# Experimental Investigation and Production of Track Resilient Pads From End-of-Life Tyres and Its Application

**Zewdie Moges Agizie**

A Thesis submitted to

The School of Civil and Environmental Engineering

Presented in partial fulfillment of the requirement for the Degree of Masters of Science

(Railway Engineering)

**Addis Ababa University**

**Addis Ababa Institute of Technology**

**Addis Ababa, Ethiopia**

**July 2016**

The undersigned have examined the thesis entitled *"**Experimental Investigation and Production of Track Resilient Pads from End-of-life Tyres and its Application**"* presented by **Zewdie Moges Agizie**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

| | | |
|---|---|---|
| Dr. Asnake Adamu | | |
| Advisor | Signature | Date |
| Mequanent Mulugeta | | |
| Co-adviser | Signature | Date |
| Dr. Abreham Gebre | | |
| Internal Examiner | Signature | Date |
| Dr. Esayas G/Youhannes | | |
| External Examiner | Signature | Date |
| | | |
| Chair Person | Signature | Date |

## UNDERTAKING

I certify that research work titled "**Experimental Investigation and Production of Track Resilient Pads from End-of-life Tyres and its Application**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred.

Zewdie Moges Agizie

# ABSTRACT

In rail way industry, vibration and structure- born- noise emission due to wheel-rail interaction disturbs the surrounding environment and the rail track structures. One of the solution for these specific problems is using more resilient materials in track structures like rail pads, sleeper pads, sleeper boots or ballast mats, which can be produced using natural rubber and recycled end-of-life tyres.

The core attention of this thesis is composing and producing railway track resilient materials from natural and recycled rubber. Track resilience pads are one of track structural components which isolate the steel rail from the concrete sleeper to protect the sleeper from damage. It has also vibration and load distribution effect due to its elasticity.

The new composite material contains elastomers, fillers activators, accelerators, plasticizers, anti-oxidants and volcanizing agent. In order to achieve the standard quality of the resilient pads, more than 12 composites are prepared and basic rubber quality tests are carried out.

The resilient material qualities are checked based on Australian, Chinese and Indian standards. Standard quality tests such as Shore A hardness, tensile strength, elongation, aging, wear resistance, stiffness and constant compression set tests are conducted. In addition, rhioline and viscosity tests are conducted to control the curing environment and the process ability of the resilient pad compound respectively. Once the required compound quality has achieved, by preparing steel rubber pad mold the final shape of a rail pad is produced using product curing machine.

Finally, railway Slab Track Bridge is modeled and analyzed with and without sleeper pad using finite element package ABQUS to illustrate the application of sleeper resilient pads in reduction of the dynamic loading effect. The result shows application of resilient rail pads and sleeper pads together reduce the vibration and stress of the slab track.



***Keywords:*** Resilient pad, Recycled (Reclaimed) rubber, slab track-bridge, ABAQUS, Modeling, Production

## ACKNOWLEDGMENTS

This master thesis was carried out in the school of Civil and Environmental Engineering Addis Ababa Institute of Technology, Addis Ababa University. It is sponsored by Ethiopian Railway Corporation, the authority responsible for Railway industry in Ethiopia. The thesis was conducted under the supervision of Dr. Asnake Adamu and Mr. Mequanent Mulugeta, to whom I want to thank next to God for their valuable guidance and advice.

Thanks also to Horizon Addis Tyre S.C. workers especially the rubber material chemist Mr. Tadesse Mekonen for his ultimate assistance during the composition and production of rubber rail pad.

Finally, I want to thank the Ethiopia Railway Corporation for the financial and technical support for the thesis work.

## TABLE OF CONTENTS

**UNDERTAKING** ........ **III**

**ABSTRACT** ........ **IV**

**ACKNOWLEDGMENTS** ........ **V**

**TABLE OF CONTENTS** ........ **VI**

**LIST OF TABLES** ........ **VIII**

**LIST OF FIGURES** ........ **IX**

**CHAPTER 1 INTRODUCTION** ........ **1**

1.1 Background ........ 1
1.2 Aim and Scope of the Study ........ 2
1.3 Structure of the Thesis ........ 3

**CHAPTER 2 LITERATURE REVIEW** ........ **4**

2.1 Railway Track ........ 4
2.2 Dynamic Properties of Railway Track Components ........ 5
2.2.1 Rails ........ 6
2.2.2 Rail pads, under sleeper pads and fastenings ........ 6
2.2.3 Sleeper/ concrete block ........ 7
2.2.4 Ballast, Sub-ballast and Sub-grade ........ 7
2.3 Railway Bridge Dynamics ........ 8
2.4 Numerical Modeling of Railway-Bridge–Vehicle Interaction Dynamics ........ 8
2.5 Elastomeric/Rubber Resilient Material ........ 10
2.5.1 General characteristics of elastomeric materials ........ 10
2.5.2 Ingredients of rubber rail pad compounding ........ 10
2.5.3 Recycled/Reclaimed Elastomeric material properties and components ........ 11
2.5.4 Production of rubber rail pad from recycled rubber material ........ 13
2.5.5 Guiding specification for rubber rail pad production quality ........ 13

**CHAPTER 3 EXPERIMENTAL STUDIES** ........ **16**

3.1 General Explanation of the Experiment ........ 16
3.2 Experimental Program Flow Chart ........ 17

3.3 Chemical Compounding of the rubber rail pad material.....18
3.3.1 Specimen Preparation and experimental testing.....18
3.3.2 Railway Resilient rubber pads material compounding.....19
3.4 Summary of Laboratory Test Results.....20
**CHAPTER 4 FINITE ELEMENT MODELING OF SLAB TRACK BRIDGE .30**
4.1 General description on slab track on bridge modeling.....30
4.2 The case study bridge.....30
4.3 Finite Element Modeling Procedure.....31
4.4 Finite element Analysis Results and Discussion.....32
**CHAPTER 5 CONCLUSIONS AND RECOMMENDATION.....37**
5.1 Conclusions.....37
5.2 Recommendation.....38
**REFERENCE.....39**
**APPENDIX A.....41**

## LIST OF TABLES

Table 2-1: Ingredients of rubber pad ........................................................................ 122
Table 2-2: Physical and chemical requirements for reclaimed rubber ........................... 123
Table 2-3: Rubber pad mechanical and physical properties specifications .................... 124
Table 2-4: Rubber pad Stiffness for different rail types according to China Standard .... 15
Table 2-5: The rail pads shape dimension based on rail type ........................................... 15
Chart 1: Experimental Program of Resilient Material Formulation and Production ........ 17
Table 3-1: Rubber Railpad Compositions ......................................................................... 19
Table 3-2: Composite of Resilient Material test summary ................................................ 21
Table 3-3: Abrasion test result of compound Type -1, Type -6 and Type -12 ................. 27
Table 3-4: Rail pad stiffness measured data and compitition result ................................ 27
Table 3-5: Material cost analysis of rail pad compound type-1 ....................................... 28
Table 3.6: Material cost analysis of rail pad compound type -12 ..................................... 28
Table 3.7: Material cost analysis of rail pad compound type -6 ....................................... 29
Table 4-1: Material parameters for the concrete bridge and sleeper ................................ 31
Table A.1: Abrasion test result of compound Type – 2 to Type-11 ................................. 53

**LIST OF FIGURES**

Figure 2-1: Ballasted Track components ........ 4
Figure 2-2: Track components ........ 4
Figure 2-3: (a) Low Vibration Slab Track Components, (b) Low Vibration Slab Track ... 5
Figure 2-4: Spring Mass Model ........ 9
Figure 3-1: Torque Vs Time graph of compound Type 1 ........ 23
Figure 3-2 Torque Vs Time graph of compound type 6 ........ 24
Figure 3-3: Torque Vs Time graph of compound type 12 ........ 25
Figure 3-4: Testometer result of Stress Vs Strain graph of compound: a) Type 1, b) Type 6 and c) Type ........ 26
Figure 4-1: Sebeta-Meisso Railway line Project Single Truck Bridge Section Layout ... 30
Figure 4-2: Basic outline of 2D ABAQUS model of a slab track on T-Girder Bridge .... 32
Figure 4-3: Vertical acceleration of the bridge with and without resilient sleeper pad.... 33
Figure 4-4: Vertical Velocity of bridge with and without resilient sleeper pad ........ 33
Figure 4-5: Vertical displacement of bridge with and without resilient sleeper pad....... 34
Figure 4-6: Stress of the bridge with and without resilient sleeper pad ........ 34
Figure 4-7: Vertical acceleration of bridge with and without resilient sleeper pad.......... 35
Figure 4-8: Vertical velocity of the bridge with and without resilient sleeper pad .......... 35
Figure 4-9: Stress of the bridge with and without resilient sleeper pad ........ 36
Figure 4-10: Vertical displacement of bridge with and without resilient sleeper pad...... 36
Figure A-1: Rheo-meter test result, and Torque VS Time graph of compound type 2 .... 41
Figure A-2: Rheo-meter test result, and Torque VS Time graph of compound type 3 ... 42
Figure A-3: Rheo-meter test result, and Torque VS Time graph of compound type 4 .... 43
Figure A-4: Rheo-meter test result, and Torque VS Time graph of compound type 5 .... 44
Figure A-5: Rheo-meter test result, and Torque VS Time graph of compound type 7 .... 45
Figure A-6: Rheo-meter test result, and Torque VS Time graph of compound type 8 .... 46
Figure A-7: Rheo-meter test result, and Torque VS Time graph of compound type 9 .... 47
Figure A-8: Rheo-meter test result, and Torque VS Time graph of compound type10 ... 48
Figure A-9: Rheo-meter test result, and Torque VS Time graph of compound type11 ... 49
Figure A-10: Testometer result of Stress Vs Strain graph of compound Type 2,3&4 ..... 50
Figure A-11: Testometer result of Stress Vs Strain graph of compound Type 5,7&8 ..... 51
Figure A-12: Testometer result of Stress Vs Strain graph of compound Type 9,10&11 . 52

# CHAPTER 1 INTRODUCTION

## 1.1 Background

The rail as supporting and guiding element was first utilized in the sixteenth century. About 1800, the first free bearing rails were applied, which were supported at the ends by cast iron sockets on wooden sleepers. Flanged iron wheels took care of the guiding, as we still practice now [2].

