission of dust from ballast resulting from high speed trains; Poor lateral and longitudinal resistance and low speed in curves; Extremely high maintenance cost; and Traffic interruption at the time of maintenance and so on (Esveld, 2001).

2.2 Components of Ballasted Railroad Track Structure

The components of conventional track structures, ballasted track, are divided into two parts, namely the superstructure and substructure which are the top and bottom parts as shown in the figure 1 below. The superstructure refers to the top part of the track which includes the rails, fastening system, and sleepers; and the substructure includes ballast, sub-ballast, compacted subgrade and natural subgrade. The superstructure is separated from the substructure by the sleeper-ballast interface, which is the most important element that governs load distribution to the deeper track section (Selig and Waters, 1994).

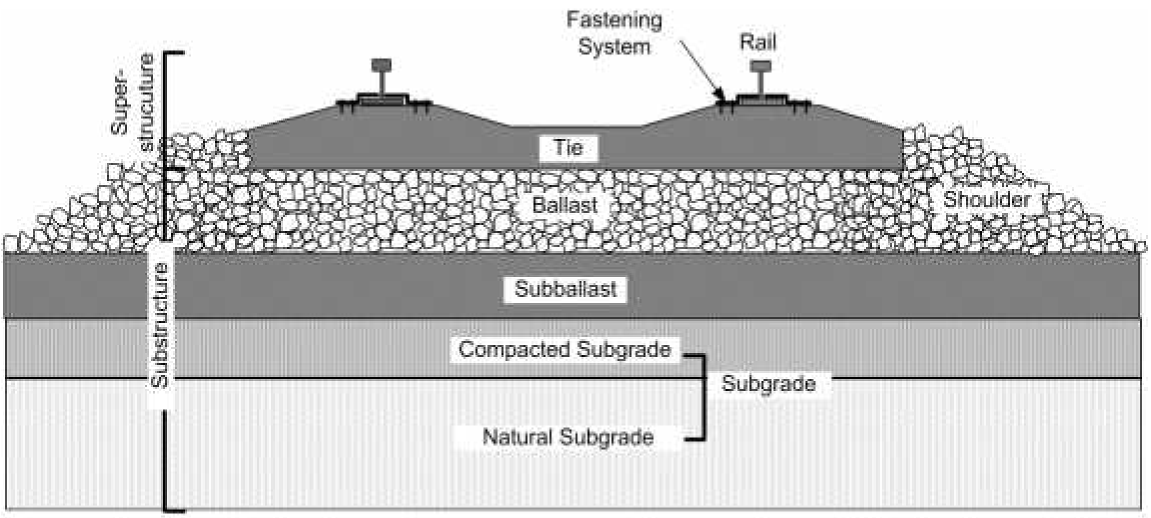


Figure 1: Typical component of superstructure and substructure in a railroad track.

Rail:- are longitudinal steel members that guide and support the train wheel loads in the vertical, lateral, and longitudinal directions and subsequently transfers the concentrated wheel loads to the supporting sleepers (timber or pre-cast concrete), which are evenly spaced along the length of track. Rails serve as electric signal conductors and ground lines for electric power trains, resist tension failure from longitudinal tensile force caused by rail temperature reduction, resist buckling from longitudinal compression force caused by rail temperature increase, resist fatigue cracking from repeated wheel loads, in switches and crossings /turnouts/set of points permit tracks to cross over each other and permit trains to switch from one track to another and moreover provides a smooth running surface and distributes accelerating and braking forces by means of adhesion. Rail properties considered in choosing the size and type of rail are: wear, hardness, ductility and rail straightness (Esveld, 2001).

Fastening System: - this fastening system includes any device or system of components used to fasten the rail to the sleeper or other support. The important functions of fastenings according to (Selig and Waters, 1994) are to retain the rail against the sleeper and resist vertical, longitudinal, lateral and overturning movements of the rail. In addition they connect sections of rail to permit safe and smooth train operation. (Esveld, 2001) states that the choice of fastening is greatly depend on the properties and structure of the sleeper. Elastic fastenings which are widely used have four primary components, which are clip, anchor, rail-pad and insulator, and are designed to perform a specific function within the fastening system according to (Gutierrez et al, 2010).

Sleeper: - is part of track superstructure which provides a resilient, even and flat platform for holding the rails, and form the basis of a rail fastening system. They are laid on top of the compacted ballast layer in a specific distance apart which is called gauge. During the passage of trains, the sleepers receive concentrated vertical, lateral and longitudinal forces from the rails, and distributed to wider area of ballast to decrease the stress at the sleeper/ballast interface to an acceptable level. The parameters used to select the preferred sleeper material include life-cycle costs, cross sleeper spacing and design methodology, rail fastening systems, cost per sleeper and number of sleepers per mile. Sleeper spacing affects rail flexural stress, compressive stress on ballast and roadbed, lateral resistance of the track structure and the flexural stress in the sleeper themselves (Esveld, 2001). According to AREMA Sec. 4.3.2.1 (2009), the recommended practices of using center-to-center spacing's of sleepers is between 510mm and 760mm, between 236cm and 274cm in length and between 20cm and 33cm in width at their bottom surface between 150mm and 250mm in depth intended for track designs. Use of longer, wider, or stiffer sleepers increases the sleeper-to-ballast bearing.

Subballast: - this is the layer of aggregates placed between the ballast layer and the subgrade. The sub-ballast layer is compacted to a much higher stiffness than the natural soil formation, such that the load distribution to the underlying subgrade is significantly reduced as well as being uniform. Where there is no subballast or where poorly designed subballast is used, saturated subgrade clay and silt-size particles can become slurred or liquefied with infiltrated water. The slurred soil may subsequently pump upwards to foul the ballast under high cyclic loading, a phenomenon commonly known as clay pumping. The main functions of the sub-ballast have been elucidated by (Selig and Waters, 1994) are reducing the traffic induced stress at the bottom of the ballast layer to a tolerable level for the top of subgrade, extending the subgrade frost protection, preventing upward migration of fine material emanating from the subgrade, preventing subgrade attrition by ballast and shedding water, i.e., intercepts water coming from the ballast and directs it away from the subgrade to ditches at either side of the track. Requirements for crushed rock aggregate of subballast materials are: maximum grain size suited for equalizing the stress distribution; fairly broadly graded grain size distribution enabling good compatibility and to fulfill filter requirements; lowest possible fines content; high impact strength; high abrasion strength; lowest possible susceptibility to chemical and frost weathering; cubic, sharp-edged grain shape; high grain surface roughness; and high water permeability and low water retention of fines separating from material (Lim, 2004). The recommended minimum subballast section depth shall be taken as 150 mm from experience of AREMA and recommendation of researchers to reduce the depth of ballast material as a result this intend reducing cost of the track.

Subgrade (Compacted and Natural):- the railroad subgrade is the load-bearing layer of a track structure, either compacted natural ground or an imported fill embankment, which provides a permanent way to support the track bed (ballast and sub-ballast layers). This layer must have sufficient bearing capacity, provide good drainage and yield a tolerably smooth settlement in order to prolong track serviceability under specific operating and climatic conditions (Kaewunruen and Remennikov, 2007). The main functions of subgrade according to (Selig T, 2004) are; to provide a stable platform to construct the track, limit progressive settlement from repeated traffic loading, limit consolidation settlement, prevent massive slope failure, and restrict swelling or shrinking from water content change. Subgrade failure which usually affect its performance are; over stressed conditions, inadequate compaction or excessive moisture content of the filling material, natural conditions such as weak subgrade soil (silt and clay), high ground water tables and erosion or sliding of embankment. For the subgrade to serve as a stable platform these failure types must be avoided and the most commonly used remedial measures, which are considered as the most economical, are to increase the ballast thickness (ballast +subballast) to reduce subgrade stresses (Radampola, 2006).

2.3 Railroad Ballasts

Railroad ballast layer, the upper stratum of the substructure which supports the rails and sleeper, is one of the most important components in the railroad track infrastructure (Aursudkij, 2007). Essentially, the term 'ballast' used in railroad engineering means coarse aggregates placed above sub ballast (finer grained) to act as a load bearing platform to support the track superstructure. Ballast serves two essential roles in rail substructure, to distribute loads from the track into the lower substructure layers and to maintain drainage. It is usually composed of quarried rock aggregates originating from high quality igneous or metamorphic rock quarries. Throughout the life of railroad construction hard crushed angular stones and rock aggregates having a uniform gradation and free of dust have been considered as acceptable ballast materials (Selig and Waters, 1994). The source of ballast (parent rock) varies from country to country depending on the quality and availability of rock, environmental regulations, and economic considerations. No universal specification of ballast are used throughout the world for its index characteristics such as size, shape, hardness, friction, texture, abrasion resistance and mineral composition that will provide the optimum track performance under all types of loading and subsoil behavior. And a wide variety of materials (e.g. basalt, limestone, granite, dolomite, and quartzite) are used as ballast throughout the world. As a component of railroad track substructure, the ballast layer can be classified in four zones according to (Selig T, 2004):

Crib**: -** ballast confined between the sleepers;
Shoulder: - ballast material beyond the sleeper ends down to the bottom of ballast layer;
Top ballast: - the upper portion of load bearing layer which is disturbed by tamping;
Bottom ballast: - the lower portion of supporting ballast layer which is not disturbed by tamping, and which is generally the most fouled portion.

To provide longitudinal stability to the track, ballast layer is filled in the cribs to the top of the sleepers as well as to provide lateral stability to the track, ballast shoulders are formed on sleeper ends to a typical width of 300-600mm depending on the type of track. For track with continuous welded rails track shoulders are heaped 125mm above the sleeper top level to prevent buckling of track. To increase the lateral resistance of track a technique called ballast gluing is used on the British Rail. Approved glue materials are used to bind the stones together at their contact points. To increase lateral stability the gluing is carried out only on shoulder ballast. The depth of gluing is typically 200mm and width is 300mm (Profillidis, 1995).

Ballasts were selected as a structural part of railroad tracks due to their physical/mechanical and chemical properties which serves in; Providing a stable and uniform load-bearing platform for sleepers; Transmitting high imposed stress at the sleeper/ballast interface to the subgrade layer at a reduced and acceptable stress level; Imparting acceptable stability to the sleepers against vertical, longitudinal and lateral forces generated by typical train speeds; Inspiring required degree of elasticity and dynamic resiliency for the entire track under dynamic train loading; Providing sufficient permeability for drainage; Inhibiting growth of weeds, absorbing noise and energy (Jeffs et al, 1989).

The chosen type of ballast material usually depends on the local availability in addition to their ability of resisting vertical, lateral, and longitudinal forces applied by trains through sleepers and providing resiliency and absorption of energy for the track (Aursudkij, 2007). The best choice of material will not necessarily be the highest quality material or the material that has the lowest delivered cost but it is a material which includes cost effective choice considering traffic, environmental conditions, and ease of deliverability to the site (Selig and Cantrell, 2001).

2.3.1 Characteristics of Railroad Ballasts

A) Constitutive Characteristics of Railroad Ballast Particles: - the mechanical characteristics of individual particles significantly influence the behavior of ballast. In the following section, various characteristics of individual grains and their influence on the mechanical behavior of ballast are discussed.

Particle size: - typically, the size of ballast grains varies in the range of 25mm–63mm in diameter (ASTM D6913). The larger particles below 63mm stabilize the track and the smaller particles above 25mm reduce the contact forces between particles and minimize breakage. Particle breakage in fines less than 25mm results to poor drainage and larger sizes above 63mm reduces the angle of internal friction. So the size of particles should not be too small and neither is too large. Under a repeated cyclic loading ballast particles breaks to a smaller fines below 25mm which will clog the ballast and reduce, in the longer term, its drainage properties (Bonnett, 2005).

Particle shape: - angularity increases frictional interlock between grains which increases the shear strength of the ballast layer. Angular aggregates give less settlement than rounded aggregates. The disadvantages of increased flakiness (extent of elongated, thin and flat particles) appear to be increased abrasion and breakage, increased permanent strain accumulation under repeated load and decrease stiffness. And he stated that cuboidal is the best shape for high quality ballast. Breakage of particle edge transforms to rounded type of ballasts under repeated movement, relocation and contact force of particle under long term cyclic loadings. So stabilizing of particle to cease relocation and movement will reduce particle edge breakage which retains their performance for long period of time (Jeffs, 1987).

Particle crushing strength: - individual particle crushing strength is an important factor governing particle degradation, including grain splitting and breakage of sharp corner under high and cyclic loadings. Particle crushing strength primarily depends upon the strength of the parent rock, grain geometry, the loading point and loading direction. Stabilization of particles with polyurethane transforms to a material with elastic coverage which becomes hard to split into parts and improves the crushing strength and particle breakage (Keene et al, 2012).

Abrasion of particles: - abrasion is a phenomenon where very small particles disintegrate from the grain surface, and this is independent of the stress level. Abrasion takes place in granular materials when particles slip or roll over each other during shear deformation which can occur even at low stress levels. Grain breakage may be absent if the stress level is low compared to particle strength, however, grain abrasion will continue at any stress level (Nakata et al, 2001).

B) Bulk characteristics of Railroad Ballast Particles: - the overall characteristics of the granular mass that govern ballast behavior include particle size distribution (PSD), void ratio (or density), and the degree of saturation. These characteristics are discussed in the following section.

Particle size distribution: - the distribution of ballast particles plays a significant role in the strength, deformation, degradation, stability, safety and drainage of tracks. A specified ballast gradation at first should satisfy the objective of higher shear strength to provide increased stability and minimal track deformation. This can be achieved by specifying well graded ballast. And secondly it should have high permeability to provide adequate drainage, hence readily dissipating excess pore water pressures and increasing the effective stress and this can be insured by specifying uniformly graded ballast. These two objectives are contradictory in terms of required particle size distribution and the optimum ballast gradation needs a balance between the uniform and broad (well) gradation. Uniform gradation provided a higher stiffness compared to well-graded aggregates and well-graded ballast gives lower settlement compared to uniform graded ballast (Indraratna et al, 2005). The requirement of optimum particle size distribution of ballast as a balance between a very uniform aggregate which will have a higher percentage of voids and larger voids but lower strength and well graded aggregate which will have less voids but higher strength (Cope, 1993).

Void ratio and density:- It has been well established that aggregates having a lower initial void ratio (i.e. higher initial density) are stronger in shear and generate a smaller settlement than aggregates with a higher initial void ratio (i.e. lower initial density). Track stability can be significantly improved by increasing the bulk density of the ballast bed by further compaction or by using well-graded aggregates. However, care should be given to a higher compaction which also increases the risk of particle breakage contributing a reduction in drainage characteristics (Indraratna et al, 2005).

Degree of saturation: - Ballast response to external mechanical forces is adversely affected by an increased degree of saturation. Water influences track settlement and particle breakage and also leads to traffic problems. Water entering micro fissures at the contact points between particles increases local stress and leads to increased particle breakage (Indraratna et al, 1998). They also conducted one-dimensional compression tests to investigate the effects of saturation on the deformation and degradation of ballast. They observed a sudden increase in ballast settlement by about 2.6mm due to sudden flooding, and reported a further increase in settlement with time (creep) under saturated conditions. They also concluded that saturation increased settlement by about 40% of that of dry ballast.