In Ethiopia, during the period of emperor Menelik II, the 781km Ethio-Djibouti legacy railway was built. Although most of the current railway tracks are still of a traditional ballasted type. Recent applications tend more and more towards non-ballasted track. The major advantages of slab track are: low maintenance, high availability, low structure height, and low weight. In addition, recent life cycle studies have shown, that from the cost point of view, slab tracks might be very competitive [2], [5], [7].

In the last 40 years, an increase in train speed and axle load around the world and other challenges in the conventional ballasted track system gave birth to ballastless railway track system. But high amount of vibration and structure- born noise, and initial capital are its basic draw dawn. In order to reduce or damp the generation of the high amount of vibration and structure- born noise, which is due to large forces between wheels and rail, the application of elastomeric resilient materials are widely used for slab track [1].

In Addis Ababa LRT project and in Ethiopia national railway project, slab track is introduced in tunnel and bridge sections. But on the superstructure of slab track, the single concrete block is directly embedded in the concrete structure without elastomeric rubber boot and resilient pad. These rubber devices are known damping material for vibration and structure born noise.

Core attention of this thesis is preparing elastomeric resilient materials from end-of-life tires based on standards and check its efficiency in laboratory tests, and finally analyzing and comparing the dynamic loading effect on slab track bridge structure with these resilient materials. The Finite Element package ABAQUS is being used to model slab Track Bridge under dynamic loading by using these materials as a resilient pad, rubber boot and under rail pad.

## 1.2 Aim and Scope of the Study

The main objective of the study is preparing elastomeric resilient material from end-of-life tires/reclaim material, and analyzing and comparing the dynamic loading effect on slab Track- Bridge. The Finite Element package ABAQUS is being used to modeling a 2-D slab track bridge under dynamic loading using the elastomeric resilient material as a resilient pad, rubber boot and under rail pad.

The thesis is limited to preparing elastomeric resilient material from end-of-life tires/reclaim materials and analyzing the quality of material in a laboratory test. And also, the work extended by analyzing and comparing the dynamic load response of these rubber resilient material on slab track bridge structures. Slab track bridge model developed using ABAQUS software to analyze the response of the system.

However, the analysis results might not give the actual system phenomena because of the some restrictions. First of all absence of field test, which is very important to show the actual strength and capability of the sample under an actual load and on an open atmosphere. Thus it has its own influence on the output result. The second limitation was need of a 3D model to analyze the actual dynamic loading effect on the bridge. It simplifies to see the result of loadings from different directions and to make the required modifications. Therefore, further field test measurement and 3D model analysis may improve the thesis result.

## 1.3 Structure of the Thesis

A short description of each chapter is presented below to catch the overview of the general structure of the thesis.

In Chapter 2, literature reviews are presented, that describes the component, type and overall dynamic property of the slab track structure. It also briefly describes bridge dynamics; Vehicle-Track interaction dynamics and about numerical modeling using ABAQUS software. This chapter further illustrates the characteristics and components of elastomeric rubber materials and property of recycled resilient rubber pads.

Laboratory experimental study of the preparation of chemical compounding of resilient rubber pad materials, and its analysis and result are described in detail in chapter 3.

The case study bridge, ABAQUS Software procedure and general description of the model of slab track-bridge are presented in chapter 4. In addition, it contains the result and discussion of the analyzed models.

Finally, in chapter 5, conclusion and some recommendations are suggested for further research.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Railway Track

Now a day, railway track system could be categorized as ballasted track and ballastless/slab track. The Ballasted railway track consists of a flat framework made up of rails and sleepers which is supported on ballast. The ballast bed rests on a sub-ballast layer which forms the transition layer to the formation. The rails and sleepers are connected by fastenings. These components and other structures, such as switches and crossings are all considered as part of the track, (see Figure 2.1). The general problem which occurs with the ballasted track is the slow deterioration of the ballast material due to traffic loading [2], [7].

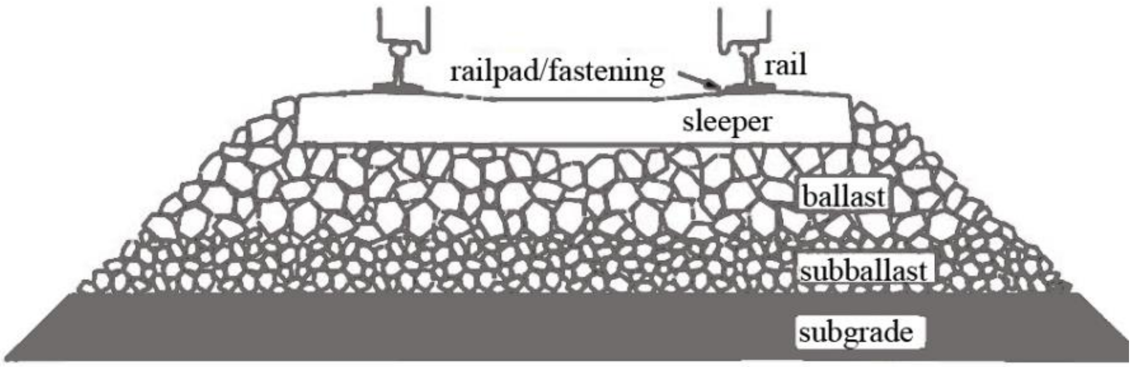



**Figure 2-1: Ballasted Track components**

In case of slab track, ballast as the load distributing element of the track system is replaced by another stable material such as concrete or asphalt, (see figure 2.2). The plastic deformation of these materials is very low under normal circumstances. The necessary elasticity has to be provided by inserting elastic elements below the rail or/and the sleeper to reduce vibration and structure born noise, as the concrete or asphalt layer is very stiff [2], [7].

**Figure 2-2: Track components**

In recent advanced railway truck construction, different vibration and noise damping materials are applied in order to reduce the stiffness of slab truck. These materials are rubber rail pads, sleeper pads, rubber sleeper boots, asphalt materials and other elastic materials which are inserted between slab track components (see figure 2.3). These materials act as a suspension system for rail track [25].

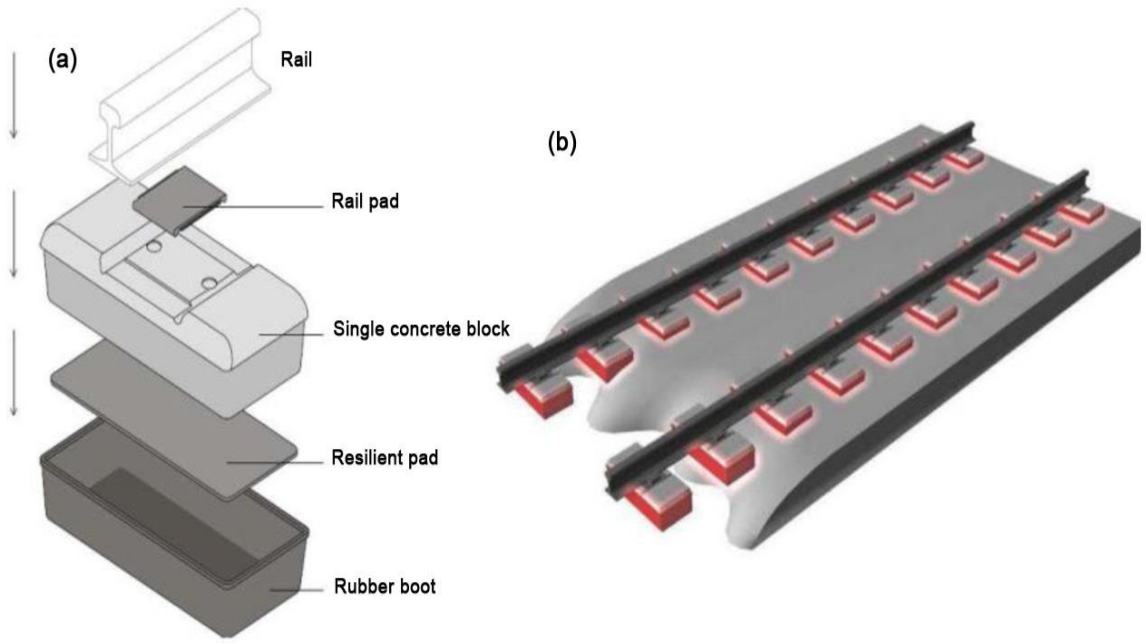



**Figure 2-3: (a) Low Vibration Slab Track Components, (b) Low Vibration Slab Track [4]**

## 2.2 Dynamic Properties of Railway Track Components

Dynamics is, in fact, the interaction between load and structure. Loads vary in time and the way this happens determines the character of the load. Distinctions can be made between periodic loads, impact loads, and stochastic load. Structures are characterized by their frequency response function which is governed by mass, damping, and stiffness. In mechanical models of railway tracks, the track components have been simulated as a type of elements which are classified according to their properties as follows:

- Components with mass and inertia properties, rail, sleepers and concrete slab;
- Components with elastic properties, rail pads, sleeper pad, ballast mat and fasteners; and

- The component with mass, inertia and elastic properties; ballast and sub-ballast [2], [6].

### 2.2.1 Rails

Rails are the longitudinal steel members that directly guide the train wheels evenly and continuously. They must have sufficient stiffness to serve as beams that transfer the concentrated wheel loads, lateral forces from the wheelsets, and longitudinal forces due to traction and braking of the train to the spaced sleeper supports without excessive deflection between supports [1], [2], [7].

The bending vibration of a free rail can be modeled as a beam with no support along with it; the rail beam model is supported only at the boundaries. The rail may be modeled either as an ordinary Euler-Bernoulli (E-B) beam or as a Rayleigh-Timoshenko (R-T) beam [3], [5].

### 2.2.2 Rail pads, under sleeper pads and fastenings

Fasteners are typically required to retain the rails on the sleepers, to maintain the track gauge and to resist vertical, lateral, longitudinal and overturning movements of the rails. Rail pads are required between the rail seat and the sleeper surface, and sleeper pads are required between the sleeper surface and concrete slab/ballast to fulfill various functions. The rail pads and fasteners represent the primary suspension of the track and the ballast layer or sleeper rubber pad represent the secondary suspension of the track [1], [2].

From a track dynamics point of view, the Rail pads and sleeper pads provide an elastic damping function which decouples vibration. Due to the rail deflection connected with elasticity, the load is distributing over several sleepers. This means that the rail pad and sleeper pads also have a load distributing effect [1], [2], [7].

The most commonly used physical model of a railpad and under sleeper pad are the spring-damper system. The spring can be assumed to be linear, and the damping is assumed to be proportional to the deformation rate of the railpad and sleeper pad. The stiffness of the fastening is normally much less than that of the railpad. Therefore, when investing track dynamics the role of the fastenings is normally neglected [5].

Dynamic rail pad models are usually on the fundamental basis of either time or frequency domain. Frequency domain model implicates dynamic properties such as resonant frequencies and damping [6].

### 2.2.3 Sleeper/ concrete block

Sleepers are essentially beams that span across and tie together the two rails. It receives the load from the rail and distributes it over the supporting ballast at an acceptable ballast pressure level. It provides a cant to the rails that help to develop proper rail-wheel contact by matching the inclination of the conical wheel shape. It also dampened rail vibration, and reduce the influence of sound and impact waves on the environment [1], [2], [7].

Depending on frequency intensity, the concrete sleeper can be modeled as either a rigid mass (at frequencies below 100 Hz) or as a flexible beam. For frequencies up to 300 or 400 Hz, the Euler-Bernoulli beam theory may suit. At higher frequencies, the Rayleigh-Timoshenko beam theory should be used for an accurate description of the sleeper vibration [3], [5].

### 2.2.4 Ballast, Sub-ballast, and Sub-grade

Ballast is made from the crushed natural rock with a particle size between 28mm-50mm. It distributes the load from the sleepers uniformly over the sub-grade and it easily drains any moisture introduced into the system. It also assists in absorbing shock from dynamic loads by having only a limited spring-like action (due to the rough interlocking particles) [1], [3], [7].

Sub-ballast is material chosen as a transition layer between ballast and sub-grade. It assists in reducing the stress at the bottom of the ballast layer to a tolerable level for the top of the subgrade. It can prevent the migration of fine material into the ballast which affects drainage [1].

Subgrade is a surface of earth or rock leveled off to receive a foundation for the track bed. Sometimes an extra layer, a formation layer, is put on the earth so as to give the correct profile of the track bed. On this material the sub-ballast and ballast layers rest. It offers the final support to the track structure [1].

For dynamic analysis, the theory of the ballast pyramid model is widely used. The pressure distribution is assumed to be uniform in a pyramid under sleepers and independent of the depth. The friction between particles transmits the loading from the top layer to the bottom of the ballast.

Thus, the ballast is divided in one block for each sleeper. Each ballast block can be modeled by a single degree-of-freedom system with a mass M, a stiffness K and a damping C. The suggested internal friction angle of ballast and sub-ballast is 20° and 35° respectively [5].

## 2.3 Railway Bridge Dynamics

The dynamics of railway bridges involves the response of bridges to the movement of vehicles and to the influence of number of parameters which increases dynamic stress or strain. The most important parameters influencing the dynamics stress in railway bridges are: [13], [15]

- The frequency characteristics of bridge structures (i.e. length, mass, rigidity of individual members )
- Vehicle frequency characteristics
- Damping in bridge and vehicles
- Vehicle velocity
- Track irregularity
- Magnitude and number of stress cycles generated in bridge
- Service life and so on.

To prevent the damage of bridges from severe earthquakes, elastic bearings for damping are often used as base isolators in bridge engineering. Conventionally, they are installed at the supports of bridge girders to serve as filters for isolating the vibration energy transmitted from the ground [15].

In bridge structures, damping comes from many sources such as from the internal friction, cracks, non-homogeneous properties of building material, friction between supports and bearing, friction in the ballast, friction in the joints of the structure, viscoelastic properties of soil, foundation and abutments and so on. The use of sleeper rubber pad and railpad have no much significant for substructure of rail bridge due to the presence of bearing [14], [15].

## 2.4 Numerical Modeling of Railway-Bridge–Vehicle Interaction Dynamics

Bridges constructed for railway lines should take care of the dynamic loads and resonance effects. Dynamic effects are usually considered in terms of dynamic amplification factor

(DAF). DAF is a measure of dynamic response with respect to static response for a moving load. Bridge structure can be modeled with Timoshenko beam elements resting on simple supports. The track system lying on the bridge is modeled with an infinite length of rail support by a continuous and homogeneous viscos-elastic foundation of springs and dampers. During 2D modeling for the two rails should be replaced with one rail and whole bridge should be replaced with one beam. Damping of the ballast is kept constant for the whole model [14].

The vehicle model can still be enhanced through consideration of the elastic and damping effects of the suspension systems. The simplest model in this case is a moving mass supported by a spring dashpot unit, the so-called sprung mass model [15].

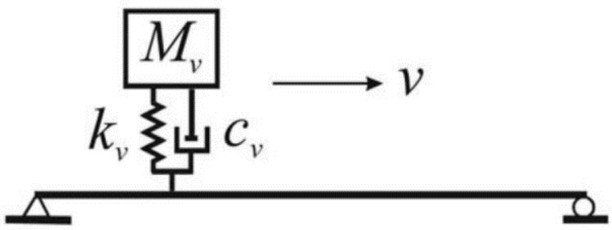



**Figure 2-4: Spring Mass Model [13]**

The factors that need to be considered in analyzing the response of the vehicle bridge interaction systems include the dynamic properties and driving frequencies of the moving vehicles, and the dynamic properties and surface roughness of the bridge [13].

One way to investigate the dynamic properties of a railway track is to load the track with a sinusoidal force and then analyze the deflection, stress, acceleration and velocity of the track structure in different frequency range [5], [13].

Dynamic behavior occurs in a fairly wide band ranging from very low frequencies of the order of 0.5-1 Hz for lateral and vertical car body accelerations to 2000 Hz as a consequence of geometrical irregularities in rails and wheel treads. The frequency range (low, mid and high) has varying effects on the railway track as a structure and on each component. Low-frequency range (0-40 Hz) produces damage to the substructure (subgrade, sub-ballast and ballast); mid-frequency range (40-400 Hz) produces damage to the superstructure excluding the rail (sleepers, fasteners, and rail pads) and high-frequency range (400-1500 Hz) produce damage to rails and distortion to fasteners [2], [6].

## 2.5 Elastomeric/Rubber Resilient Material

Elastomers are substantially super condensed gases because most of them derive from monomers that are gases. Elastomers are typically amorphous polymers having a random coil molecular arrangement [9].

Rubbers/Elastomers can be divided broadly in two categories: thermosets and thermoplastics. Thermosets are three-dimensional molecular networks with very long molecules that are held together by chemical bonds. They can absorb solvent and swell without dissolving and it is impossible to reprocess them simply by heating, and are used for their better elasticity, resilience, and durability. On the contrary, Thermoplastic molecules are not connected by primary chemical bonds and so they can dissolve in suitable solvents and soften on heating. There are some applications in tires production [8], [9].

### 2.5.1 General characteristics of elastomeric materials

Elastomers are based on polymers which have the property of elasticity. They are made up of long chains of atoms, mainly carbon, hydrogen, and oxygen, which have a degree of cross-linking with their neighboring chains. The crosslinking bonds that pull the elastomer back into shape when the deforming force is removed. Their resilience enables them to return quickly to their original shape. Most of the elastomers share the property of elasticity and resilience. Elasticity is the ability of a material to return to its original shape and size after being stretched, compressed, twisted or bent. And resilience is the ability to return quickly to their original shape after a temporary deflection. In other words, it indicates the speed of recovery, unlike compression set, which indicates the degree of recovery [8], [9].

### 2.5.2 Ingredients of rubber rail pad compounding

The basic properties of elastomers are highly dependent on the polymers/chemicals used in their manufacture. Chemistry of the compound is so complex that increase/decrease of any ingredient may result into increase in some properties and simultaneously decrease in some properties. Table 2.1 shows the basic ingredient of rubber compounds and their functional effect during composition and service [9].

### 2.5.3 Recycled/Reclaimed Elastomeric material properties and components

The recycled elastomeric material known as rubber reclaims material. The recycled rubber is the inert component and it is derived from used tires and rubber factory leftovers. The inert is obtained from the scraping of tire external surface. Because of its origin, the recycled rubber is SBR (Styrene Butadiene Rubber) that is the main component of tires together with the natural rubber. In a recycling factory, these ingredients are processed using the mechanic-chemical method of sulfur devulcanizing agent. Sulfur devulcanization can be achieved by subsequent reduction of rubber particles by using ashless inorganic salts as anti-stick additives, and then apply amino acids or amide group containing organic compounds as reactants for disconnection of sulfur crosslink [8],[16],[17].

Recycled/reclaim material has some same chemicals content of that of the recipes of source tires. But it is devulcanized. In chemical composition during rubber compound production, it is considered as filler. For most rubber compound up to 15 parts per hundred of rubber (PHR) of reclaim, content has no any significant impact on basic mechanical properties. The aging characteristics of the reclaim rubber containing vulcanizates are superior compared to the compound doesn’t contain any reclaim rubber. From the economy perspective, the addition of reclaim material on basic railpad compounding, reduce overall cost significantly [8], [17], [19], [20].