2.3.2 Ballasted Railroad Track Loads and Their Transfer Mechanism

The loads imposed on the track structure can be classified as either mechanical or thermal and they are applied to the track structure in the form of repeated vertical, lateral and longitudinal forces resulting from traffic and changing temperatures. Lateral and longitudinal forces are more complex and harder to predict than vertical forces, which act perpendicular to the plane of the rails. Within this thesis only vertical forces resulting from traffic wheel loadings are considered. Vertical loads applied to the track from moving trains are a combination of a static load and a dynamic component. The static wheel load is the dead weight of the train divided by the number of wheels while the dynamic component is caused by interactions between the wheels and the rails and is a function of the track, vehicle, and train characteristics, such as track irregularities and train speed (Selig and Waters, 1994).

In order to analyze and design a ballasted railroad track structure, the type and magnitude of loads that may be imposed during its lifetime must be quantified. The loads are exerted by the standing or running trains (wheel-rail-sleeper interactions), and are a quasi-static complex combination of ‘moving’ static loads and dynamic forces. The requirements for the bearing strength and overall quality of the track depend largely on the vertical load per axle which determines the required strength of the track, tonnage borne as the sum of the axle loads which determines the deterioration of track quality, such as, increase in geometrical deviations, increase in rail fractures, and rail wear, alerts an indication for maintenance and renewal needed, and the running speed which determines the dynamic load of horizontal and vertical track geometry (Esveld, 2001). In order to understand the damage mechanism of the track and the deterioration of the track geometry, it is necessary to recognize then all the forces to the railroad track from a train running above it and the responses made to these forces. It is also important to fully understand the causes of these induced forces and their transfer mechanism in order to be able to minimize or remove them from the track and therefore extend the life of the track asset. So that in order to effectively design the track substructure, it is essential to know the magnitude of sleeper/ballast contact stress and the distribution of stresses with depth through the ballast, sub-ballast and subgrade layers. The ballast thickness required for a track structure should depend on maximum stress intensity at the sleeper/ballast interface, acceptable bearing pressure of the underlying layer (subballast or subgrade) and stress distribution within the ballast body. Typical distribution of wheel load to the rails, sleepers, ballast, subballast and subgrade, is shown in figure 2 below (Selig and Water, 1994). The vertical stresses on the top of ballast surface and on the formation which are due to wheel loads will be considered as the determining stresses for the load-bearing capacity of the layer system and the maximum permissible sleeper/ballast contact stress can be taken in the vicinity of 500kPa. Generally the distribution of the contact pressure between sleeper/ballast in rail track is very erratic (liable to unpredicted change) but for the purpose of design the contact pressure between them is assumed to be uniform and simplified by (Esveld, 2001);

$$\sigma_b = \left(\frac{R_d}{BL}\right) * F_2 \le \sigma_h = 0.5Mpa$$ (Allowable stress)……………………….**Equation 1**

Where σ_b- maximum stress at the top surface of the ballast , F_2 – factor depending on the sleeper type and track maintenance, B – width of sleeper, L – effective length of sleeper supporting the rail seat load.

$$R_d = \gamma * (1 + \alpha) * \frac{P}{2}$$……………………………………………………...**Equation 2**

Where R_d - is the maximum rail seat load, P-axle load, $\gamma = 0.48$ factor that contains the maximum wheel load distribution on sleeper, $\alpha =$ integrated dynamic load factor, and 1.5 for general track 1.0 for heavy track.

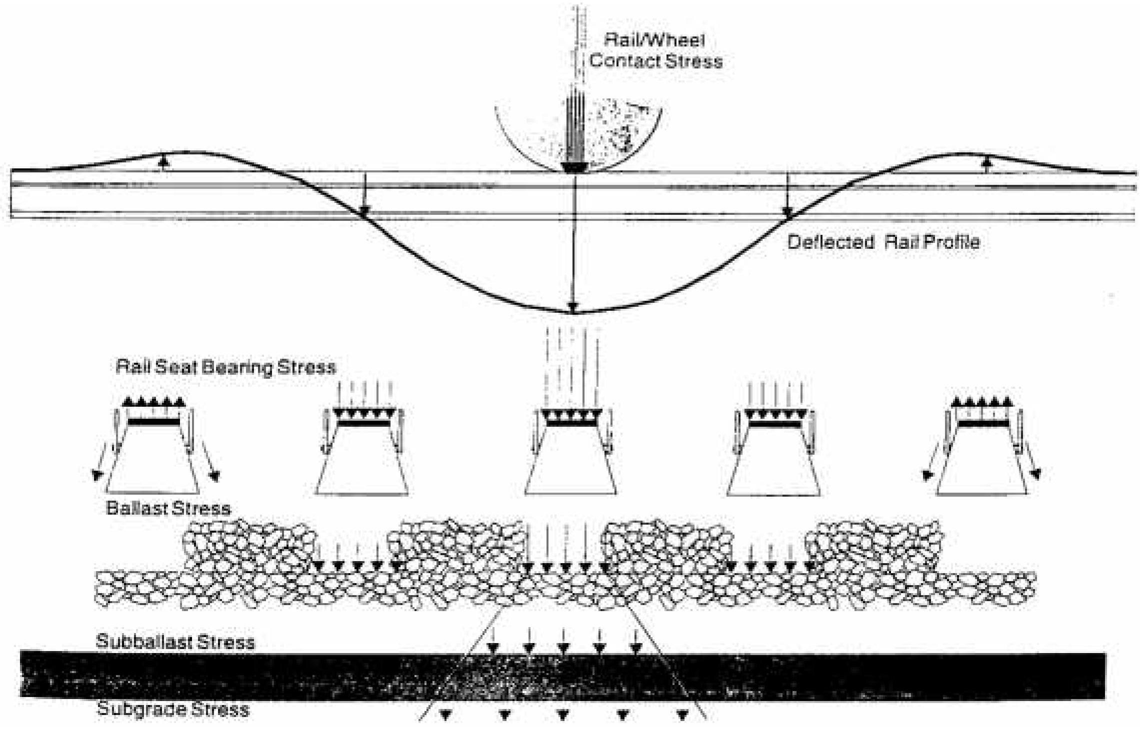


Figure 2 Ballasted railroad stress distribution method and track deflection profile.

2.3.3 Causes of Railroad Ballasts Mechanical Behavior Failure

Ballast particles may fracture or/and diminish in volume due to abrasive wear at points in contact with each other, i.e. originally cornered stones become rounded, thus occupying less space. And consequently the continued volume reduction, i.e. densification of the ballast, causes particle rearrangement or relocation and leads ballast particles to sink into the sub-ballast. Although any material that clogs the voids of the ballast could be considered as fouling content, sources of fouling can be from outside of ballast layer, from underneath the ballast layer, and from the ballast layer break-down. A ballast structure is said to be seriously fouled (not functional) if the fouling index is greater than 25% and moisture content between $5*10^{-6}$m/s to $1.5*10^{-3}$m/s. Examples of fouling content coming from outside and underneath the ballast layer can be coal dust spilled from coal freight trains and soil intrusion from subgrade, respectively. Fouling content from breakdown of ballast layer itself, on the other hand, is produced from powdering of aggregates due to abrasion and degradation. Among these three sources, ballast layer break-down was identified as the primary source that creates more than 70% of the fouled material in the ballast (Selig and Waters, 1994).

Generally ballasts should be designed to withstand axial static and dynamic pressure and large cyclic loading to provide protection against both progressive volume change (excessive plastic deformation) and progressive shear strain. According to his study, under cyclic wheel loading causing lateral plastic deformation (lateral displacement) occurs due to particle rearrangement to a more dense packing and particle breakage with the smaller particles moving in to voids of the larger particles. Lateral stability is accounted as a function of vertical track loading and longitudinal forces which is merely a behavior depending on the level of compactness and consolidation. In addition, under these loadings causing vertical plastic deformation (differential settlement) occurs because the vertical stress in the layers in the loaded state is greater than the horizontal stress. Furthermore the continuous degradation process causes the originally sharp angular particles into relatively less angular or semi-rounded grains, thereby reducing inter-particle friction. This reduction in frictional resistance leads to a further increase in plastic strains. The shear strain produces a tendency for horizontal spreading with accompanying vertical shortening of the layer. These shortcomings in ballast mechanical behavior are compensated for by frequent and costly maintenance operations, which disrupt traffic (Brown et al, 2007b).

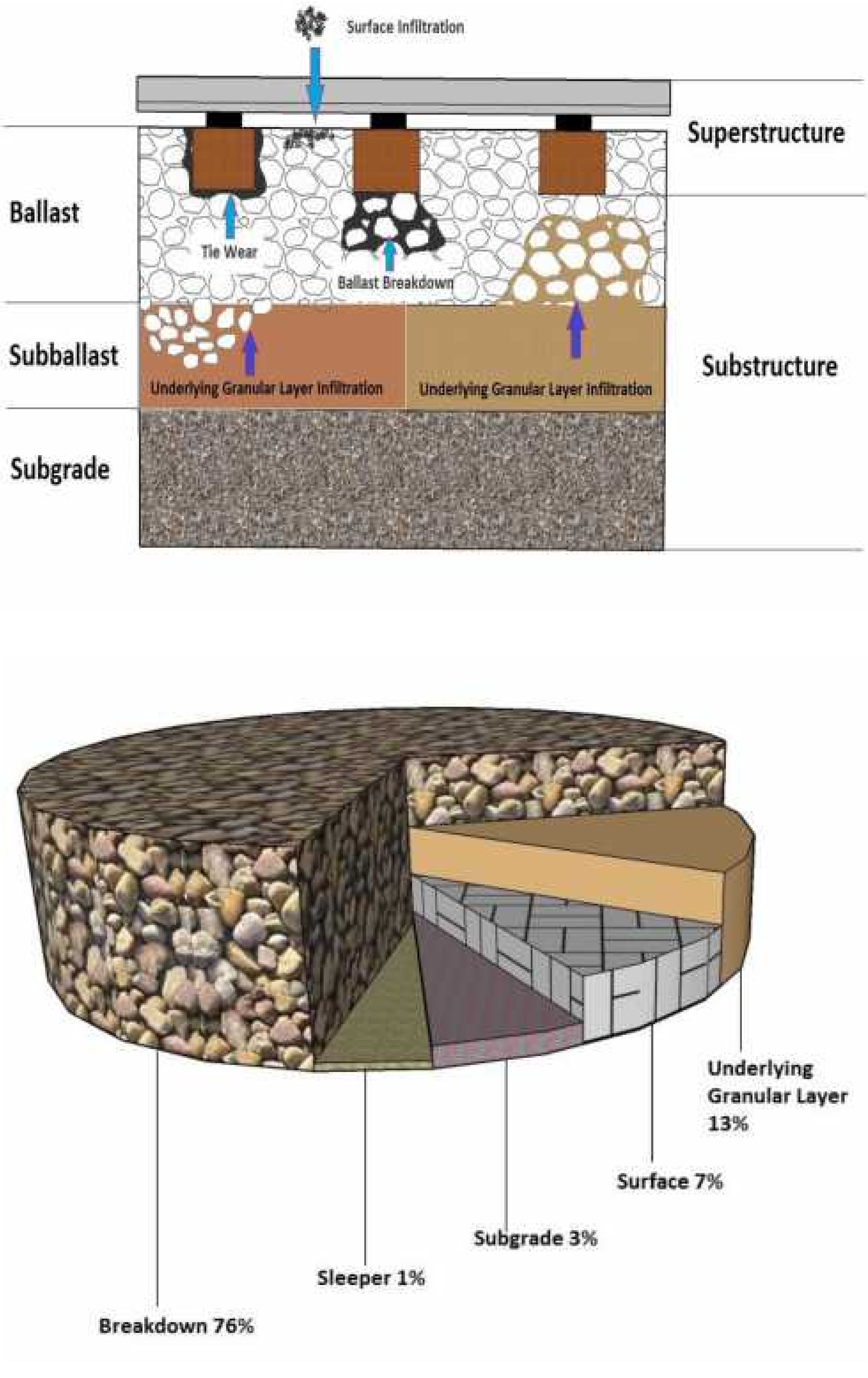


Figure 3 Different modes of ballast railroad layer failure with their respective share.

2.3.4 Railroad Ballast Maintenance Measures

Several railroad companies spend significant amount of capital to maintain the railroad track. According to the Federal Railroad Administration, between 1980 and 2008 traffic on Class 1 railroads increased 93% while the length of total track owned decreased 42%, thus leading to a large increase in traffic density (Keene et al, 2014). Despite numerous advancements in maintenance technology within the rail industry, railroads annually invest billions of dollars in maintenance activities, including the removal and replacement of ballast. Because demand for railroad transportation (freight and passenger) is increasing, new methods of rail substructure maintenance and improvement must be adopted. Most of the maintenance in the track is done mainly for geometry correction to prevent excessive dynamic loads from further deteriorating the track. The superstructure typically has much longer lifecycle than the substructure; however, the superstructure lifecycle is dependent upon substructure conditions and substructure maintenance intervals (Huang 2004).

Ballast spreads the load from underneath the sleepers to the foundation. This loading causes pressure between the contact-points of the grains which leads the ballast roadbed to deteriorate. Decreasing the average pressures on the ballast will lead to a lower rate of deterioration and consequently, the structural integrity of 'seriously fouled ballast' defined in (Selig and Waters, 1994) and minimum degradation due to particle breakage, settlement and lateral displacement explained in (Brown et al, 2007). In recent years ballast maintenance, such as stone blowing, tamping, shoulder cleaning and renewal, are routinely performed by railroads, especially on tracks serving heavy axle load unit trains, as the preventive measure of these negative consequences (Ebrahimi, 2011). Some of the maintenance measures are discussed below;

Ballast Tamping: - this is primarily the preferred maintenance application for track geometry correction. It consists of lifting the track and laterally squeezing the ballast beneath the sleeper to fill the void spaces generated by the lifting operation. The sleepers thus retain their elevated positions. However, tamping on the other hand causes degradation through abrasion and breakage of ballast aggregates. When such abrasion is combined with degradation caused by track loading, ballast layer increases it’s fouling to a level that does not permit proper drainage. Consequently, ballast layer tends to settle even earlier more than expected and requires more frequent tamping which in the long run disturbs the ballast structure generating future geometry issues and operational activities (Selig and Waters, 1994; Lim, 2004). The deterioration that tamping causes in a ballast layer is divided into two parts; inserting metal tines and squeezing caused by vibration. While former one break down aggregates in several pieces, latter one causes surface wear, which produces powdered aggregates and therefore fouled ballast (Aursudkij, 2007).