**Table 2-1: Ingredients of rubber pad**

| Items | Purpose | Ingredients |
|---|---|---|
| **Elastomer** | Basic compound | Natural Rubber (NR) +Synthetic Rubber (SR) Blended with<br>• Styrene Butadiene Rubber (SBR)<br>• Aryls Nitrile Butadiene Rubber (NBR)<br>• Butadiene Rubber (BR)<br>• Reclaim rubber* |
| **Vulcanizing agents (Curatives)** | Basic compounds are too hard to be processed directly. So it transformed into a true elastomeric state. | Sulfur or Sulfur donors |
| **Accelerators** | For increasing the speed of Vulcanization. | Organic substances containing both Sulfur and Nitrogen. |
| **Activators** | Activators to activate the accelerator & to improve its effectiveness. | Zink oxide, Stearic acid, Litharge, & Magnesia, Amines, etc. |
| **Retarders** | Retarders to reduce the scorchedness of a compound | ZCyclohexy-N-Thiophthalimide, Phthalic, Salicylic acid, Sodium acetate, etc. |
| **Anti-degradient** | To retard the deterioration by Oxygen, Ozone, Heat, Light, Metal catalysis, Mechanical flexing, etc. | Bisphenols, Phenols, Polymeric hindered phenols, MBI, 6PPD, TMQ, ANTILUX etc. |
| **Processing Aids** | To facilitate dispersion of fillers. | Stearic acid, Zinc and Calcium soaps, residues of atty alcohols, etc. |
| **Fillers** | To obtain high Tensile Strength and to improve abrasion &tear resistance, Also determines hardness. | N 770 (SRF) or N 990 ( MT), Kaolin, Calcium carbonate, Barium sulfate, Zink oxide, Magnesium carbonate,N-660/GPF etc. |
| **Plasticizers, Softeners and Tackifiers** | To facilitate processing. To serve as softeners. So that compound is fabricated. | Mineral oils, Animal and vegetable oils. Rosin, Tar, Pitch, DUTREX RA-3 etc. |
| **Color Pigments** | To add color. | |

** From this thesis result recycled rubber/reclaim rubber can be basic compound of rail pad*

According to Indian standard, reclaim rubber should fulfill the following requirements, shown on table 2-2.

**Table 2-2: Physical and chemical requirements for reclaimed rubber [18]**

| Characteristics | Requirement | | |
|---|---|---|---|
| | **Whole tire rubber reclaimed** | **Tube reclaimed rubber -natural rubber** | **Isobutylene-isoprene rubber** |
| Volatile matter, percent by mas, max | 1 | 1 | 1 |
| Acetone extract, percent by mas, max | 16 | 10 | 10 |
| Ash content, percent by mas, max | 8 | 7 | 6 |
| Carbone Black, percent by mas | 27+3 | 25+3 | 34+3 |
| Rubber hydrocarbon percent by mas, min | 50 | 52 | 52 |
| Relative density | 1.16+0.03 | 1.2+0.03 | 1.13+0.03 |
| Mooney viscosity, ML at 100ºC 1+4 | 40+5 | 40+5 | - |
| Tensile strength, N/mm2, min | 8 | 5 | 6 |
| Elongation at break, % | 280 | 280 | 280 |

### 2.5.4 Production of rubber rail pad from recycled rubber material

Production of rubber goods consists of the production of natural rubber from crops, synthetic rubber from petroleum and recycled rubber from end-of-life tires. Then input ingredients are processed into finished goods through the mechanisms of mastication of the elastomers, mixing chemicals in sequence and shaping for curing through milling machine. Finally, using railpad molds and hydraulics curing machines the desired product can be vulcanized [11], [21].

### 2.5.5 Guiding specification for rubber rail pad production quality

In particular, People's Republic of China Railway Industry Standard TB/T 2626-1995 is used. The specification has given a different dimension for the shape of rail pad and required stiffness based on rail seat load. But it doesn't specify the mechanical or physical properties of the railpad based on loading or service life. It gives the same quality for all rail pads regardless of loading and design period. It is applicable for the service life of 5 years or 200GMT.

**Table 2-3: Rubber pad mechanical and physical properties specifications [11],[12],[22],[23]**

| No. | Property/test | Unit | China (1995)** For 200GMT | India (2006) For 200GMT | India (2008) For 300GMT | Australia 2001 For 300GMT |
|---|---|---|---|---|---|---|
| **1.** | Shore A hardness | degree | 72~82 | >75 | >75 | 68±5 |
| **2.** | Tensile strength | MPa | >12.5 | >11.77 | >11.77 | >16.7 |
| **3.** | Elongation | % | >250 | >200 | >170 | >300 |
| **4.** | Relaxed modulus at 100% elongation | MPa | | 4.5 - 5.9 | 4 - 5.9 | |
| **5.** | 200% fixed secondary stress | MPa | >9.5 | | | |
| **6.** | Constant Compression set (50% at $100^0$C, 24hr) | % | <30 | <30 | <30 | <30 |
| **7.** | Tension set50% stretch at 100±1ºC for 24+/-2 hrs. | % | | <30 | <25 | |
| **8.** | Ake Eagle Wear | Cm3/ 1.61 km | <0.6 | | | |
| **9.** | Working resistance | MΩ | >1 | 100 | 100 | |
| **10.** | **Hot air aging (1000C, 96h +2hr) in case of china 1000C, 72h** | | | | | |
| **10.1** | Tensile Strength | MPa | >10 | >9.81 | >9.81 | |
| **10.2** | Elongation | % | >150 | >150 | >150 | |
| **10.3** | Relaxed modulus change after aging | % | | <30 | >-10 | |
| **10.4** | Retention for tensile strength | % | | >80 | >80 | |
| **10.5** | Retention for elongation | % | | >65 | >65 | |
| **11.** | brittleness temperature | ºC | -50 | | | |
| **12.** | Load Compression Test at 15tonn | mm | | 04 – 0.6 | 0.4 – 0.8 | |
| **13.** | Ash Content | % | | <30 | <25 | <20 |
| **14.** | Specific gravity | - | | <1.35 | <1.25 | 1.18 |
| **15.** | Secant Stiffness | KN/mm | 90–130* | | <150 | 65 - 100 |
| **16.** | Impact Attenuation | % | | | >30 | |

** Note that this study adopts the Chinese and Australian standard because of Addis Ababa Light Rail Transit Project and the Ethio-Djibouti national railway project are constructed based on Chinese standard. The Australian standard formulated for 300 GMT of service life.*

*** Required stiffness for 10mm railpad with nine trenches for rail type 50kg /m which is marked as 50-10-9 rail pad type.*

To make the study illustrative and comparative, Australian and Indian code of standards are also used. As a test methodology, ASTM standard and Chinese standard GB are used. Table 2-3 above shows rubber pad mechanical and physical properties specification of China

TB/T2626-1995, Indian standard IRS: T-47-2006, for service life of 200 GMT or 5 years, Indian standard for improved railpad (provisional 2008) for service life of 300 GMT or 8 years, and Australian standard AS1085 for service life of 15 years specification for rail pad production. Table 2-4 below shows the Chinese standard stiffness property requirement of rail pad for different rail type.

**Table 2-4: Rubber pad Stiffness for different rail types according to China Standard.**

| Rail pad type | Static stuffiness Values (KN/mm) | Conditions of Use |
|---|---|---|
| **43-7-7** | 100~130 | |
| **43-10-7** | 80~110 | |
| **50-7-9** | 110~150 | |
| **50-10-9** | 90~130 | |
| **60-10-11** | 90~120 | R<600m curve |
| **60-10-17** | 55~80 | R$\geq$ 600m curves and |
| **60-12-17** | 40~60 | Straight lines rail joints |

According to the Chinese standard, the dimension of rail pad varies with rail type or rail loading condition. For this particular research, steel compression rubber mold prepared for 10 mm thick with 9 trench railpad for 50kg/m rail type and which is marked as 50-10-9 according to TB/T2626-1995.

Table 2.5 shows the dimension and shape of the rail pad. The positional angular spacing of the railpad should be compatible with the concrete sleeper. The upper length of the railpad where the rail is laid should be wider than the width of the rail. The trench on the rail pad helps to drain the water and to elastic the railpad in the compartment.

**Table 2-5: The rail pads shape dimension based on rail type**

| Steel Trackpad for Rail type kg/m | Plate dimensions and bias (mm) | | | | **Trench Total Article** | **Marked** |
|---|---|---|---|---|---|---|
| | Upper length | Positioning angular spacing | Width | Thickness | | |
| **43** | **185** | $\mathbf{170^{+3}_{-1}}$ | $113^{+15}_{-2}$ | $7^{+0.5}_{0}$ | 7 | 43-7-7 |
| | | | | $10^{+0.5}_{0}$ | 7 | 43-10-7 |
| 50 | | | $\mathbf{131^{+1}_{-1}}$ | $7^{+0.5}_{0}$ | 9 | 50-7-9 |
| | | | | $\mathbf{10^{+0.5}_{0}}$ | **9** | **50-10-9** |
| **60(or 75)** | | | $149^{+1}_{-2}$ | $10^{+0.5}_{0}$ | 11 | 60-10-11 |
| | | | | $10^{+0.5}_{0}$ | 17 | 60-10-17 |
| | | | | $12^{+0.5}_{0}$ | 17 | 60-12-17 |

# CHAPTER 3 EXPERIMENTAL STUDIES

## 3.1 General Explanation of the Experiment

The rubber resilient material compounding should satisfy the basic requirements that are illustrated in the standards. In order to examine the quality of the rubber compound, number of standard quality tests are carried out. These are shore A hardness, tensile strength test before and after aging, elongation test before and after aging, constant compression set test, wear resistance test and stiffness test. Tests like Rheo-line and viscosity tests are also done to examine the condition of compound workability and production curing environment.

The rubber pad compound test results such as tensile strength, elongation, hardness, abrasion, breaking load, 200% fixed secondary stress, constant compression set test result and Rheo-line test results of curing temperature and time are recorded. After production of the rail pad, the static stiffness of rail pad is determined using Universal Testing Machine.