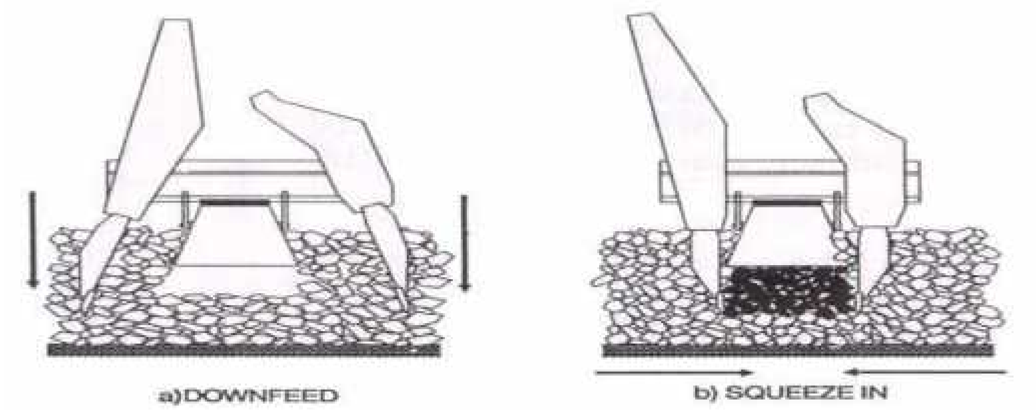


Figure 4: Tamping action (Selig & Waters, 1994).

Stone Blowing: - this is a new mechanized method of restoring railroad track to its desired line and level. The mechanized version of this process is known as 'pneumatic ballast injection' or 'stone blowing'. The stone blowing machine lifts the sleeper and blows a predetermined amount of small single size stones into the void beneath the sleeper to create a two layer granular foundation for each sleeper. Even though stone blowing helps preventing some settlement occurring by reducing the ballast disturbance, however at critical track assets that are highly loaded, such as switch & crossings, ballast movement is inevitable (Anderson et al, 2001).

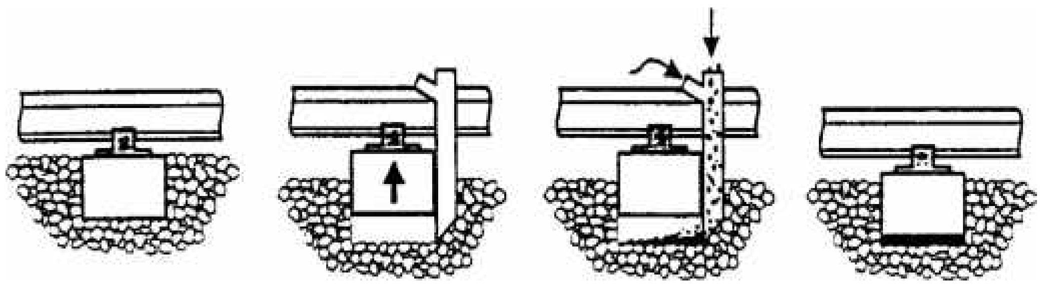


Figure 5 Operational steps of ballast maintenance by stone blowing.

Ballast renewal: - As mentioned above, when ballast gets excessively fouled (beyond a threshold value), its function is impaired even after using other maintenance techniques (e.g. tamping or stone blowing). In that case, the contaminated ballast must be cleaned or replaced by fresh ballast. When ballast becomes excessively dirty, it may need to be totally removed rather than on-track cleaning and then replaced with fresh ballast. However fouled ballast removal and ballast resurfacing processes can be disruptive to railroad traffic, because it necessitates efficient fouled ballast removal, separation, cleaning, and resurfacing. The use of this operations leads to traffic interruption, transportation and delivery costs, and environmental impacts. To minimize further quarrying for fresh ballast, preserve the environment, and most importantly, to minimize the track maintenance, ballast performance improvement measures should be considered in the time of design and construction (Becker and Patrick, 2005).

2.3.5 Stabilization of Railroad Ballast Using Polyurethanes

Different railroad companies had done extensive research and development to improve railroad track performance and they brought different mitigation measure which helps in continues and safe operation in addition to minimizing closure of the line for maintenance. To list some of the improvement measures emerged, but not limited too; they use a heavier rail-profile which spreads the load over more ties by decreasing the distance between the sleepers, increase the bearing surface of the sleepers themselves by making them longer or broader so that stresses transmitted to ballast layer will be reduces, laying geo-synthetic materials under subballast layer, replacing the whole track with slab track technology and stabilizing ballasts using polyurethanes (Keene et al, 2012, Kennedy, 2009). Among all the improvement measures, this thesis focuses on polyurethane stabilization.

Otto Bayer is known as the inceptor of the polyurethane technology with his invention of the diisocyanate (polymeric isocyanate) and poly-addition process in 1937 at Bayer laboratories. Polyurethanes are polymer materials whose physical properties can be changed in wide ranges by engineering their components. This versatility makes them replaceable for materials as soft as rubber to materials as hard as metals. Polyurethane materials can be found in the forms of foams, coatings, adhesives and sealants, and elastomers as well. The need of the replacement of rubber materials in the Second World War led polyurethane technology to grow. Polyurethane market especially started to grow in 1970's with the involvement of large companies. Today, polyurethane technology can be found in many markets in the world (Prisacariu, 2011).

Polyurethane materials are hydrophobic polymers formed in an exothermic chemical reaction of specific chemical components that lead to a product designed to be either foamed or compact and soft (cushiony), semi-rigid (flexible), or rigid (stiff). The chemical mix consists of molecules containing two or more isocyanate groups and polyol molecules containing two or more hydroxyl groups. The polyols involved in the formation of polyurethane are usually either polyether or polyester, which are typical polymers used in many manufactured products. The isocyanates are responsible for the highly reactive process that takes place, but selection from the wide varieties of polyols available dictates the resulting polyurethane. Each compound involved in the reaction can be adjusted so that variation in the exothermic reaction and physical outcome can be targeted (Randall and Lee, 2002).

A small number of investigations have been conducted concerning the use of polyurethane in ballast layer stabilization for rail infrastructure. The polyurethane reinforcement was considered over several alternatives due to problematic geotechnical conditions and potential loss in revenue due to track closure/reconstruction (Kennedy et al. 2009). Concerns over constructing a concrete slab-track involved potential water pressure developing underneath the slab under cyclic loading conditions and creating a foundation transition, which can be problematic at bridge approaches. Concrete pile installation would have come at high cost and generated foundation transition problems (Woodward et al. 2007). Three examples of polyurethane materials used for ballast reinforcement are RPF (Rigid-Polyurethane-Foam), Elastotrack® and XiTRACK™ developed by BAYER MATERIAL SCENCE, BASF and DOW chemical companies, respectively (Keene et al, 2012, BASF, 2012; Dow, 2012).

Ballast Stabilization Using Rigid-Foam-Polyurethane (RPF 486STAR-4 BD)

RPF is thermo-set polyurethane-resin foam synthesized using the reaction of two liquid components, polyester or polyether polyol and an organic poly-isocyanate, which are proportionately mixed in the presence of a catalyst. The foam structure is the result of gas bubbles formed during the polyurethane polymerization process, known as ‘blowing’. Gas bubble formation is the result of introducing a chemical ingredient known as a ‘blowing agent’. The early stages of the reaction called cream phase consist of foaming and lead to the gel phase where the mix is no longer liquid after it has been initiated within 5seconds. Considerable material expansion occurs during the cream phase, which typically lasts 30sec. Transition into the gel phase is identified when the foam begins sticking to objects. The transition from gel to tack-free can be characterized as a molten resin or foam flow which typically lasts less that 30sec. Expansion of the material continues into the tack-free phase, which begins when the foam is no longer tacky (i.e, sticky) to the touch. From initialization of the tack-free phase, rate of expansion lessens and decays until expansion has reached the maximum amount, at which point the material is considered at the end-of-rise phase. End-of-rise occurs up to 60–90sec after mixing (Szycher, 1999). Results of RPF ballast stabilization studied by **(keene et al, 2012)** are discussed below.

Figure 6: Front and section view of RPF stabilized ballast aggregates (PSB).

<u>Plastic Deformation</u>: - regarding plastic deformational behavior of PSB in compression, PSB cylindrical specimens were tested at σ_d of 300, 350, 375, and 400kPa using a cyclic triaxial method where minimal accumulation of plastic strain, ε_P, was observed over 200,000 loading repetitions at a representative state of stress (Ebrahimi, 2011). Specimens tested up to 500,000 loading repetitions had a marginal increase in plastic strain. Over the first 200,000 loading repetitions, PSB plastic strain (ε_P=0.22%) was far less than clean ballast (ε_P=0.96%). As the range of σ_d from 300 to 400kPa was applied, the ε_P of PSB over 200,000 cycles ranged from 0.22% to 1.3%. The increase in ε_P of PSB from 0.22% to 1.3%, when increasing the deviator stress from 300 to 400kPa is a significant increase. However, the ε_P in PSB (1.2%) was only marginally higher than clean ballast (ε_P= 0.96%) tested at 300kPa. Therefore, track substructure materials (e.g.,

clean ballast) when stabilized with RPF have superior resistance to accumulation of plastic strain compared to untreated substructure materials and is thus an applicable tool for maintaining track geometry and preventing ballast layer settlement.

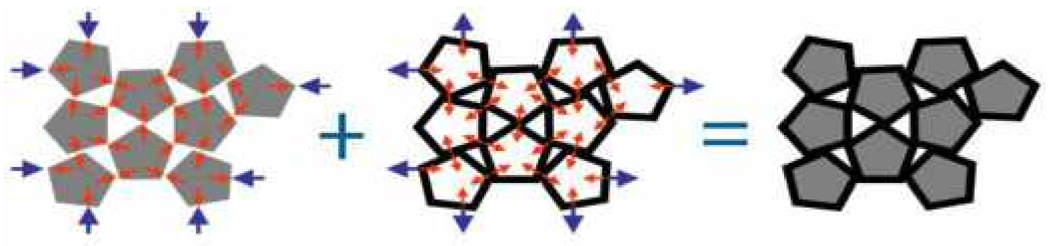
Elastic Deformation and Resilient modulus: - From the cyclic triaxial compression tests conducted on PSB and clean ballast in this study, the elastic strain and resilient modulus was calculated from measurements taken throughout the test. When comparing PSB and clean ballast at the representative state of stress defined in (Ebrahimi, 2011), the elastic strain of clean ballast decreased 26% over 200,000 cycles, whereas the PSB specimens decreased only 5-9%. Therefore, Over the 200,000 loading cycles, PSB resisted change in elastic strain. The resistance to change in elastic strain is an indicator that the material retains its elastic properties despite numerous loading repetitions. However, the resilient and Young's modulus of PSB (average of 110MPa and 90MPa, respectively) is less than the resilient modulus of clean ballast (250MPa) at the representative state of stress defined in (Ebrahimi, 2011).

Flexural Strength: - results of flexural strength and fatigue tests clearly reveal that appreciable bonding and tensile capacity are present in PSB. Flexural strength of PSB (AVG 938kPa) is similar to that of Cement-stabilized soils (AVG 1,030kPa); however, flexural modulus of PSB (274MPa) is much lower than cement-stabilized soils (AVG 13,800MPa). This pattern between the two materials is similar when comparing PSB to other materials (i.e., clean ballast, concrete, asphalt, etc.); therefore, use care must be taken when designing use of PSB in applications where stiffness (i.e., functionality) controls design rather than overall strength (i.e., capacity).

Compressive Strength: - the average strength of the PSB was 2.60MPa with a coefficient of variation (COV) of 6.85% and average ρ_{PSB} was 1,674kg/m3 with COV of 4.32%. Average ballast compressive strength, at 100kPa confining pressure, is 594kPa or 77% less than PSB. The average Young's modulus determined from the UCS tests was 89.7MPa which is less than the ballast (270Mpa). Because PSB has lower compressive modulus than clean ballast, numerical modeling was conducted and confirmed that there would be minimal difference in elastic strains of the substructure from PSB formation in the ballast layer. The functionality of PSB that is used in rail infrastructure would be driven by PSB compressive modulus. However, this study shows that, for typical PSB modulus, the impact could be minimal.

Ballast Stabilization using XiTRACK Polyurethane

XiTRACK is a viscous-elastic polymer which when poured onto ballast forms an in-situ polymer and ballast geo-composite. The polymer cures as it penetrates up to a specified depth into the ballast to form a 3-dimensional matrix or 'reinforcing cage'. The polymer is applied in-situ by mixing two chemical components through a mixing lance. The polymer typically cures within 10 to 15 seconds. It achieves 50% of its designed strength within minutes and reaches 90% of its strength within 1 hour. The XiTRACK technology has several key benefits. The well-known benefits are presented below; Very Quick Setting**:-** replacement of any ballast on top of the XiTRACK layer can occur immediately after application of the polymer as it sets in seconds. Under normal conditions XiTRACK can be loaded by site traffic, including vibro-plates, 15 minutes after polymer application and by rolling stock 30 minutes after polymer application; Long Service Life:- the long life characteristics of polyurethanes are well documented. The design is prepared such that the material operates within its yield strength; Free Draining:- approximately 30% of the void structure will be occupied by the XiTRACK polyurethane in treated ballast, leaving the remainder open for drainage; Scheme Cost Benefits:- XiTRACK is a value engineered solution that will produce life cycle cost benefits. Savings are possible through much reduced compensation payments to Train Operating Companies and Freight Operating Companies as a direct result of its very rapid installation and curing time leading to smaller blockades and disruptive possessions. In addition as it is an engineered 'solution' to recurring defects it will help reduce spend on future maintenance; Can be applied at any time of the year; and Energy-absorbing polymer network; A robust system that can be applied in a wide range of climatic conditions (Balfour Beatty Rail, 2015). Breakdown of the polymer, is unlikely, however if breakdown occurs it leads to a conventional ballasted 'state' and drainage is still maintained. Bonding of the polymer to the ballast will occur but this is not critical, as the primary function of the treatment is to generate polymer-reinforcing elements at every level in the ballast matrix, both vertically and horizontally, essentially encapsulating the ballast. Bonding of the polymer, to the ballast, is not therefore required for the technique to work, which is the fundamental difference with ballast gluing where the system's inherent strength comes from the cohesive bond.



Compressive Strength of Ballast   Tensile Strength of Polymer   Inherent Geo-composite Strength

Figure 7: Characteristic of XiTRACK stabilized ballast and their mechanical nature

Research results on stabilization of ballasts using XiTRACK are discussed below.

(Kennedy et al, 2009) conducted full-scale model tests to determine the deformational characteristics of the ballast layer with and without XiTRACK polyurethane. The full-scale model consisted of a superstructure system of several rails and sleepers and substructure layer with a subgrade and a ballast layer. They were thought that subgrade stiffness and applied vertical load are two of the most significant parameters that influence track substructure deterioration. In their study, 500,000 loading repetitions which simulate railroad traffic loading conditions was applied to full-scale model to measure plastic strain of ballast. The results showed the settlement of the ballast layer in the model was 92-95% less for the stabilized full-scale model substructure than the untreated substructure modeled at their facility. And GRAFT tests demonstrated that XiTRACK stabilization improved the stiffness of un-stabilized track by between 55 and 65% within subgrade tangent modulus of 25MPa. The settlement for untreated ballast is as high as 50mm after only 100,000 cycles whereas for XiTRACK stabilized ballast the settlement is only 6mm after 500,000 cycles. The XiTRACK sample remained fully free draining at end of the test and showed no signs of fatigue.

Figure 8 XiTRACK sample still free draining after 200,000 load Cycles

(Woodward et al, 2012) they extensively studied the XiTRACK technology for several years. In their study published in 2004, they reported a successful application of XiTRACK at turnout ballast stabilization in Bletchley Points on the West Coast Main Line of the UK rail network. The train speed and the maximum axle load on the turnout were 177km/h and 25tons, respectively. Annual track load of the turnout was approximately 30million gross tons (MGT). The stabilization was applied in the ballast layer in March 2000. They claimed that geometry corrections had to be made in Bletchly Points every 3 months before XiTRACK was applied. The last report regarding that project was by (Woodward et al, 2009) stating that no maintenance was necessary after the XiTRACK application. (Woodward et al, 2005) described the condition of track location prior to XiTRACK stabilization. They stated that ballast layer was fouled, and a complete cleaning was not possible at the time. Consequently, XiTRACK was applied into that ballast layer in fouled condition. The penetration of XiTRACK into ballast layer was successful with few predicaments even in fouled ballast. They compared measurements made with track recording vehicle (TRV) at both stabilized and un stabilized locations and concluded that stabilization decreased deformation tendency and no maintenance was necessary for almost one year. Another XiTRACK stabilization application by (Woodward et al, 2004) reported was the stabilization of track parts near the Harford bridges. The application differed from others according to the methodology used. Edge beams were constructed at both ends of the sleepers with XiTRACK stabilization placed to prevent lateral movement. Geometry corrections such as tamping would be applicable in future since ballast between the sleepers and ballast shoulder was left unbound. The construction took place in 2003 and (Woodward et al, 2005) reported in a later publication that no maintenance was necessary in the lateral direction but few maintenance applications had to be applied to correct the track vertically. One of the concerns of polymer stabilization is removal of the stabilized layer from track. They gave an example of removal application at the Bridge 159 on the West Coast Main Line in Scotland. The train speed on the line was reported as 225km/h. XiTRACK stabilization was applied 18months prior to bridge renewal in order to prevent ballast fluidization. By the time of renewal, the stabilized layer was successfully extracted within 20minutes and recycled to be used for another problematic railroad location. To summarize, even though XiTRACK after the injection prevents: (1) ballast particle breakage, (2) relocation of ballast particles, (3) friction wear of particles through reducing plastic strain and increasing strength, but, the main goal of the XiTRACK application is to create this

3-dimensional polyurethane net that surrounds ballast aggregates rather than bonding them at particle contacts. The application does not fulfill considerable amount of voids. Therefore, it does not prevent free drainage of ballast layer much more.

Figure 9: Close view of XiTrack Stabilized railroad ballast (woodward et al, 2007)

Ballast Stabilization using ELASTOTRACK Polyurethane

ELASTOTRACK is a two-component urethane cross linked composition rigid-compact type of polyurethane used to coat the ballasts. It is developed for the reinforcement and stabilization of ballast stones on railroad tracks. As defined in a technical data sheet from BASF Company, it is a liquid, cold curing and solvent less railroad ballast binder sprayed on the ballast stones to increase the rigidity of ballast track and enable stiffness adjustment. It is a material with hydro and chemical weathering resiliency. It consists of two components, isocyanate and resin. The components are mixed to create the polyurethane mixture. Gelling of the mixture occurs in about 30 minutes to 1 hour; however, the setting time can be adjusted by engineering the polyurethane components such as using an additional catalyst. The ballast particles become bound after the gelling occurs. The bonds between ballast particles create a stabilization matrix that eventually increases the strength of the ballast. In one day, ballast becomes resilient and stable. The strength of these bonds, on the other hand, continues to increase for over 28 days. ELASTOTRACK can be applied in two ways; coating ballast particles before construction or pouring it over the surface of ballast layer. Since the mixture only forms a thin coat on the surface of the aggregates, it does not clog any voids and prevent drainage. The Geo-composite exhibits many desirable properties, such as significant increases in strength, stiffness (as appropriate), good drainage, ductility, reinforces ballast stones, preventing any movement of them from the dynamic forces of passing trains, reducing structure-borne noise emissions, preventing ground erosion, protect track geometry, provides cushioning effect and improves safety and comfort (Boler, 2012).

Figure 10: Ballast with and without ELASTOTRACK polyurethanes

According to BASF company material product specification the application of this polymer has many functions to railroad track structure. To list some of them; Reinforcing function: it binds the loose stones together, preventing them from flying and pulverization of particles, which results in fortifying (making strong) of ballasts; Permeability: it provides porous structure which allows rainwater and other liquids and solvents to pass through for better drainage; Weather and chemical resistance: as an environmentally friendly solution for sustainability development, it contains over 50% renewable raw materials; Ductility: the material exhibits ductile properties which absorbs energy; Stabilizing the track: it reduces the feeling of bumpiness for passengers and provides a buffer zone for the high speed trains; Maintenance cost: the treatment inspires long-term solutions to significant reduction in future massive track maintenance and upgrading; Its application requires simple machines and easy technical skills which results in local employment development with minimum training required; Setting time: It needs minimum setting and hardening time and the fast reactivity and curing time which shorten the installation time will further bring the construction time unaffected; Prevents spill of stones/gravel which could result in accidents; Reducing maintenance cost from replacement of stones due to theft; Prevents deterioration of rails and fastening due to corrosion from contamination with acidic rain, carbon dioxide and other corrosive substances stored in dust. Thus, impacts cost to repair; Reduces stray power current if rail is electrified to ground in turn causing pre mature rusting of any steel pipelines underground within many metres of the train lines; and Excellent physical property in extreme change in temperature.

Researches on stabilization of ballasts using ELASTOTRACK are discussed below.

(Dersch et al, 2011) they conducted research on coating of ballasts via tumbling of ballast aggregates and the polyurethane mixture together. After mixing the polymer with ballasts, the mixture starts curing; this eventually creates bonds at contacts of ballast aggregates. As curing time increases, the strength of the bonds increases. Eventually, ELASTOTRACK stabilizes ballast layer in 3-dimension through chemical bonds at particle contacts. The coat layer on aggregate surface and the bonds between them keep ballast particles separated apart. The ballast aggregates could stay in the reinforcement matrix because of the polyurethane, even when they are broken. Figure 12 present broken aggregates stayed intact because of the coating and a single block survived as one piece after direct shear testing. They stated that polyurethane coating increased shear strength of ballast aggregates considerably. They mentioned that shear strength of the samples increased with longer curing time for up to 14 days. Further, they investigated fast curing performance by pouring the mixture with the addition of a catalyst over the aggregates instead of coating all the surfaces. They stated that in 6hours the shear strength of the samples increased considerably. However, in the case of 1hour curing much less shear strength gain was observed. They commented that as the liquid between particles were not cured, it did not provide enough bonding and therefore, a decreased friction between aggregates. Using a direct-shear box test, the shear strength of the stabilized ballast was measured under varying confining stresses and polyurethane curing times after 14 days. In the study, the shear strength of the treated ballast specimen was 40-60% greater than uncoated clean ballast. After each of the direct shear tests, a powdering test was conducted where the amount of breakage was measured by percent particles passing a 13-mm sieve, the stabilized ballast samples had 3-5% less breakage than untreated ballast. Therefore, they identified that polyurethane treatment greatly increases shear strength of ballast and reduces breakage of ballast particles under loading.

Figure 11: A close view of ELASTOTRACK coated ballast aggregates

Figure 12 ELASTOTRACK coated ballast aggregates stay intact even after breakage**.**

(Boler, 2012) states that shear stress is the maximum stress that a material can take to resist excessive shear deformation leading to a total failure. Failure by shear arises when a soil mass reaches a critical stress state, which is a combination of limiting shear and normal stresses. He uses Coulomb's shear strength equation described by (Terzaghi et al., 1996) to determine the shear strength of ELASTOTRACK stabilized ballasts:

$$S = C + \sigma tan\emptyset \quad \textbf{Equation 3}$$

Where S = Shear strength; σ = Normal stress on the failure plane; $\emptyset$ = Friction angle;

C = Cohesion.

He assumed that the cohesion ability of uniformly sized coarse aggregates is none; therefore, cohesion intercept should ideally be zero. However, the nonlinear nature of Mohr-Coulomb failure envelope produces such an apparent cohesion intercept. He, however, calculated the average shear strength of unbound granite aggregates and ELASTOTRACK polyurethane stabilized granite aggregates at different normal pressure 103KPa, 173KPa and 242KPa, using Mohr-Coulomb failure envelope.

Table 1: Average shear strength of unbound granite aggregates

Test material type	Cohesion, C (KPa)	Friction Angle, ǿ	Average shear strength	%increase in shear strength
Unbound granite aggregates	97.4	40.7	245.91	
Bound granite aggregates 1 day cured	201.2	29.3	298.10	18%
Bound granite aggregates 3 day cured	267.4	30.2	367.89	33%
Bound granite aggregates 7 day cured	271	34.8	391.01	37%

According to him the average shear strength polyurethane coated ballasts was 18%, 33% and 37% more than the average shear strength of unbound ballast aggregates at 1day cured, 3day cured and 7 day cured test results respectively. Grand average shear strength of EPSB was 29.3% greater than clean ballast.

CHAPTER 3 MECHANICAL BEHAVIOR OF EPSB AND CLEAN BALLAST UNDER LABORATORY TESTING

Compressive strength testing is typically used for determining strength and Young's modulus of materials. Monotonic uniaxial compression test was considered as a special case of compressive test in many researches (Ebrahimi, 2011). Cyclic uniaxial compression testing was also used for determining plastic and elastic deformational behavior of infrastructure materials commonly exposed to repetitive compressive loading. Plastic and elastic deformation of material in rail track substructure is an important aspect for determining required maintenance frequency and track life cycle. The resilient responses of materials in the track are important aspects for determining required maintenance frequency and life cycle of bound layers.

In this study, the mechanical properties of ELASTOTRACK polyurethane stabilized ballasts (EPSB) are presented by considering: the extent to which the void space of ballast is filled by the ELASTOTRACK Polyurethane (EP) and the strength and degree of bonding that occurs between the ballast particles and EP. The hydraulic conductivity, K, of ballast (K = 0.025–0.050 m/s) is much greater than that of a typical clay (K = 10^{-10} m/s), (Buzzi et al, 2010). Due to the large particle size and resulting aperture of the pore space within ballast, fluids would flow more easily through it than typical clay and thus the geometry of the ballast pore space conveniently allows injection of polyurethane. This geometry allows room for expansion of the EP and ability to meet target volume and density. In contrast, the highly porous ballast layer has the potential to inhibit low viscosity or liquid-phase (nonexpanding) polyurethanes from reaching targeted areas and having the intended effect. This chapter will present; the material development of EPSB; perform EPSB and clean ballast laboratory testing; and evaluate the results to determine the mechanical behavior of EPSB.

3.1 EPSB Constitutive Materials and Their Phase Relationships

Specimens were prepared comprising of basaltic ballast. Calculations commonly used in soil mechanics for determination of index properties and phase quantities of soils were used in this study to define the density of ballast and EPSB of the fabricated specimen. The ballast was compacted into a prefabricated mold with the intention of one specimen for clean ballast and three for EPSB prior to EP injection utilizing the compaction procedure developed in (Ebrahimi, 2011). These compaction characteristics were targeted for fabrication of each ballast layer prototype in this study. A specified weight of ballast ($W_{b\,=}$ 7.92kg) was compacted into the initial mold volume. With the specified weight, initial volume (V_b = 0.004915m^3) of the compacted ballast, dry unit weight of ballast 15.8KN/m^3 and specific gravity of solid ballasts (Gs=2.6), the void ratio (0.64) and dry density ($\rho_b = 1614 kg/m3$) were found as per the calculation.

Table 2 Material property of basaltic ballasts used in the test

Material Property	Clean Ballast
Particle size	25-63mm
Dry unit weight	15.8KN/m3
Density	1614kg/m3
Specific gravity	2.6
Liguid and Plastic limit	No
Confining stress	90KPA
Initial Volume	0.00491
Initial Weight	7.92kg

Therefore, the void space for use in EP injection quantity becomes (Ebbrahimi, 2011);

$$e = \frac{Volume\ of\ voids}{Volume\ of\ solids} \qquad \text{.......Equation 4}$$

$$Volume\ of\ voids = e * Volume\ of\ solids = 0.64 * 0.004915 = 0.003146 m3$$

Upon injection, the interaction process began and resulted in EP filling the ballast void space. After EP injection, the EPSB-1 specimen was weighed (W_{EPSB} = 9.32kg) and measurements was taken to determine the final volume and becomes (V_{EPSB} = 0.00561m3). Then the EPSB density (ρ_{EPSB}) was determined by;

$\rho_{EPSB} = \frac{W_{EPSB}}{V_{EPSB}} = \frac{8.49kg}{0.00561} = 1514kg/n\,3$……………………………………**Equation 5**

The remaining subsection demonstrates calculations for determining the quantity of each material phase within the composite. The new ballast density is found using;

$\rho_b = \frac{W_b}{V_{EPSB}} = \frac{7.92}{0.00561} = 1411.76kg/m3$……………………………………**Equation 6**

After injection, the EP weight (W_{EP}) and density (ρ_{EP}) is calculated from the following;

$W_{EP} = W_{EPSB} - W_b$**= 8.49 – 7.92 = 0.5735kg……...………………………Equation 7**

During reaction, the effects of the blowing agent cause a release of CO2 gas (Szycher, 1999). For simplicity in these calculations, the mass loss of the gas is assumed negligible. Finally, the following equations are used to calculate EP by weight and by volume;

$\%EP\ by\ weight = \frac{W_{EP}}{W_{EPSB}} = \frac{0.5735}{8.49} = 6.7\%$……………………………………**Equation 8**

$\%EP\ by\ volume = \frac{V_{EP}}{V_{EPSB}} \frac{0.000505}{0.00561} = 9\%$……………………………………**Equation 9**

For the EPSB-1 specimen, ballast was 93.3% by weight and 64% by volume; EP was 9% by volume and 6.7% by EPSB weight.

Generally the ballast and EP by weight and by volume of the entire test specimen are tabulated in table 3 below.

Table 3 Clean Ballast and EP by weight and Volume in EPSB

Sample No.	EPSB			
	Ballast by Weight	EP by weight	Ballast by Volume	EP by volume
Clean Ballast	93.30%	0	64%	0
EPSB - 1	93.30%	6.70%	64%	9.0%
EPSB - 2	93.30%	5.40%	64%	7.30%
EPSB - 3	93.30%	4.20%	64%	5.7%

3.2 Compressive Strength Laboratory Testing Methods

Compressive strength testing is typically used for determining strength and elastic modulus of materials as a reference index to verify that other mechanical properties can be confirmed in the material. Methodology from different standards was combined for testing on EPSB and clean ballast specimens. In order to compare performance consistently in the tests, all ballast samples had the same grading. Ballast sample was poured into the specimen molds until the ballast thickness reached 300mm, and the top of the ballast was then leveled by hand. The nominal dimension of the specimens for the test was 300mmx160mm x160mm. Although the dimension of the specimen sample doesn't fulfill the ASTM-D5311 guidance of 1:6 ratio, according to (keene et al, 2012) the ratio doesn't impact results. The EPSB test segments were subjected to UCS tests, which involved placement in a loading machine that compressed the specimens while measuring load and displacement. And clean ballast test were subjected to confined compressive strength with confining pressure of $\sigma_3 = 90KPa.$ The confined compression strength test for clean ballast consists of applying a confining pressure (σ_3) to a specimen that is contained within a membrane and sealed in the prepared rectangular chamber. A plunger or piston that extends through a seal in the top by rectangular plate applies the load to the test specimen through mechanical testing machine system. The specimen was initially rough at the top as it was intended to perform the test similar with the actual topography of the rail infrastructure, but the testing machine was not able to do so and accordingly the top and the bottom of the surface was covered smoothly with a mortar having mix ratio of 1:3, with consideration of AASHTO designation T-140. The stress that was distributed from the mortar to EPSB and clean ballast has taken as the compressive strength of the specimen. In the testing process ASTM D1634, standard test specimen for concrete was used. And the depth to width ratio was confirmed according to the standard $\frac{D}{W} = \frac{300}{160} = 1.875 > 1.8$. In addition according to British concrete society technical requirement the diameter to maximum aggregate size (taking top surface length as a diameter) $\frac{D}{M.Aggregate\,size} = \frac{160}{50} = 3.2 > 3$, was also satisfied. Analysis of unconfined compressive strength (σ_{UC}) was done through the equation given below;

$$\sigma_{UC} = \frac{F}{A} \qquad \textbf{Equation 10}$$

Where F is peak axial load applied and A is the area over which it is applied.