The laboratory test result shows that rubber compound type 1, type 6 and type 7 could be applicable for the service life of 300 GMT (gross Million of tonnage). Rubber compound type 12 satisfies the Chinese standard.

All laboratory experimental studies were conducted in Horizon Addis Tyre S.C. Chinese GB and ASTM standards are the sole guide for test methodology and product quality reference. The production of reclaim material from end-of-life tyre was not possibly done due to the unavailability of recycling machine. Therefore, the processed recycled material is used. In order to achieve the standard quality of the rail pad, more than 12 specimens are prepared and for each 12 basic rubber quality tests are carried out due to the variable impact of chemicals concentration in the compound. After the achievement of the required compound quality, the final shape of the rail pads is produced in the Production Curing machine using prepared steel rubber pad mold which is prepared for this purpose.

## 3.2 Experimental Program Flow Chart

This experiment is done based on the design program described in Chart 1-1 shown below.

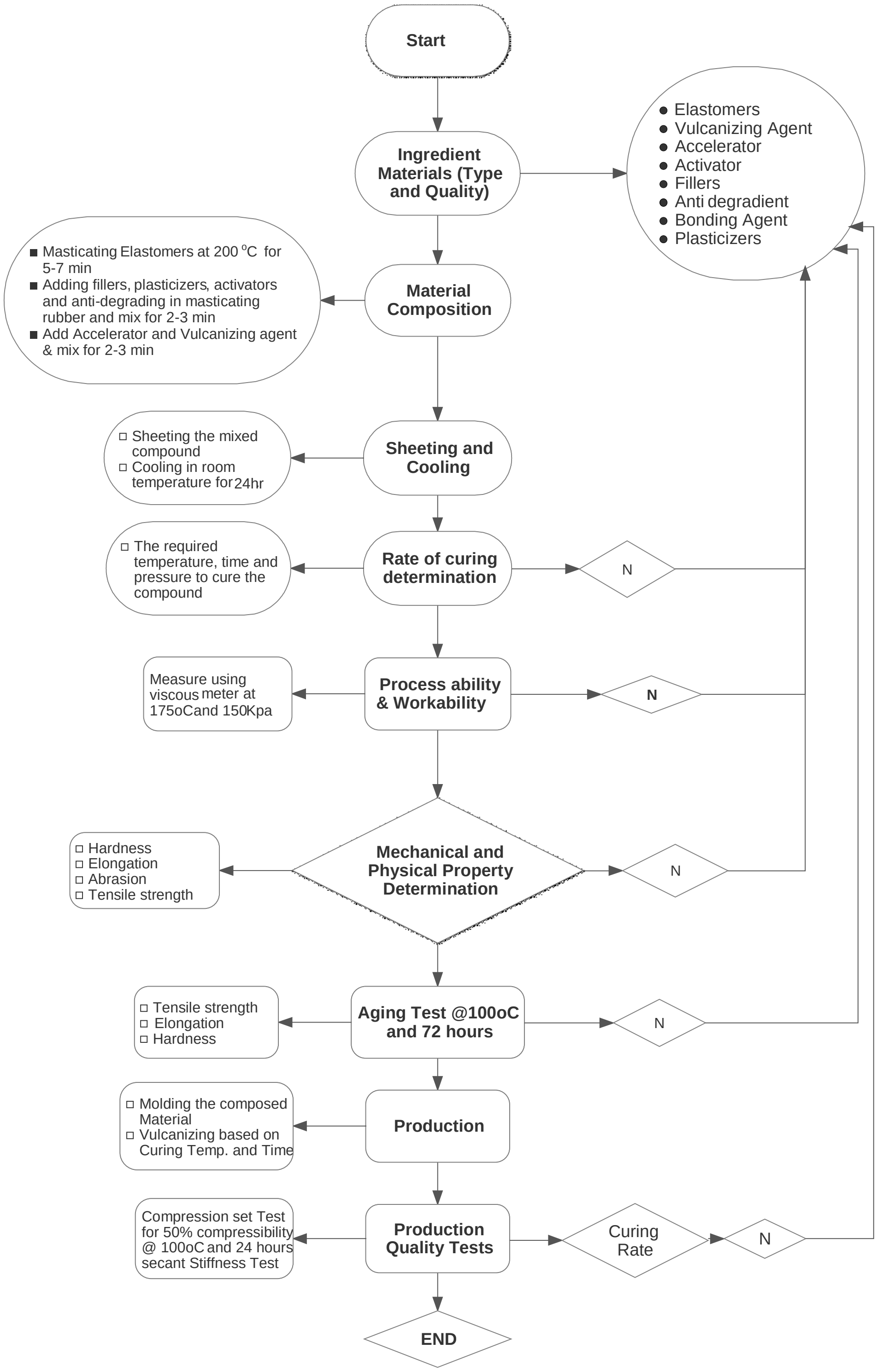



**Chart 1-1: Experimental Program of Resilient Material Formulation and Production**

## 3.3 Chemical Compounding of the rubber rail pad material

The property of each ingredient has a positive and negative effect on overall rubber compound. For example, if the amount of Carbon Black increases, the hardness property of the compound increase. On the contrary, the elongation property of compound decrease. In order to achieve the standard of rubber rail pad compound properties, more than twelve lab specimens are prepared and investigated.

The other constraint in rubber pad production is the economic aspect. For single one-kilometer railway track, more than 3,400 rail pads are required. In order to reduce the unit price, application of recycled rubber material/ reclaimed rubber is one basic option. Beside this, using recycled rubber material gives positive environmental impact. Therefore, up to 50 PHR (Parts per Hundred of Rubber) of reclaimed material is used in the rail pad compounding.

### 3.3.1 Specimen Preparation and experimental testing

Ingredient preparation and weighing, mastication, and milling, vulcanization and molding are the basic processes during test specimen preparation. After measurement of ingredients, elastomers (Natural Rubber and Natural Reclaim Rubber material) are masticated for 5-7min in 200$^{o}$C using Ambry mixer or 10-12min in 80$^{o}$C using cord mixing machine. After mastication organic and inorganic fillers (Carbon Black, Silica or Calcium Carbonate), Plasticizers (DUTREX-RA3 oil), activators (Zink Oxide and Stearic Acid), anti-aging or anti-ozone and anti-oxidant (ANTILUX, 6PPD or/and TMQ) are added and mixed with masticated rubber for 2-3min, and finally accelerator (TBBS) and vulcanizing agent (sulfur) are added and mixed for 2-3 min.

The mixed compound is processed in milling machine for sheeting and cooling. The rubber sheets are taken to the prepared ventilated area for 24hrs to give up the temperature and slow down the reaction process. Then the samples are taken and molded for viscose meter, Reo-line and bra bender machine for measurement of viscosity, curing rate /Torque and specific gravity of compound respectively.

The cooled rubber compound is cut and put in the laboratory mold in vulcanized press machine with 175$^{o}$C and required curing duration.

The cured compound is molded for tensile and elongation test (Testo-meter), abrasion test, compression set test, and hardness test. In case of aging test, the molded specimen is placed in the oven at a temperature of 100ºC, for 72 hr. After aging, tensile strength, elongation and hardness tests are measured.

### 3.3.2 Railway Resilient rubber pads material compounding

Rubber resilient material contains basic compound elastomer (i.e. natural rubber, Styrene Butadiene Rubber (SBR), reclaim rubber), the vulcanizing agent, activators, accelerators, organic and inorganic filler, anti-aging, plasticizers and other processing aid materials are composed based on per hundred of rubber content. Table 3-1 briefly describe the ingredient and their proportion during composition.

**Table 3-1: Rubber Railpad Compositions**

| **RECIPE OF COMPOUND:** Railway Resilient Pads | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **APPLICATION: Rail pad for lab. Tests and rubber rail pad preparation** | | | | | | | | | | | | |
| INGREDIENTS | **Type -1 in PHR** | **Type -2 in PHR** | **Type -3 in PHR** | **Type -4 in PHR** | **Type -5 in PHR** | **Type -6 in PHR** | **Type -7 in PHR** | **Type -8 in PHR** | **Type -9 in PHR** | **Type -10 in PHR** | **Type -11 in PHR** | **Type -12 in PHR** |
| Natural Rubber - SMR-20 | 85.00 | 90.00 | 85.00 | 90.00 | 90.00 | 90.00 | 85.00 | 80.00 | 70.00 | 60.00 | 50.00 | 50.00 |
| SBR 1500 | 15.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural Reclaim Rubber | 0.00 | 10.00 | 15.00 | 10.00 | 10.00 | 10.00 | 15.00 | 20.00 | 30.00 | 40.00 | 50.00 | 50.00 |
| N-660/ Gpf Carbon Black | 40.00 | 40.00 | 40.00 | 40.00 | 60.00 | 60.00 | 60.00 | 70.00 | 70.00 | 70.00 | 50.00 | 50.00 |
| Dutrex Ra-3 | 0.00 | 0.00 | 5.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 10.00 | 10.00 |
| Calcium Carbonate | 0.00 | 0.00 | 15.00 | 10.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zinc Oxide (98%) | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Stearic Acid 1600 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Silica / Vulcasil's | 30.00 | 30.00 | 15.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 |
| Antilux | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 | 2.00 | 2.00 | 1.50 |
| 6ppd | 0.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 4.00 |
| Tmq | 1.50 | 0.00 | 2.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.00 |
| Normal Sulphur | 1.00 | 6.00 | 6.00 | 3.00 | 3.00 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.00 |
| TBBS | 2.50 | 2.50 | 2.50 | 1.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 |
| **TOTAL** | **183.0** | **199.5** | **212.0** | **210.5** | **221.5** | **220.0** | **225.0** | **240.0** | **237.0** | **242.0** | **227.0** | **227.0** |

## 3.4 Summary of Laboratory Test Results and Discussion

Physical and mechanical tests on the material are performed according to Chinese test standard GB and American's test standard ASTM for rubber material. Mechanical and physical properties of the compound like stress at break, stress at 100 % strain, stress at 200 % strain, elongation at break, stress and elongation after aging, shore A hardness, abrasion loss and constant compression set test results are presented as a summary on Table 3-2.