And analysis of confined compressive strength (σ_C) was done through the equation 11 given below;

$$\boldsymbol{\sigma_C = \sigma_{UC} - \sigma_3}$$ ………………………………………………………………**Equation 11**

Under the application of axial load, typical phenomenon in elastic-plastic material, initially elastic strain (ε_e) increases linearly with axial stress until reaching the yield point at about 90KN in EPSB testing, where plastic strain (ε_p) increases and the relationship to stress was no longer linear. The axial stress in clean ballast test was taken with in the application of 90KN, just to have similar comparison with the result of EPSB. Young's modulus, E, occurs within the linear region and is defined;

$$\boldsymbol{E = \frac{\sigma_a}{\varepsilon_e}}$$ ……………………………………………………………………**Equation 12**

Where σ_a is the axial stress being applied within the elastic range of the material.

3.3 Evaluation and Discussion on Laboratory Test Results

3.3.1 Compressive Strength and Young's Modulus

Compressive strength testing was conducted to measure the strength and Young's modulus to determine degree of loading and stiffness of the material respectively. The compression test was often considered as a special case of monotonic uniaxial test in many researchers (Woodward et al, 2007). Monotonic uniaxial unconfined compressive testing for EPSB and monotonic uniaxial confined compressive testing with confining pressure of 90KPa for clean ballast specimen was performed. In case of EPSB testing, at the beginning of compression tests, there was an accumulation of strain that occurs due to accumulated polyurethane in the time of percolation at the bottom of the specimen. However, for rigid cellular plastics, non-linear behavior may occur earlier in the test. For non-linear behavior and polyurethane accumulation, methodology was adopted from ASTM-D1633/34 for applying a compliance correction that allowed consistent data analysis techniques of EPSB specimens evaluated using UCS tests and this accumulation of strain is removed by applying the compliance correction (10%), where the linearly sloped line indicating the elastic range (i.e., Young's modulus) of the material is shifted to the origin. Figure 13 shows results from UCS testing without confinement of EPSB compared to monotonic uniaxial compression tests on clean ballast a confining pressures of 90KPa;

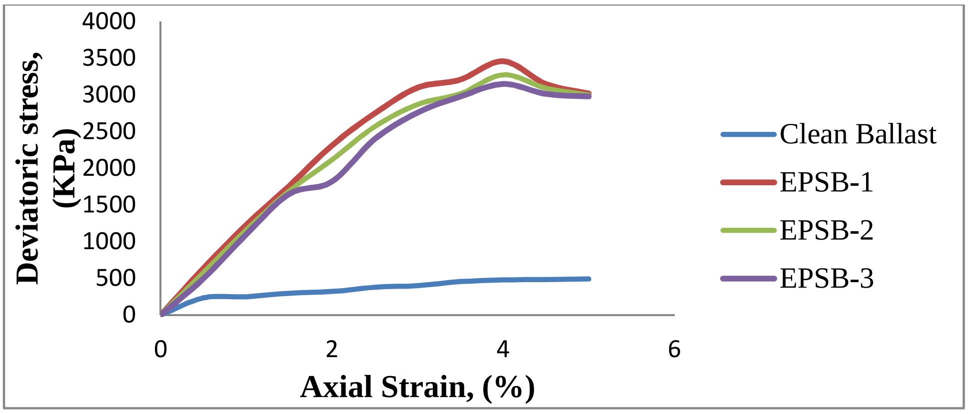


Figure 13 Unconfined monotonic uniaxial compression tests and confined monotonic uniaxial compression tests conducted on EPSB and clean ballast respectively.

Results from UCS testing without confinement are compared to monotonic uniaxial compression tests on clean ballast at confining pressures of 90KPa. In unconfined compression tests, EPSB possessed much higher ultimate strength than clean ballast as shown in figure 13. The failure mode observed during testing was a delaminating and ductile response, which is unlike that of materials with brittle attributes (i.e., glass, or acrylic). Similar to that of most soils and geo-materials, clean ballast has a non-linear stress-strain relationship as observed from monotonic uniaxial compression tests on clean ballast. The EPSB specimens exhibit linear-elastic behavior after compliance correction.

As it is shown in the figure 14 below the elastic modulus of EPSB is less than that of clean ballast under different compressive strength. The resistance to change in elastic modulus was may be due to the injection of the EP material. Elastic modulus of clean ballast, average of 250Mpa, was decreased to elastic modulus of EPSB, 90MPa. The comparison of their elastic modulus under different compressive strength is shown below

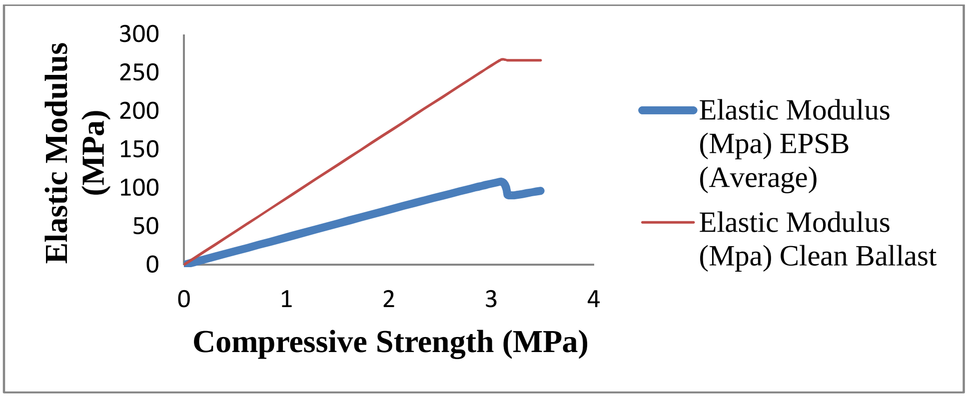


Figure 14 Young's modulus and compressive strength of EPSB and Clean Ballast

The compressive elastic response of railroad substructure with respect to density is an important attribute in evaluating track response to loading. Accordingly the young's modulus with respect to average density of clean ballast and EPSB, are as shown in figure 15 below.

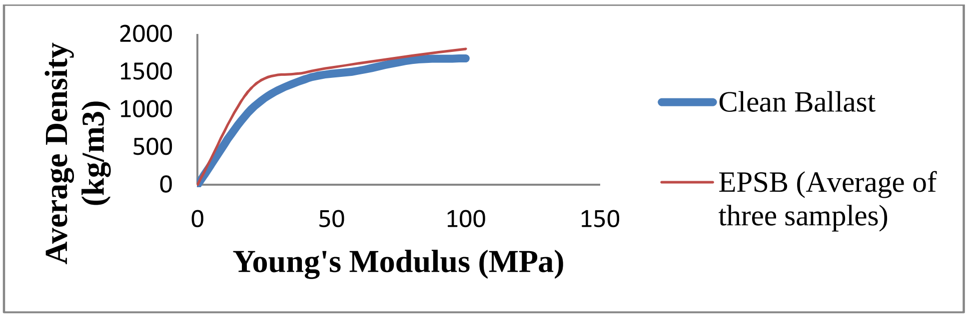


Figure 15 Density and Elastic modulus of EPSB and Clean ballast

As it was shown in the figure 15 EPSB density increased with increased Young's modulus more than clean ballast. The same behavior exists in concrete modulus compared to concrete design strength as the design strength and concrete density increase the Young's modulus increases (Grider et al. 1999). Therefore, these comparisons confirm that EPSB mechanical properties are similar to that of other bound materials (i.e., concrete, asphalt, and cement-stabilized soil) used in transportation infrastructure studies.

3.3.2 Deformational behavior and Resilient Modulus

The important aspect of track response to loading is the plastic deformational behavior of railroad substructure. The cumulative permanent plastic deformation characteristics of the ballast are a function of both the confining pressure and the cyclic deviator stress. It is universally accepted that settlement is related to the logarithm of the number of repeated load applications (Selig and Waters, 1994). This thesis has adopted the relationship presented below to determine the plastic strain of EPSB;

$\varepsilon_P = 0.82(100n - 38.2)q^2 * [1 + 0.2\log(N)]$…………………...………**Equation 13**

Where ε_P the permanent strain after *N* cycles, *n* is the initial porosity of ballasts and *q* is the compressive stress. Since the initial void ratio of ballast was e=0.64, substituting to the equation:

$\boldsymbol{n = \frac{e}{e+1} = \frac{0.64}{1+0.64} = 0.39}$……………………………………………………...**Equation 14**

(Shenton, 1974) investigated the influence of loading frequency on the accumulation of permanent strain in ballast. He found that the loading frequency does not affect the accumulation of permanent strain. But for axle load of 25ton and representative traffic quantity of 22.67MGT, the number of load cycles can be calculated as;

$\boldsymbol{N = \frac{Traffic\ quantity\ (MGT)\square 10^6}{axle\ load\ \ (ton)} = \frac{22.67*10^6}{25} = 906,800}$……………………**Equation 15**

q= 1.35Mpa, the permanent strain of EPSB according to Equation 19, it becomes;

$$\boldsymbol{\varepsilon_P = 0.82(100 \square 0.39 - 38.2) * 1.35^2 \square (1 + 0.2\log(906800)) = 1.94}$$

Accumulation of plastic strain in ballast can be attributed to two possibilities: (1) ballast particle breakage and localized rearrangement of fractured ballast particles (i.e., movement of fractured particles within or (2) frictional wear and degradation due to the interaction of fragmented ballast (Keene et al, 2012). Through similar procedures the

EPSB specimen with full confinement during EP injection had cumulative average plastic stain, ε_P, of 0.145 or 92.53% less than clean ballast (1.94), over 906,800 loading cycles. The cumulative plastic strain of EPSB and clean ballast for different volume of EP injected to the specimens are as shown in the figure 16 below. As the figure shows the volume of EP has a slight effect in arresting plastic strain in EPSB. So procedures should be followed to standardize the volume needed in the time of injection.

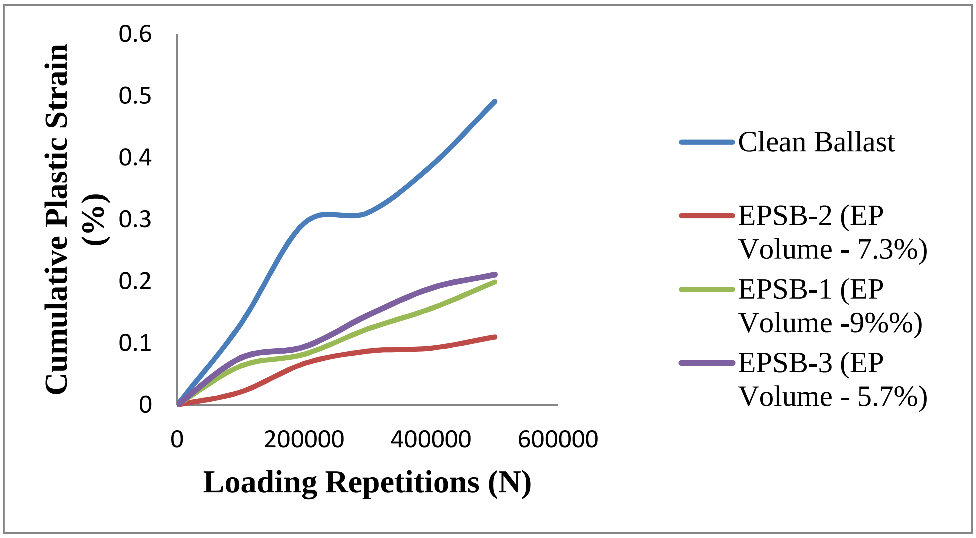


Figure 16 Cumulative Plastic strain and loading repetitions

This thesis initially determines the resilient modulus of EPSB using the correlation equation given by (keene et al, 2012). Accordingly the density and percent EP by volume influenced plastic deformational behavior of rigid polyurethane foam stabilized ballasts. As shown in the figure 17 below, the average resilient modulus of EPSB (153.34MPa) was less than the average resilient modulus of clean ballast (250MPa). The influence of these material properties on resilient modulus of EPSB was adopted from correlation relation given by the equation 22 below;

$$M_r = 1.46[\gamma_{EPSB} * (1 - \%EP by\ weight)] - 1909 \qquad \textbf{Equation 16}$$

$$M_r = 1.46[1514kg/m3 * (1 - 0.067)] - 1909 = 153.34MP$$

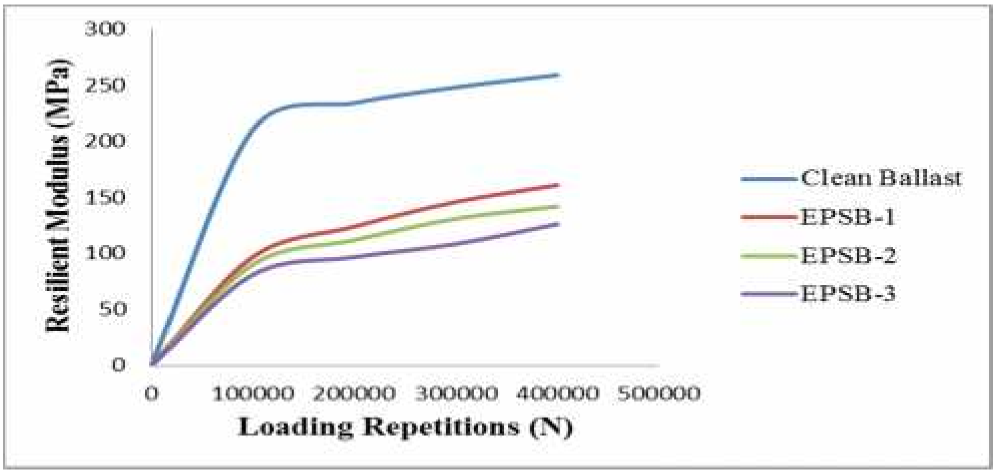


Figure 17 Resilient Modulus and Loading Repetitions

Accordingly the elastic strain of EPSB is given by (Selig and Waters, 2004) as follows;

$$M_r = \frac{\sigma_P - \sigma_r}{\varepsilon_E}$$ ……………………………………………………………...**Equation 17**

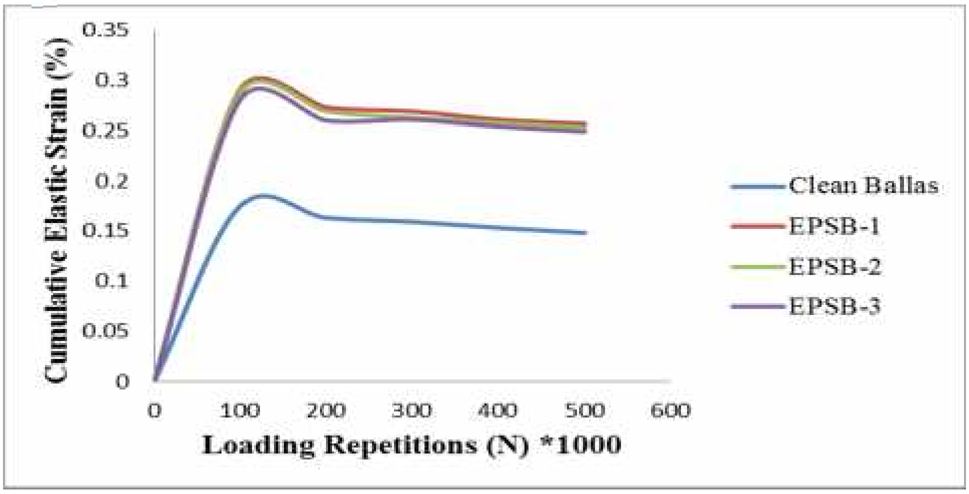


Figure 18 Cumulative Elastic Strain VS Loading Repetitions

The elastic deformational behavior and the resilient modulus of EPSB are higher than clean ballast. Possible micro mechanisms for the accumulation of permanent strain which occurs under repeated loading are particle rearrangement and particle breakage. The influence of stress level on permanent strain is very significant. So when ballasts are stabilized with EP, they will have superior resistance to accumulation of plastic deformation (non-recoverable deformation) compared to untreated ballast materials and is thus an applicable tool for maintaining track geometry and preventing ballast layer settlement as well as massive maintenance work and cost of infrastructural and operational materials.

3.3.3 EPSB Mechanical Properties Compared To Clean Ballast

In this subsection, modulus and strength of EPSB, EP (from BASF company material specification profile) and clean ballast are compared to EPSB composite properties. The average UCS strength of the EPSB specimens (3.16MPa) is greater than that of clean ballast (1.35MPa) which is 57.3% greater. However, the average EPSB compressive elastic modulus (90.8MPa) is less than clean ballast (200MPa). The EP (ρ_{EP} = 200 kg/m3) compressive strength (3.75MPa) is higher than the ballast compressive strength at 90kPa confining pressure (1.35MPa). Increase in EPSB compressive strength, relative to ballast compressive strength, is likely attributed to both the higher tensile strength of EP and high characteristic ballast compressive strength. Since EPSB and EP strengths are far greater than the clean ballast compressive strength (at the representative confining stress), the capacity of EPSB in rail infrastructure would likely be driven by EPSB compressive strength.

The deformational behavior of the EPSB, measured by accumulation of plastic strain, 92.53% less than clean ballast within many loading repetitions; therefore, EPSB can be expected to have a much higher resistance to plastic deformation under normal cyclic loading conditions. The plastic strain is far under the range of the Federal Rail Administration (FRA) limit for maintenance (2.5-3%) (Keene et al, 2012). So the material resisted permanent deformation far better than clean ballast and it has resistance to permanent deformation at higher loads and has superior performance relative to that of clean ballast.

An important aspect of track response to loading is the elastic deformational behavior of the superstructure and substructure. Maintenance and design based on elastic response of the track under loading is important for ensuring rider comfort, reducing dynamic loading effects on the track, and providing proper interaction with the rail car suspension system (Aursudkij et al. 2009). When comparing EPSB and clean ballast, the elastic strain of clean ballast decreased 33% over many loading cycles from the elastic strain EPSB. When evaluating the resilient modulus, MR, of EPSB and clean ballast; EPSB (average-153.34MPa) at density of 1714kg/m3 has the lowest MR than that of clean ballast (270MPa). However, for use of EPSB in rail infrastructure, a finite element modeling was used to determine the effect on the overall track elastic response of having EPSB with lower compressive modulus formed in the ballast layer.

CHAPTER 4 RAILROAD FINITE ELEMENT MODELING

4.1 Constitutive and Finite Element Modeling Background

Finite element modeling (FEM) has commonly been used by mechanical engineers for modeling the mechanistic response of a complex system of various moving parts. In civil engineering, a common application of FEM has been used for structural analysis under static and dynamic loading conditions. The use of finite element analysis for modeling elements in transportation infrastructure and geotechnical engineering has been growing as FEM software, pre-constructed material models, and computational resources have increased. The use of FEM for geotechnical modeling applications allows modeling of complex problems such as in situ soil behavior. Complex materials models can be defined by researchers for investigating the mechanistic integration of soil layers, in situ stabilization, and interaction and interface between materials of differing composition and mechanical properties. Finite element modeling was used to investigate track resilience and substructure foundation elasticity for railroad bridges and bridge approaches. In their study, they modeled a bridge approach, which involved the typical stiffness of ballasted railway track and track on a concrete rail bridge. In the model, constitutive soil models and models involving bridge behavior to loading were used. The purpose of their investigation was to model vertical deflection of the railway segment approaching the railway bridge and the rails on top of the bridge deck. Due to the elasticity of the bridge approach segment relative to the bridge deck, as expected, the deflection was greater in the rails on the ballast foundation and far less in the rails on the bridge deck. The magnitude of stress was greater during the bridge approach due to the effect of dynamic loading, which was generated by the transition of the carload from the stiff bridge deck to the more elastic ballast-track foundation. This increase in stress due to dynamic loading, from change in track elasticity and deflection of the railroads, was found to contribute to further superstructure and substructure degradation (Woodward et al, 2007).

(Koskinen, 2005) was used to model a railroad bridge using XiTRACK, with ABAQUS where the response of a railroad embankment and bridge structure to loading was investigated. From the finite element analysis (FEA), the distributions of stresses and deflections were observed in the modeled railroad bridge and the ballast-track foundation. The model was validated by comparing full-scale tests conducted in the field to the model results. He demonstrated that ABAQUS and finite element modeling is an appropriate tool for modeling railroad segments and features.

(Salim, 2004) constitutive model was developed for modeling the deformational behavior of railroad ballast and for representing the effects of cyclic loading using ABAQUS. Each of the models was compared to laboratory tests (i.e., triaxial compression) conducted on ballast specimens. In the laboratory tests, monotonic triaxial compression tests were conducted at varying confining stresses. During the triaxial tests, the volumetric strain in the specimen, the change in friction angle with varying confining stress, and the amount of particle breakage was measured. The model takes into account effects of volumetric strain, changes in friction angle due to particle breakage and states of stress so that ballast deformation due to static loading can be reasonably predicted. From the empirical data, an incremental constitutive model was created which successfully predicted the deformational behavior of ballast, ballast breakage, and volumetric strain that occurred in the monotonic triaxial compression tests. The model used in ABAQUS was the Drucker-Prager model, which modeled similar results to the ballast behavior in the triaxial compression tests, but was not similar for the volumetric stain. The model was a better predictor of the deformational behavior of the ballast in the triaxial compression tests compared with the Drucker-Prager model in ABAQUS.

4.2 Full Railroad Track Modeling Using FEM ABAQUS

The numerical analysis can be used to determine the impacts that location, thickness and properties of polyurethanes reinforcement in the ballast layer have on track resilient behavior. This 2D model will provide insight on whether the use of polyurethane to ballast layer influence the track modulus and performance of railroad structure. The construction of a finite element model was conducted in ABAQUS 6.13-1 using several sources for the geometry of the track segment, mechanical and material properties of the superstructure and substructure, and typical representative railway loads. ABAQUS/CAE (Complete ABAQUS Environment) is used to create complex models, analyze and visualize results following the procedures. It contains module inputs which need to be followed in order to get highly accurate output. These model inputs are discussed below as follows:

Material and Geometric development: - The geometries of the substructures of different models consists of compacted subgrade soil (moderately stiff clay), basalt ballast aggregate layers with and without polyurethane stabilized that typically makes up a railroad embankment. The superstructure consisted of the rails, railpads and the sleeper. A typical cross-section for tangent track was used for basic model construction, shown as in figure 19 below. The selected model geometry was based on construction plans used for building a railroad track and based on other numerical modeling studies involving a track cross-section and foundation dimensions and constraints. The dimensions and model inputs are listed in the table 4 and table 5 below.

Table 4: Geometrical and loading input parameters for the model

Component	Young's Modules (E, Pa)	Density (ρ, kg/m3)	Dimension (l,w,d) (m3)	Poison's ratio
Rail (UIC-54)	2.10E+11	7850.00	3.24x0.14x0.16	0.22
Concrete sleeper	4.20E+10	2900.00	0.26x0.18	0.22
Ballast	150E6/200E6	1614.00	3.24x0.4	0.3
Subgrade	6.00E+07	1800.00	3.24x0.6	0.3
EPSB	9.10E+07	1541.00	3.24x0.4	0.3

N.B.- Rail pad stiffness (K) were 270E6N/m with damping (c) of 50E3Ns/m and height of 0.075m. Wheel parameters ware given in table 5.2 below

Table 5: Wheel parameters

Symbol	Name	Unit	25t Axle Model
Mw	Mass of wheel	kg	300
Iwx	Wheel moment of inertia about x-axis	kgm2	700
Iwy	Wheel moment of inertia about y-axis	kgm2	100
Iwz	Wheel moment of inertia about z-axis	kgm2	0
ρ	Density of wheel	kg/m3	7850
E	Modulus of elasticity of wheel	Pa	2.10E+11
υ	Poison's ratio of wheel		0.3
D	Diameter of wheel	m	0.84

Assembling the Model:- when we create a track component (part), it exists in its own coordinate system, independent of other track component (parts) in the model. In contrast, in this assembly section we create instances of our track components and position the instances relative to each other in a global coordinate system, thus creating the assembly. We position track component instances by sequentially applying position constraints that align selected faces, edges, or vertices or by applying simple translations and rotations.

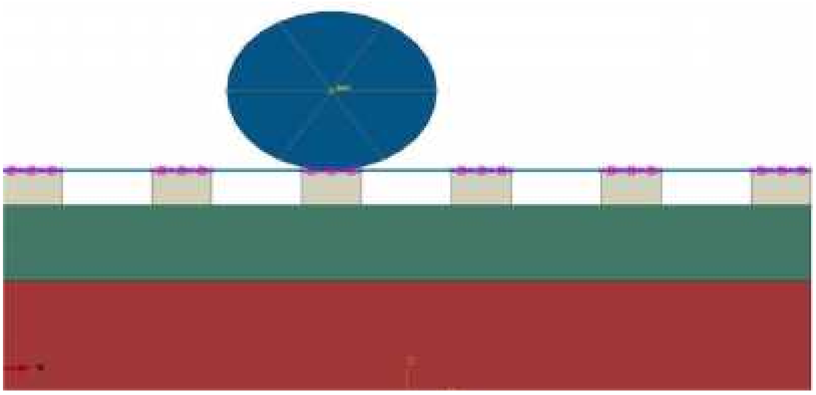


Figure 19: Typical railroad longitudinal section for FEM analysis**.**

Interaction of Track Components:- in order to move and rotate the wheel a rigid body constraint is applied for the wheel at the reference point which needs to be created at the center of the wheel. Since 2D analysis is used, all the three degree of freedoms i.e. in x, y, and z-axis must be constrained to move together. In addition to the above interaction, in this thesis two contact properties were used. In ABAQUS a penalty contact method can be assigned so that the contact force is proportional to the extent of penetration of one element or part into an adjoining element or part depending on master and slave surface assignment. This setting is selected so that rail penetration into the ballast layer is allowed to occur during model computation. Penalty contact method also prevents over constraints, alleviating stress concentration buildup from model inaccuracy. Linear normal behavior with “hard” contact is assigned with separation allowed after contact. Penalty contact method was also used for defining normal behavior between the rail and the sleeper. Remaining specifications were default properties. Tangential behavior was assigned when sleepers contact the ballast layer, defined by isotropic friction with coefficient of 0.35. This was done to simulate the level of interface friction that occurs between ballast particles and, concrete ties used as part of the superstructure. Penalty contact method is used to define tangential behavior. Default normal behavior with "hard" contact is assigned for simplicity in model calculations with separation allowed after contact. Remaining specifications were default properties. Tangential behavior was assigned for any two geo-materials (e.g., ballast, subballast, and subgrade) in contact, defined by isotropic friction with coefficient of 0.35. Remaining specifications were default properties. For all layer interfaces, finite sliding was selected to allow movement layers relative to the next in order to prevent unintended stress concentrations during model calculations and optimize model calculations involving interface behavior. When surfaces of separate parts (i.e., ballast layer and subballast layer interface) are in contact in ABAQUS, their interactions must be defined (e.g., tangential and normal behavior). The tangential behavior was assigned between wheel and rail hertzian contact and the interaction were defined by isotropic friction of coefficient 0.25.

Boundary condition development: - zero vertical displacement at the base of the subgrade layer, and zero lateral displacement of the edges parallel to the direction of the model-track geometry (i.e., subgrade). Zero lateral displacements were applied to the rail model edges, but vertical displacement was left unconstrained. The rotational degrees of freedom are constrained between the two model parts to simulate the constraint between rail and sleeper in the track superstructure.

Loading development:- The dynamic explicit procedure type has been used for step calculation in this thesis. The explicit scheme appeared to be very computationally demanding and is more appropriate to use when the time interval is very small. The loads selected for application in the model were based on wheel load and application identified in several studies. The main responses studied were layer displacements and layer strains and the track modulus. Two load cases were applied to the model. Initially concentrated wheel load of 125kN were assumed on the reference point of moving rigid wheel with a time period of 0.0001second. The moving load case with velocity of 100km/hr (27.87m/s) was selected. The time taken by the wheel to cover 1.8m length track was taken as 0.072second. The developed model was two-dimensional and symmetric with one wheel load applied to the rail. The purpose of this was for realistically modeling the load application to the rail into the superstructure; in addition, applying over a surface area prevents unrealistic strains in the rail that could adversely affect the model.

Elemental meshing development:- The model railroad embankment was modeled in two-dimensional space using ABAQUS 6.13-1. The software has vast capabilities including modeling of complex geometries with several interacting parts possessing differing mechanical properties and material models. The choice of the linear-elastic modeling of the railway embankment was used for validation with modeling variations in track resilient response. Since the scope of the study was to understand the effects of having zones of differing mechanical properties in the ballast layer and the resulting effect on track modulus response, linear elastic material models were selected for the different layers and for the modeled stabilized zones. In order to perform 2D finite element analysis the model was discretized into a basic first-order (linear), 2D constant stress free tetrahedral element mesh. ABAQUS meshing verification tool was used to ensure no elements were distorted based on meshing of each part. For computational efficiency, mesh density was decrease with depth of the rail embankment in the model. The mesh sizes taken for the wheel, rail, and sleeper parts are 0.01m, for ballast/EPSB 0.05 and for that of subgrade part it is 0.1m.