Resilience material compound Type-1 contain basic natural rubber and styrene betadine rubber (SBR) as a basic elastomers with 85 PHR and 15 PHR respectively. Test results shows that, this compound has a good mechanical and physical properties for 300 GMT load service. It satisfies the material quality requirement of Australian and Indian improved resilience pad code of standards. This composite material uses as a bench mark for the other material composition which uses recycled rubber as elastomeric ingredients. The recycled rubber replaces SBR to give contribution for environment pollutant reduction.

Resilience material compound Type-2 is prepared using 10 PHR recycled rubber which is completely replace the SBR material. In addition, the amount of volcanizing agent, sulfur, increased to 6 PHR in order to enhance the curing process. But, the compound had changed its physical and mechanical properties. Even the concentration of activators and oil ingredients changed and sulfur amount constant in compound type 3, that much no significant mechanical and physical properties as compared with compound type 2. These implies that the concentration of sulfur is one of the cause of composite material properties lose.

In resilience material compound Type-4 sulfur, concentration reduced to 3 PHR and the amount of Dutrex oil increase to 15 PHR and other ingredient amounts are the same as compound Type 3. Tests result show that most of the required compound properties are achieved except Aging test for tensile strength. One of the approach to increase the tensile strength of the compound is increasing the amount of organic filler, carbon black. In compound Type 5 the amount of carbon black concentration increased to 60PHR and others ingredient constant. The result shows that the tensile strength increase significantly but material elongation fall below standard range. To increase the elongation properties, the amount of sulfur reduced from 3 PHR to 1.5 PHR in compound Type 6 and Type 7 with recycle material concentration 10 PHR and 15 PHR respectively, so that the required standard for 300 GMT loading service is achieved.

**Table 3-2: Composite of Resilient Material test summary**

| Rail pad Compound No. | LAB. TEST RESULT (average) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Shore A Hardness (º) | Abrasion Loss (%) | Breaking load (Kg) | Tensile strength (MPa) | Modulus at 100% (MPa) | 200% fixed secondary stress (MPa) | 300% fixed tertiary stress (MPa) | Elongation (%) | Constant compression set (100º,24hrs) |
| Type 1 | 70 | 5.94 | 28.606 | 19.432 | 4.919 | 11.887 | 17.864 | 329.17 | 29.23 |
| After Aging | 78 | | 20.396 | 13.794 | 5.632 | - | - | 220.95 | - |
| Type 2 | 79 | 6.07 | 19.907 | 12.221 | 6.871 | 12.51 | - | 187.21 | 35.36 |
| After Aging | 86 | | 9.727 | 6.853 | - | - | - | 28.95 | - |
| Type 3 | 75 | 6.05 | 12.803 | 8.428 | 5.604 | - | - | 152.15 | 33.69 |
| After Aging | 82 | | 7.689 | 5.417 | - | - | - | 34.908 | - |
| Type 4 | 65 | 4.43 | 19.362 | 13.095 | 3.851 | 10.998 | 13.466 | 295.25 | 29.42 |
| After Aging | 77 | | 12.449 | 8.166 | 4.11 | - | - | 187.36 | - |
| Type 5 | 70 | 5.45 | 20.32 | 13.743 | 5.274 | 11.442 | - | 254.67 | 29.98 |
| After Aging | 79 | | 13.48 | 11.213 | 5.784 | - | - | 193.81 | - |
| Type 6 | 66 | 5.02 | 24.879 | 17.527 | 4.459 | 11.815 | 15.482 | 342.75 | 29.63 |
| After Aging | 78 | | 13.975 | 11.345 | 4.265 | - | - | 186.45 | - |
| Type 7 | 64 | 6.32 | 23.77 | 16.081 | 3.854 | 11.400 | 14.400 | 338.86 | 29.76 |
| After Aging | 75 | | 14.368 | 10.864 | 4.954 | - | - | 193.48 | - |
| Type 8 | 69 | 5.98 | 21.971 | 14.184 | 4.508 | 11.418 | 13.752 | 307.52 | 29.85 |
| After Aging | 79 | | 14.512 | 9.56 | 5.657 | - | - | 200.36 | - |
| Type 9 | 73 | 5.22 | 20.449 | 14.404 | 7.259 | 13.250 | - | 227.34 | 29.95 |
| After Aging | 81 | | 13.102 | 9.231 | 5.689 | - | - | 90.158 | - |
| Type 10 | 74 | 5.62 | 17.934 | 12.635 | 6.458 | 11.870 | - | 224.16 | 29.91 |
| After Aging | 81 | | 14.025 | 10.223 | 9.99 | - | - | 103.564 | - |
| Type 11 | 65 | 5.98 | 17.249 | 12.493 | 5.17 | 10.550 | - | 251.68 | 29.89 |
| After Aging | 79 | | 13.538 | 10.351 | 9.289 | - | - | 108.62 | - |
| Type 12 | 73 | 6.00 | 16.108 | 13.882 | 3.462 | 10.588 | 13.582 | 304.52 | 29.95 |
| After Aging | 80 | | 15.297 | 10.777 | 5.912 | 9.453 | - | 200.98 | - |

Resilience material compound Type-8, Type-9, Type-10, Type-11 and Type-12 are conducted by increasing the amount of recycled rubber from 20 PHR to 50 PHR. The test result shows that as the amount of recycled rubber increased, the physical and mechanical properties of the compound significantly reduced. As result, material compound Type 12 with more reclaim material, 50PHR, used for 200 GMT service load.

Finally, the material composition of Type 1, Type 6 and Type 12 successfully satisfy the basic railpad material quality.

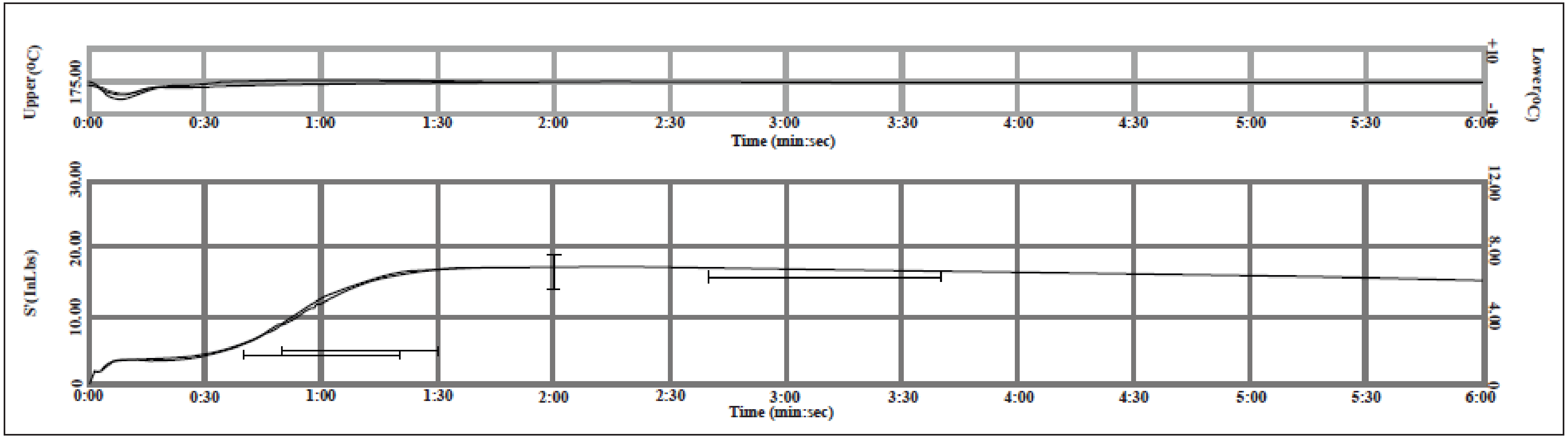
Required curing temperature and time for each type of resilient rubber composite material is different. Rhioline test machine measures curing temperature and time. On this experiment, the Rhioline measures torque resistance of the composite material at a given 175$^{o}$C temperature. It gives the measured result of 90% curing time of the compound. 90% curing time (T-90) shows that 90% of the compound has been cured with 175$^{o}$C on indicated T-90 time duration. In addition, during the service life of the pads 100% of curing is achieved. Rhioline measures deta of composite material Type-1, Type-6 and Type-12 are presented in graphs from figure 3-1 to figure 3-3.

The test result shows that, composite material Type-1 cured with 175$^{o}$C and T-90 time duration of one minute and 18 seconds; Type-6 cured with 175$^{o}$C and T-90 time duration of 2 minutes and 07 seconds; and Type-12 cured with 175$^{o}$C and T-90 time duration of 2 minutes and 21 seconds. The result indicates that as the amount of recycled rubber increase on composing material, the required curing time and temperature also increase. That means the recycled material reduce rate of composing and process ability.

Beside this, the Rhioline test shows ether the composite material reverse or increase its mechanical and physical properties during overheating. Torque versus Time graph of the Rhioline test result shows that all resilient composite material are not reversed by overheating or as the time of heating increase, the material gain more physical and mechanical properties.

Figure 3-4 shows tensile strength and elongation Testo meter test results of  composite material Type -4, Type -6 and Type -12. It shows recyled materials reduced the tenile strength and elaticity of the material as there content incrsease in material composion.