From the strains generated in the field and a parametric study conducted using computer modeling of the states of stresses versus strains, (Stewart and Selig, 1982) proposed nominal values for the moduli of the substructure layers and typical wheel loads applied to the track depicted in the table.

Table 6: Parameters Used in GEOTRACK Model and in This Study

Reference	(Stewart and Selig (1982)	This Study
Program	GEOTRACK	ABAQUS
Rail E (MPa)	207,000	210,000
Sleeper E (MPa)	10,300 wood	29,000 Concrete
Ballast E (MPa)	210	150/200
Ballast v	0.3	0.3
Ballast t (m)	0.38	0.4
Subballast E (MPa)	90	100
Subballast v	0.4	0.3
Subballast t (m)	0.15	0.15
Subgrade E (MPa)	55	60
Subgrade v	0.4	0.4
Subgrade t (m)	0.9	0.6

4.3 Discussion and Validation on Model Output Results

As it was stated the main objective of this model was to understand effects on track modulus due to polyurethane stabilization having different elastic modulus, that is lower modulus as well as higher modulus than the ballast layer. These will be ascertained using the general determination of track performance using track modulus.

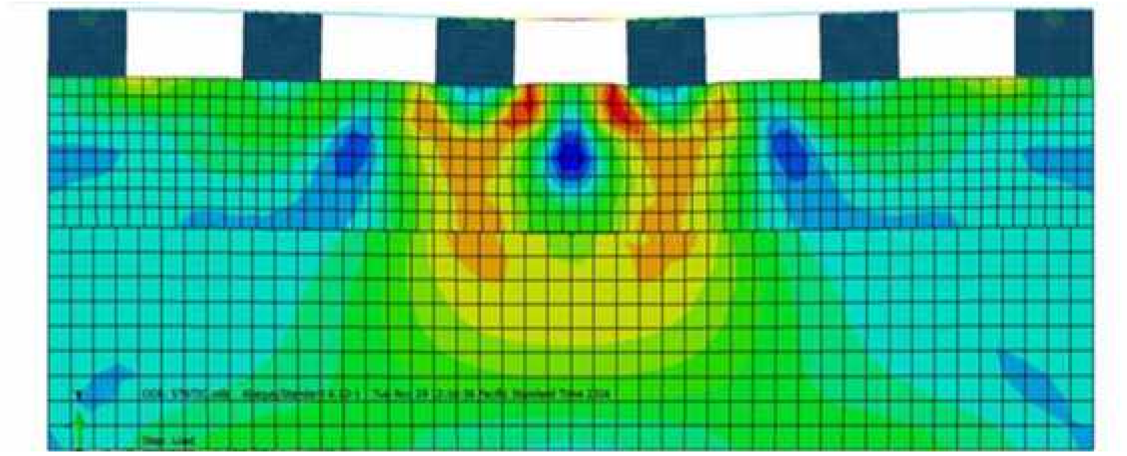


Figure 20: Strain output (model width = 3.24m) from general loading scenario and analysis with typical material properties and wheel loading.

The base model was analyzed under various loads, and strains were measured in the ballast and subgrade layers. Based on different EPSB modulus values used in the model, the average strain in the stabilized ballast and subgrade layers, was as shown in the figure 21-(a,b,c) below, under different lower loadings (25KN to 75KN) and higher loadings (75KN to 125KN).

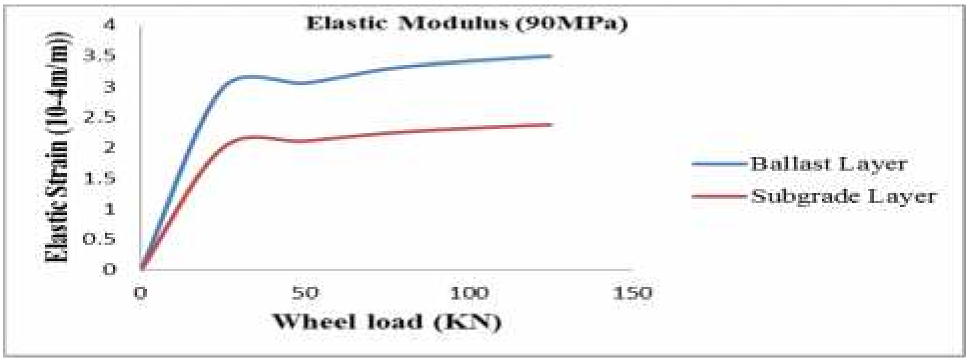


Figure 21-a Elastic Strain VS Wheel load under Elastic modulus of 90MPa**.**

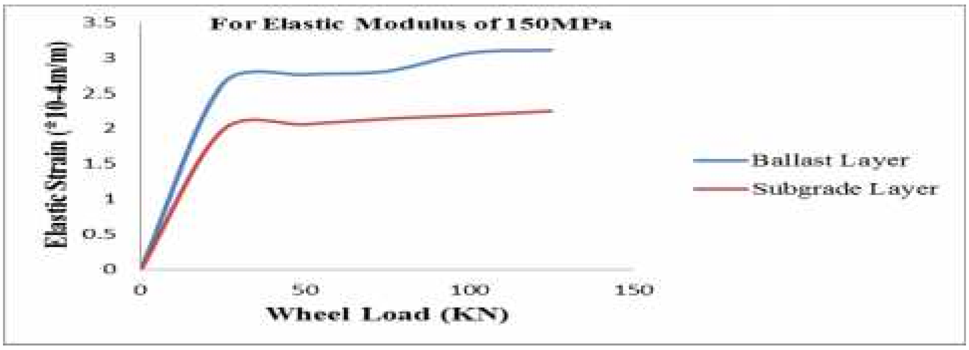


Figure 22-b Elastic Strain VS Wheel load under Elastic modulus of 150MPa

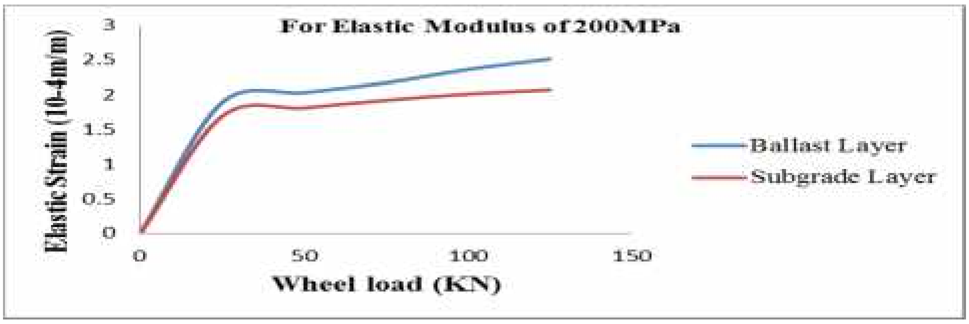


Figure 23-C Elastic Strain VS Wheel load under Elastic Modulus of 200MPa.

At lower loads model track shows nominal strains; however, at higher loads the model track exhibited higher strains. Therefore, the model is more conservative at higher loads for the strain in the substructure layers. Consequently, the stabilized ballast layer is more susceptible to change in strain due to EPSB formation in the ballast layer even-thought the difference was too small and this decrement is may be due to having localized areas of lesser modulus (EPSB formation) in the ballast layer.

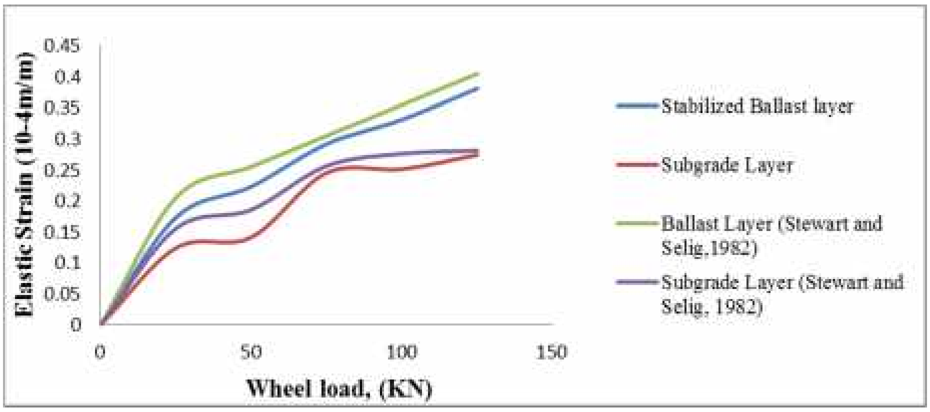


Figure 24 Comparison results of Elastic Strain of stabilized ballast and subgrade layers of this thesis and ballast and subgrade layers of (Stewart and Selig, 1982).

The strain model output presented in this thesis was validated using comparisons to the GEOTRACK model presented in (Stewart and Selig, 1982). The model geometry was adjusted to closely match the material properties, layer depths, and sleeper spacing used in their study. In comparison, the strains in each layer of their study were slightly less than those measured in this thesis. At lower loads the strain of substructure layers measured in this study are almost similar to those measured in their study; however, at higher loads the base model track corporates in this study exhibited slightly higher strains than those measured in their study as it is depicted in the figure 24 above.

TRACK MODULUS is defined as the coefficient of proportionality between the vertical rail deflection and the vertical contact pressure between the rail base and track foundation (Cai et al., 1994) and it is also a measure of elasticity of ballast and relates pressure imposed on the ballast by the sleeper to the deflection of the top table of the rail (Cope, 1993). Railroad track has several components that all contribute to track modulus, including the rail, subgrade, ballast, subballast, sleepers, and fasteners. The subgrade resilient modulus and subgrade thickness have the strongest influence on track modulus and it increases with increasing subgrade resilient modulus and decreases with increasing subgrade layer thickness. Ballast layer thickness and fastener stiffness are the next most important factors, and increasing the thickness of the ballast layer and/or increasing fastener stiffness will increase track modulus (Selig and Li, 1994). The model presented in this research measures the net effective track modulus that includes the secondary factors holding the primary factors constant. Both low track modulus and large variations in track modulus are undesirable. Low track modulus has been shown to cause differential settlement that then increases maintenance needs and large variations in track modulus, such as those often found near bridges and crossings have been shown to increase dynamic loading. According to (Lim, 2004) the effect of individual track system components parameters analyzed in his study on track elastic modulus is, namely rail(0.2%), rail-pad(34%), tie(0.8%), ballast(22%) and subgrade(43%). Trackside measurements of the deflection at the point where the load is applied are taken for a known load, and track modulus (U) can then be calculated using (Selig and Li, 1994).

$$U = \frac{1}{4}\sqrt[3]{(\frac{P}{\delta})^4 \cdot \frac{1}{EI}}$$ ………………………………………………………...**Equation 18**

Where, δ deflection of rail beneath wheel load, EI is bending stiffness of rail.

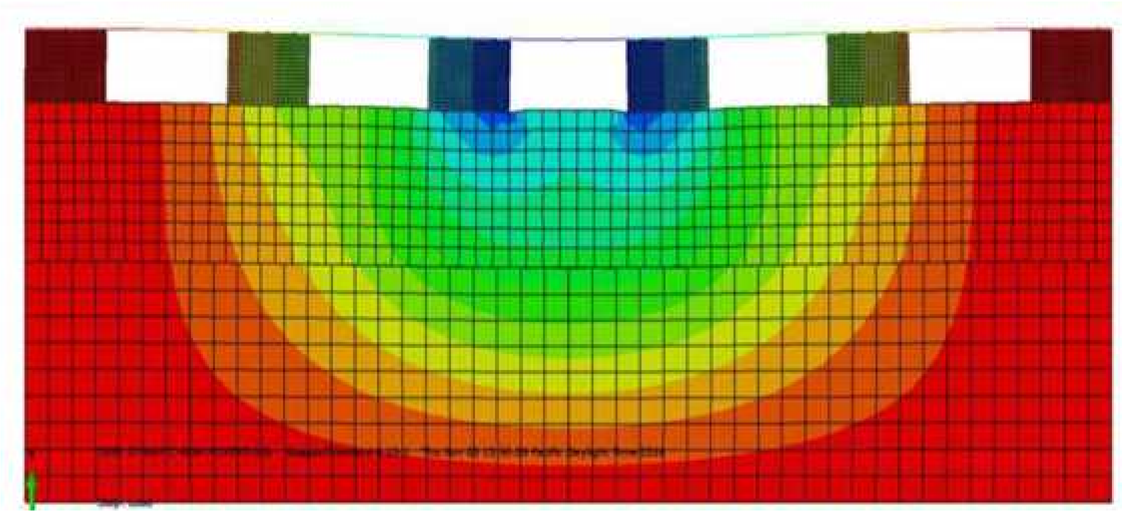


Figure 25 Model deflection output (model width = 3.24m)

Since strains modeled in each layer had only minimal change due to EPSB formation in the ballast layer, track modulus was calculated to understand elastic response of the entire track in this model. Track surface deflection, δ calculated from the numerical model was used as input into Equation 25 for determining track modulus. As shown in figure 26-(a,b,c), as the stabilized ballast layer modulus was 90MPa/150MPa/200MPa, the average track modulus under higher loading for maximum rail deflection became 30.27MPa/29.63MPa/28.94MPa respectively (± 4.4%). Therefore, EPSB modeled was found to have an inconsequential effect on track elastic response compared to other key components in the track. A larger range of EPSB modulus, than observed in the laboratory, was also incorporated into the numerical model, which revealed that implementation of EP stabilization would still have a negligible impact on the track modulus commonly used in track structural design.