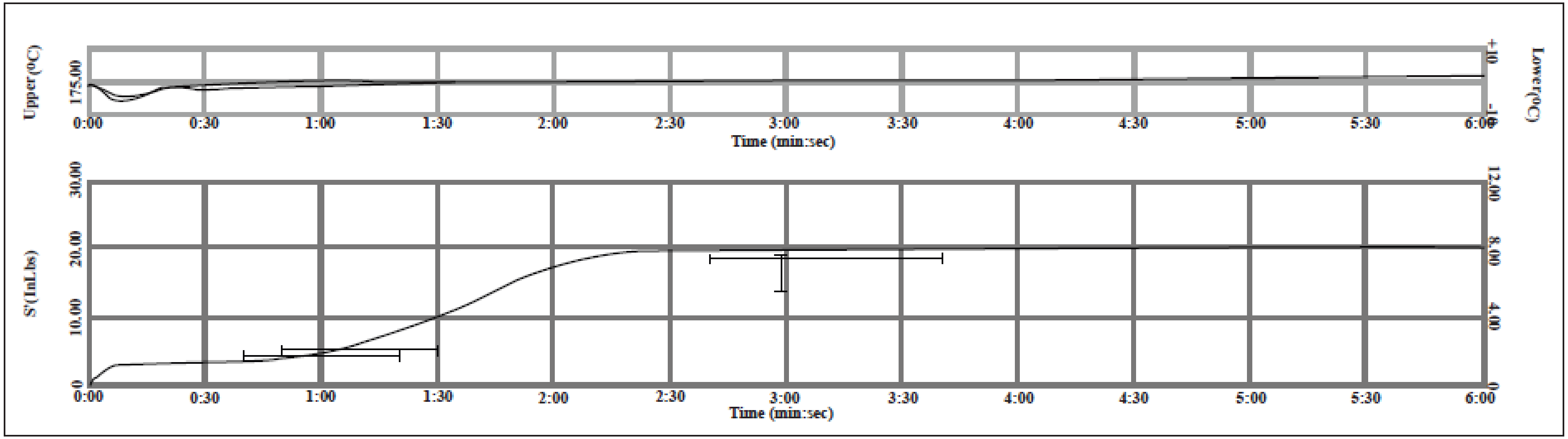
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00ºC | 0.5º |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TSI | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pad test-1-02 | Result 1 | 5/29/2015 5:17:31 AM | | 3.68 | 3.59 | 17.19 | 15.46 | 0:31 | 0:34 | 0.55 | 1:19 |
| Pad test-1-01 | Result 1 | 5/29/2015 5:10:41 AM | | 3.49 | 3.38 | 17.36 | 15.36 | 0:31 | 0:34 | 0.54 | 1:18 |
| | Mean | | | 3.59 | 3.49 | 17.27 | 15.41 | 0:31 | 0:34 | 0.55 | 1:18 |
| | Std Dev.(p) | | | 0.10 | 0.10 | 0.08 | 0.05 | 0:00 | 0:00 | 0.01 | 0.00 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0.00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0.00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 9.81 | 0.00 | 289.25 | 83.87 | 0.00 | 22.52 |
| | Cpk | | | 0.00 | 0.00 | 6.77 | 0.00 | -132.45 | -65.81 | 0.00 | -61.38 |

**Figure 3-1: Torque Vs Time graph of compound Type 1**

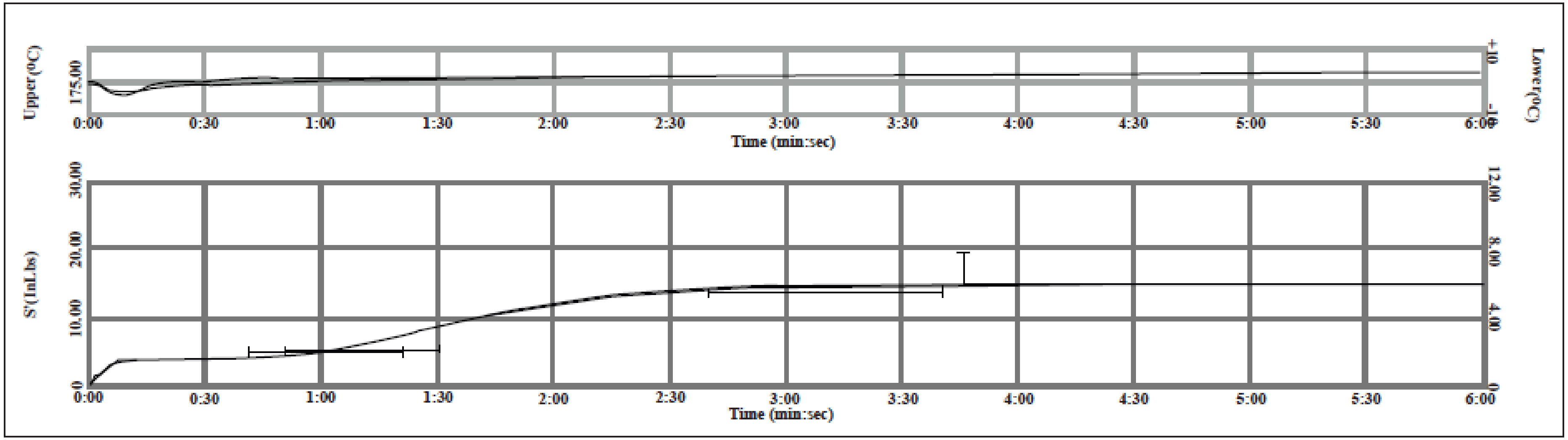
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00ºC | 0.5º |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TSI | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pad test-6-2 | Result 2 | 6/9/2015 8:26:43 AM | | 4.10 | 4.10 | 120.18 | 19.15 | 0:56 | 1:03 | 1.37 | 2:07 |
| Pad test-6-1 | Result 1 | 6/9/2015 8:20:06 AM | | 4.16 | 4.16 | 20.26 | 19.12 | 0:55 | 1:03 | 1.37 | 2:08 |
| | Mean | | | 4.13 | 4.13 | 20.22 | 19.11 | 0:56 | 1:03 | 1.37 | 2:07 |
| | Std Dev.(p) | | | 0.03 | 0.03 | 0.01 | 0.01 | 0:00 | 0:00 | 0.00 | 0.00 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0.00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:10 | 0:50 | 0.00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 22..05 | 0.00 | 29.87 | 33.05 | 0.00 | 22.82 |
| | Cpk | | | 0.00 | 0.00 | -10.77 | 0.00 | 23.25 | 21.10 | 0.00 | -24.98 |

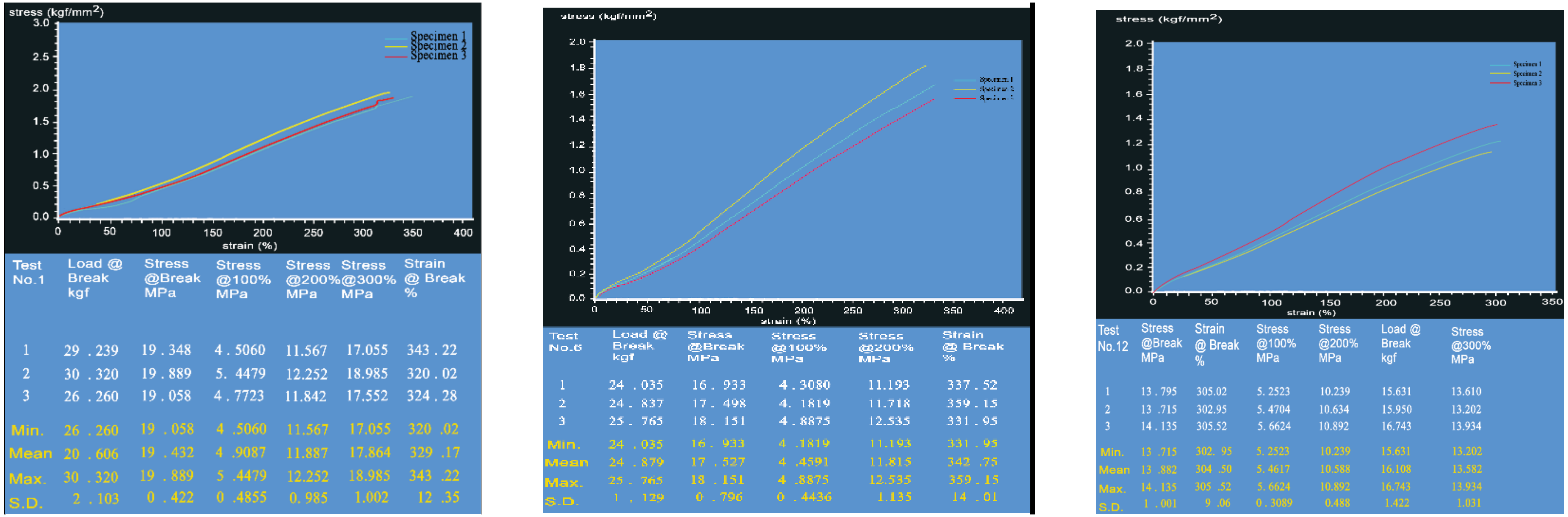
**Figure 3-2 Torque Vs Time graph of compound type 6**

| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00ºC | 0.5º |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TSI | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pad test-12-01 | Result 1 | 7/22/2015 11:37:21 AM | | 3.94 | 3.78 | 13.93 | 13.69 | 0:58 | 0:60 | 1.34 | 2:22 |
| Pad test-12-03 | Result 1 | 7/22/2015 11:30:25 AM | | 3.75 | 3.74 | 14.18 | 13.86 | 0:56 | 0:59 | 1.33 | 2:21 |
| | Mean | | | 3.84 | 3.76 | 14.06 | 13.78 | 0:57 | 0:59 | 1.34 | 2:21 |
| | Std Dev.(p) | | | 0.10 | 0.02 | 0.12 | 0.09 | 0:01 | 0:00 | 0.00 | 0.01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0.00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0.00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 6.71 | 0.00 | 10.21 | 17.30 | 0.00 | 19.94 |
| | Cpk | | | 0.00 | 0.00 | 0.15 | 0.00 | 8.69 | 7.99 | 0.00 | -12.30 |

**Figure 3-3: Torque Vs Time graph of compound type 12**




a) b) c)

**Figure 3-4: Testometer result of Stress Vs Strain graph of compound: a) Type 1, b) Type 6 and c) Type 12**

Abrasion loss test results of the rail pad compound Type 1, Type 6 and Type 12 are briefly shown in Table 3-3. Even if that much no abrasion effect on resilience material, all composite materials have a great resistance of abrasion when the result compare with Chinese standard limit.