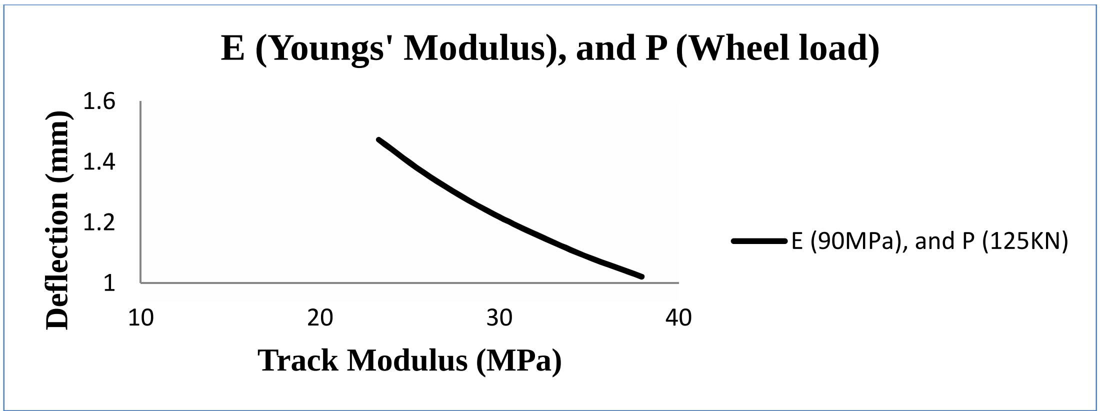


Figure 26-a Track modulus VS EPSB Elastic modulus (90MPa)

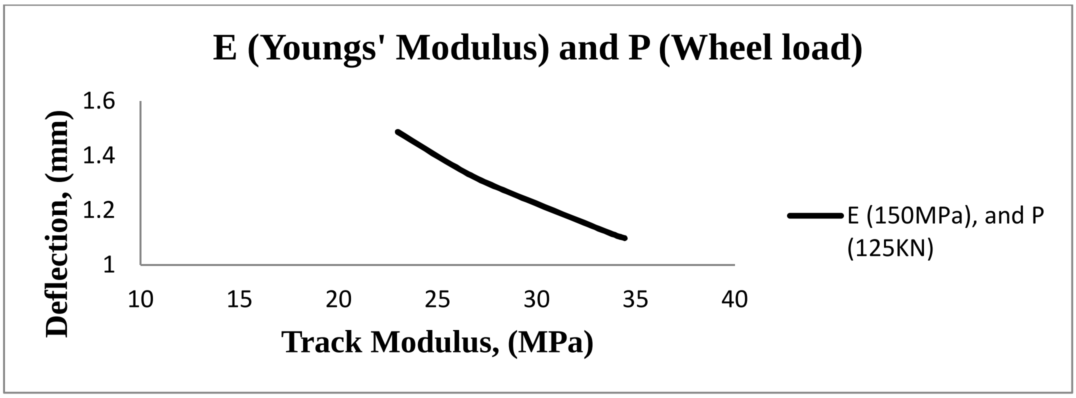


Figure 27-b Track modulus VS EPSB Elastic modulus (150MPa)

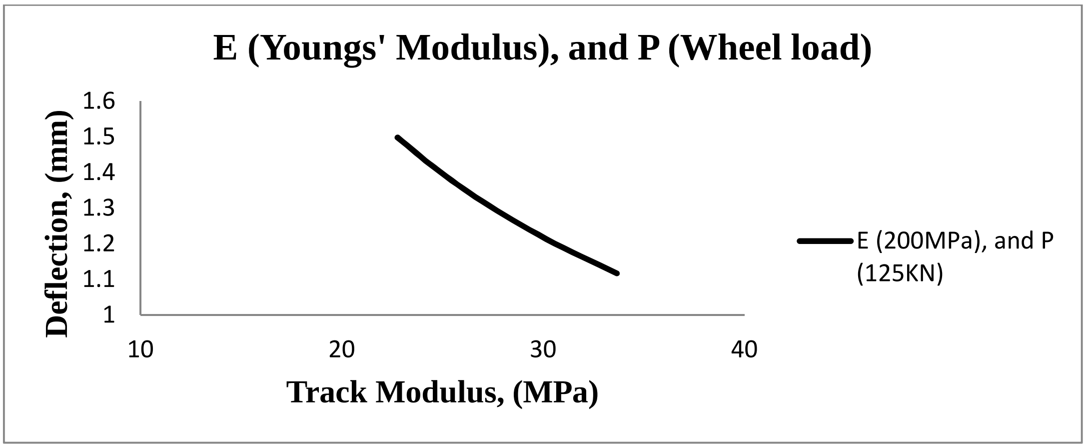


Figure 28-C Track modulus VS EPSB Elastic modulus (200MPa)

Track modulus values resulted from the base model was validated with the results of (Stewart and Selig, 1982). They determine the nominal track modulus and it was 33.8MN/m/m and ranged from 15.5 to 39.5MN/m/m. They also recommended that track modulus values less than 15.5MPa indicate poor track performance, while values between 15.5MPa and 28MPa indicate average performance. And track modulus value of 28MPa may therefore be considered a minimum for good track performance under traffic loading. The range in track modulus was due to the variation in the parameters analyzed in their study, namely the fastener stiffness, ballast modulus, and sleeper spacing. In the developed track model there were marginal differences in track modulus. With wheel loads ranging from 25-175kN, the track modulus ranged ± 2.63MPa. Variation in track modulus, as wheel loads varied, can be associated with the changing interaction of the entire track (i.e., interaction and behavior of the superstructure and substructure) as they were stated. Very high track modulus values above 38MPa can cause component failure including ballast degradation and sleeper cracking due to increased dynamic loads.

4.4 Life Cycle Cost Analysis of EPSB

The first step is to clearly state the main direct objectives of improving the performance of railroad transport project; that is, improving track performance for high speed and huge tonnage for long period of time and minimizing the maintenance and its cost induced over service life. The second largest step, the socio-economic objectives of railroad transport projects, are generally related to the improvement in travel conditions for goods and passengers both inside the study area and to and from the study area (accessibility), as well as improvements in both the quality of the environment and the well-being of the population served. A good starting point for briefly, but clearly, identifying the infrastructure is to state its functions, which should be coherent with the objectives of the investment. This should be followed by a description of the type of intervention, which is whether it is a completely new road, or a link to a larger infrastructure, or part of an extension or modification to an existing road or railway. This thesis deals with the following type of transport problems; modifying ballast track assets for improvement of the performance of a railroad track structure, and reducing maintenance and traffic delay costs. The case for stabilizing ballast layers depends on its capacity to generate performance increment and maintenance cost reduction benefits to compensate for increased cost of the polyurethane stabilization. Whether polyurethane stabilization investment is economically preferable depends on local (availability) and national (financial priority) conditions, which determine the magnitude of costs, demand levels and external benefits such as comfort and safety of from environmental impacts.

The critical economic factors considered for whole life cycle costing of the project here are investment (construction) cost, maintenance cost and traffic disruption (delay) cost. Life-cycle costing (LCC) is defined as the process of economic analysis to assess the total cost of construction, maintenance, operation and disposal of a product (Project). This analysis provides important inputs in the decision-making process for different life phases of the product. Main variables that should be considered in measuring the life cycle cost of polyurethane stabilization are; financial resources and economic priority trend of the country; rate of increase of traffic and tonnage over time; value of time for the economic trend and forecast of the country; number of years necessary for the full efficiency of the infrastructure; investment costs for the purchase, transport and stabilization of all necessary inputs; and maintenance costs and traffic disruption cost.

Total life cycle costs of building and operating a high speed railroad line consist of the producer, the user and the external costs. *User costs* are mainly related to total time costs, including access, egress, waiting and travel time invested, reliability, probability of accident and comfort. *Producer costs* involve two major types of costs: infrastructure, maintenance and train operating costs. *External* costs are associated to construction (e.g. barrier effect and visual intrusion) and operation (e.g. noise, pollution and contribution to global warming). Generally this thesis adopted the producer cost as an input in the equation given by (Zoeteman, 1999b) model which is described below in Equation 32 to quantify LCC of the railway infrastructure. It includes investment (construction) costs (IC), periodic maintenance and renewal costs (MC), and delay costs (DC). Every single cost is estimated for a specific year y and discounted to the base year considering a constant discount rate r throughout the lifecycle n.

$$\mathbf{LCC} = \sum_{y=0}^{n} \frac{IC(y)+MC(y)+DC(y)}{(1+r)^y} \quad \text{..} \textbf{Equation 19}$$

Investment Costs (IC):- Building new high speed railroad infrastructure involves three major types of costs: planning and land costs, infrastructure building costs and superstructure costs (UIC, 2005). Feasibility studies, technical design, land acquisition, legal and administrative fees, licenses, permits, etc. are included in *Planning and land costs*, which can reach up to 10% of total infrastructure costs in new railway lines requiring costly land expropriations. *Infrastructure building costs* involve terrain preparation and platform building. Depending on the characteristics of the terrain, the need of viaducts, bridges and tunnels, these costs can range from 45 to 60% of total investment. Finally, the rail specific elements such as tracks, sidings along the line, signaling systems, catenary, electrification communications and safety equipment, installations, etc., which are called *superstructure costs*. Railway infrastructure also requires the construction of stations. Although sometimes it is considered that the cost of building rail stations, which are singular buildings with expensive architectonic design are above the minimum required for technical operation, these costs are part of the system and the associated services provided affect the generalized cost of travel (for example, quality of service in the stations reduces the disutility of waiting time). (Profillidis, 1996) compiled the cost data from tracks for high-speed trains built during recent years. He gives us a first rough estimation of building cost (planning and land costs, and main stations excluded) of a new high-speed ballasted single track railroad line. According to him for un-stabilized ballasted railroad line with speed of 100Km/hr, topography of average difficulty and economic life (ballast cleaning) of 7.5-11MGT-Km/year and (ballast renewal) of 10-18 MGT-Km/year, the investment cost is approximately 3-12million $\frac{EUR}{Km}$. Preliminary estimates of financial investment costs for ELASTOTRACK polyurethane stabilization have been provided by the supplier BASF. Accordingly the cost of the ELASTOTRACK polyurethane stabilized ballast layer is averagely 15-20% greater than the cost of untreated clean ballast layer and 1.2% greater than the total investment cost of the track based of the neatness of ballast particles. The cost includes all necessary technical and mechanical tools which will be used for the implementation on the site.

Maintenance and Traffic Disruption Cost:- There are two types of costs in maintenance efforts; that are direct and indirect maintenance costs. Direct maintenance is an effort to perform a specific maintenance task, such as cleaning or replacing ballast. The effort and costs of direct maintenance are defined as those functions directly involved in the maintenance task that should be common to all rail applications. The definitions of direct maintenance effort with the supporting organizational effort/cost and material costs to implement productive maintenance are fundamental for this project. Indirect maintenance efforts considered in this research are loss due to traffic disruption for maintenance, travel from a staging area to a site, mid-level supervision, material stores costs (material stock-pile efforts, including purchasing activities, inventory, etc.), equipment procurement and maintenance, clothing allowances, training, and organization overheads that are not captured in the direct costs or other category. Accordingly the maintenance and traffic disruption cost of railway line with speed of 100Km/hr, topography of average difficulty and economic life (ballast cleaning) of 7.5-11MGT-Km/year and (ballast renewal) of 10-18MGT-Km/year is approximately 20,000EUR/year/km (Profillidis, 2006).

So the life cycle cost of a railroad line with and without ELASTOTRACK polyurethane stabilized ballast (improved for about eight years) for speed of 100Km/hr, topography of average difficulty and economic life of 10-18MGT-Km/year is given as follows taking into account the average value of the investment cost about 8Million-EUR/Km . From Equation 30 assuming 20years of service life in the analysis with discount rate of 5%;

Table 7: investment, maintenance and traffic disruption cost (EUR/year/km)

Cost Items (EUR/year/km)	Track with clean ballast	Track with EPSB
Investment cost	400,000.00	404,800.00
Maintenance and traffic disruption cost	20,000.00	12,000.00
Total (IC+MC+DC)	420,000.00	416,800.00

Table 8: LCC of track with and without ELASTOTRACK polyurethane stabilization

Years	Track with Clean Ballast	EPSB
0	420000	416800
1	400000	396952.381
2	380952.381	378049.8866
3	362811.7914	360047.5111
4	345535.0394	342902.3915
5	329080.9899	326573.7062
6	313410.4666	311022.5773
7	298486.1587	296211.9784
8	284272.5321	282106.6461
9	270735.7448	268672.9963
10	257843.5665	255879.0441
11	245565.3014	243694.3277
12	233871.7156	232089.8359
13	222734.9673	221037.9389
14	212128.5403	210512.3228
15	202027.1812	200487.9265
16	192406.8392	190940.8824
17	183244.6088	181848.4594
18	174518.675	173189.0089
19	166208.2619	164941.9133
20	158293.5828	157087.5365
LCC	**5,654,128.34**	**5,611,049.27**

As the table 7 above displays the LCC of tracks with ELASTOTRACK polyurethane stabilization have economic advantage of about **43,079.07**EUR/km than clean ballast which increases the benefits expected from rail transport projects. So it is better to use ELASTOTRACK polyurethane stabilization in new high speed railroad line for improved performance and economic benefits.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

After strategic injection of polyurethane into the ballast layer, areas that primarily absorb railroad loads in the substructure (i.e., ballast beneath the bearing surface of the tie) are fortified and become monolithic; particle rearrangement and settlement are averted. Large differences in mechanical behavior of clean ballast before and after polyurethane stabilization indicate that the introduction of EP to ballast creates a geo-composite, referred to herein as EPSB, with different and generally superior mechanical properties to that of clean ballast. In unconfined compression tests, EPSB possessed much higher unconfined compressive strength (3.16MPa) than clean ballast (1.35MPa) under confining pressure of 90KPa. Deformational behavior of EPSB in compression shows, minimal accumulation of plastic strain, (ε_P=0.145%), over many loading repetitions compared to clean ballast (ε_P=1.94%). EPSB samples had lower elastic and resilient modulus than the clean ballast. Numerical modeling was conducted to confirm that there would be minimal difference in elastic strains of the substructure from EPSB formation in the ballast layer. And through full track modeling this study shows insignificant impact. The LCC analysis performed on a typical representative sample clarifies that, EPSB has also an economic advantage than clean ballast. The ease of injections and negligible curing period for implementation of EPSB makes it an attractive alternative for railroad infrastructure. EPSB has found as an appropriate application for areas that cannot afford track shutdown or where traditional maintenance capabilities are impeded or unachievable. Generally concluding EPSB material cures immediately (reaching 90% of full strength in two hours) avoiding extended line closure; as it cures it does not shrink and continues to bond the ballast particles. Furthermore, ease of drainage in EPSB prevail the strategic advantage. From results obtained herein and models developed, EPSB has a much longer life cycle compared to traditional track-substructure material, ballast. Therefore, use of EPSB in track areas that undergo higher than anticipated loading can greatly increase track lifecycle and reduce maintenance requirements. Thus stabilization of ballast with ELASTOTRACK polyurethane is an applicable tool for maintaining track geometry and preventing ballast layer settlement.

5.2 Recommendation for Future Work

EPSB samples had lower elastic modulus that clean ballast and EPSB elastic deformational behavior becomes a primary focus in future work studies. The first focus of future research would be performing laboratory testing mechanisms on ELASTOTRACK polyurethane stabilized substructure materials to: (i) explore the performance of already fouled ballast with various types of fouling materials (e.g., coal, clay, and minerals), quantity, and moisture condition when injected with polyurethanes; (ii) understand the rheological properties of polyurethanes injected in to ballast with varying compositions for distinguishing the mechanisms that governs: what substructure conditions are treatable and the extent of the treatment that will be accomplished; (iii) develop modulus and strength parameters for numerical analysis as a function of varying material compositions (i.e., specific fouling levels and moisture contents).

The second focus may be the field implementation and evaluation that would involve use of EPSB in test real track equipped with pressure plates and strain gauges to measure stresses and strains in substructure layers, depending on injection method used (e.g., percolation injection or substructure injection). Use in the field would involve calibrating the injection procedure developed herein and confirming the enhanced mechanical response and life cycle of the track resulting from the EP stabilized ballast layer. Collaboration with railway industry could also be undertaken to get access to field measurements. These field conditions could then be simulated in full track testing model. The result from such a study could be used to engage the railway industry in fully accepting the result from full scale testing facility.

Increase in temperature has pronounced effects on previous polyurethane materials above 58^{o}C (136.4^{o}F) (Traeger, 1967). As was the case for most material properties, the strength and stiffness occurred above may be affected over time. So effects of temperature on EPSB mechanical properties should be evaluated in order to fully recommend that utilization of ELASTOTRACK polyurethane in railroad substructure materials as an excellent stabilizing agent.

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