After sample of resilience pad production, the stiffness test carriedout using universal testing machine. The computational result is described here in Table 3-4. The average stiffness is 92.99KN/MM. According to standards, the rail pad type 50-10-9 has stiffness range between 90-130KN/mm. Thus, it is satisfactory

**Table 3-3: Abrasion test result of compound Type -1, Type -6 and Type -12**

| Rail pad Compound No | Test sample No | Abrasion Test Result | | | |
|---|---|---|---|---|---|
| | | Before Abrasion (kg) | After Abrasion (kg) | Difference (kg) | Loss (%) |
| **Type 1** | 1 | 3.26 | 3.06 | 0.2 | **5.94** |
| | 2 | 3.26 | 3.07 | 0.19 | |
| | 3 | 3.24 | 3.05 | 0.19 | |
| | Average | 3.25 | 3.06 | 0.19 | |
| **Type 6** | 1 | 3.38 | 3.21 | 0.17 | **5.02** |
| | 2 | 3.39 | 3.22 | 0.17 | |
| | 3 | 3.39 | 3.22 | 0.17 | |
| | Average | 3.39 | 3.22 | 0.17 | |
| **Type 12** | 1 | 3.33 | 3.13 | 0.20 | **6.00** |
| | 2 | 3.34 | 3.13 | 0.21 | |
| | 3 | 3.33 | 3.14 | 0.19 | |
| | Average | 3.33 | 3.13 | 0.2 | |

**Table 3-4: Rail pad stiffness test data and result**

| Test No. | Load (KN) | Displacement (mm) | Stiffness*k=f/d,[KN/mm] (average) |
|---|---|---|---|
| **1** | 200KN | 2.18 | 91.74KN/mm |
| **2** | 200KN | 2.32 | 86.21KN/mm |
| **3** | 200KN | 1.98 | 101.01KN/mm |
| **Average** | 200KN | 2.16 | **92.99KN/mm** |

* Stiffness is the rigidity of an object, the extent to which it resists in response to an applied force.

$$K=F/D \tag{1}$$

Where,

K= Stiffness, F= Applied force, D= Displacement

The material cost analysis of the rail pad compound of type 1, type 12 and type 6 is presented in tables 3-5. 3-6 and 3-7 respectively. The economy analysis shows that it is advantageous to use recycled contained. The result shows Cost of rail pad/kg reduces from 35.42 birr to 32.12 birr. For 300 gram (one rail pad weight) the material cost reduces from 11.80 birr to 10.70 birr. This is a discount of about 9.6%. Cost of composite material Type-12 is significantly cheap as compared with others because of its large amount of recycled rubber content.

**Table 3-5: Material cost analysis of rail pad (Type-1)**

| Rail pad /Test-1: RP M1 ($1^{st}$ Masterbatch) | | | | | |
|---|---|---|---|---|---|
| Ingredients | %PER COMP | PHR | Weight (Kg) | Unit Cost (Birr) | Compound Cost (Birr) |
| SMR-20 | 64.45 | 85.00 | 0.465 | 38.59 | 17.93 |
| SBR 1500 | 8.20 | 15.00 | 0.082 | 51.07 | 4.19 |
| N-660/GPF | 21.86 | 40.00 | 0.219 | 24.18 | 5.29 |
| Zinc Oxide (98%) | 2.73 | 5.00 | 0.027 | 56.74 | 1.55 |
| Stearic Acid 1600 | 1.64 | 3.00 | 0.016 | 26.87 | 0.44 |
| Silica /Vulcasils | 16.39 | 30.00 | 0.164 | 28.01 | 4.59 |
| TMQ | 0.82 | 1.50 | 0.008 | 65.27 | 0.54 |
| S.Total | 98.09 | 179.50 | 0.981 | | 34.52 |
| RP M1 ($1^{st}$ Master batch) | 98.09 | 179.50 | 0.981 | 34.52 | 33.86 |
| Normal Sulphur | 0.55 | 1.00 | 0.005 | 14.94 | 0.08 |
| TBBS | 1.37 | 2.50 | 0.014 | 108.18 | 1.48 |
| TOTAL | 100.00 | 183.00 | 1.00 | | 35.42 |

**Table 3-6: Material cost analysis of rail pad (Type -12)**

| **Rail pad /Test-12: RP M1 ($1^{st}$ Masterbatch)** | | | | | |
|---|---|---|---|---|---|
| Ingredients | %PER COMP | PHR | Weight (Kg) | Unit Cost (Birr) | Compound Cost (Birr) |
| SMR-20 | 35.09 | 80.00 | 0.356 | 38.59 | 13.75 |
| Reclaim Rubber | 21.93 | 50.00 | 0.223 | 18.47 | 4.11 |
| N-660/GPF | 21.93 | 50.00 | 0.223 | 24.18 | 5.39 |
| DUTREX-RA3 | 4.39 | 10.00 | 0.045 | 33.49 | 1.49 |
| Zinc Oxide (98%) | 2.19 | 5.00 | 0.022 | 56.74 | 1.26 |
| Stearic Acid 1600 | 0.88 | 2.00 | 0.009 | 26.87 | 0.24 |
| Silica /Vulcasils | 8.77 | 20.00 | 0.089 | 28.01 | 2.50 |
| Atilux | 0.66 | 1.50 | 0.007 | 85.52 | 0.57 |
| 6PPD | 1.75 | 4.00 | 0.018 | 81.87 | 1.46 |
| TMQ | 0.88 | 2.00 | 0.009 | 65.27 | 0.58 |
| **S.Total** | **98.46** | **224.5** | **0.985** | | **31.35** |
| RP M1 ($1^{st}$ Master batch) | 98.46 | 224.5 | 0.985 | 31.35 | 30.87 |
| Normal Sulfur | 0.44 | 1.00 | 0.004 | 14.94 | 0.07 |
| TBBS | 1.10 | 2.50 | 0.011 | 108.18 | 1.19 |
| **TOTAL** | **100** | **228.00** | **2.73** | | **32.12** |

**Table 3-7: Material cost analysis of rail pad (Type -6)**

| Rail pad /Test-6: RP M1 (1st Masterbatch) | | | | | |
|---|---|---|---|---|---|
| **Ingredients** | %PER COMP | PHR | Weight (kg) | Unit Cost (Birr) | Compound Cost (Birr) |
| **SMR-20** | 45.45 | 100 | 0.463 | 38.59 | 17.87 |
| **Reclaim Rubber** | 4.55 | 10.00 | 0.046 | 18.47 | 0.86 |
| **N-660/GPF** | 27.27 | 60.00 | 0.278 | 24.18 | 6.72 |
| **DUTREX-RA3** | 6.82 | 15.00 | 0.069 | 33.49 | 2.33 |
| **Zinc Oxide (98%)** | 2.27 | 5.00 | 0.023 | 56.74 | 1.31 |
| **Stearic Acid 1600** | 1.36 | 3.00 | 0.014 | 26.87 | 0.37 |
| **Silica /Vulcasils** | 9.09 | 20.00 | 0.093 | 28.01 | 2.59 |
| **6PPD** | 1.36 | 3.00 | 0.014 | 81.87 | 1.14 |
| **S. Total** | **98.18** | **216.00** | **0.982** | | **33.18** |
| **RP M1 (1st Master batch)** | 98.18 | 216.00 | 0.982 | 33.18 | 32.58 |
| **Normal Sulfur** | 0.68 | 1.50 | 0.007 | 14.94 | 0.10 |
| **TBBS** | 1.14 | 2.50 | 0.011 | 108.18 | 1.23 |
| **TOTAL** | 100 | 220.00 | 1.000 | | 33.91 |

As a summery, railway track resilient materials are composed from recycled end-of-life tires/reclaim rubber. During material composition, the reclaimed material is masticated and milled with natural rubber to react with fillers and other chemicals (such as activators, accelerators, plasticizers, anti-oxidants and volcanizing agent) to achieve the resilient pads quality. In order to achieve the standard quality of the resilient pads, more than 12 specimens are prepared and basic rubber quality tests are carried out due to the variable impact of chemicals concentration in the compound.

The resilient material quality is checked based on Australian, Chinese and Indian standards using laboratory tests. Standard quality tests such as Shore A hardness, tensile strength test before and after aging, elongation test before and after aging, relaxed modulus at 100% elongation, secondary stress at 200% elongation, constant compression set test, wear resistance test and stiffness tests were conducted for test specimens. Rhioline and viscosity tests are conducted to control the curing environment and the process ability of the resilient pad compound respectively. During material composition up to 50PHR (Parts per Hundred of Rubber) of recycled rubber material is applied. Once the required compound quality has achieved, by preparing steel rubber pad mold, the final shape of the rail pad is produced using production curing machine.

# CHAPTER 4 FINITE ELEMENT MODELING OF SLAB TRACK ON BRIDGE SECTION USING SLEEPER PAD

## 4.1 General description on slab track on bridge modeling

The application of the prepared resilient pads (physical and mechanical properties of the prepared resilient pads) are illustrated on Slab Track Bridge. The Railway Slab Track Bridge with sleeper pad and without sleeper pad is modeled and analyzed using ABAQUS Finite Element solver to determine the effect of sleeper pad in dynamic loading. A moving wheel load is running over the simple supported T-Girder Bridge for dynamic explicit analysis and steady-state dynamic analysis in both time and frequency domains to determine bridge displacement, stress and deck acceleration.

## 4.2 The case study bridge

Slab Track on the bridge that is used for modeling to compare the sleeper pad effect on Slab-track-bridge is a part of the Sebeta-Meisso national railway line project on the east of Ethiopia. A Sebeta-Meisso line is a present contract for a new railroad between Addis Ababa and Djibouti. The bridge is a T-Girder with a span of 32 m, a height of the girder is 2.5m and a width of 2.1 m. The dimensions of the bridge are shown in Figures 4.1.

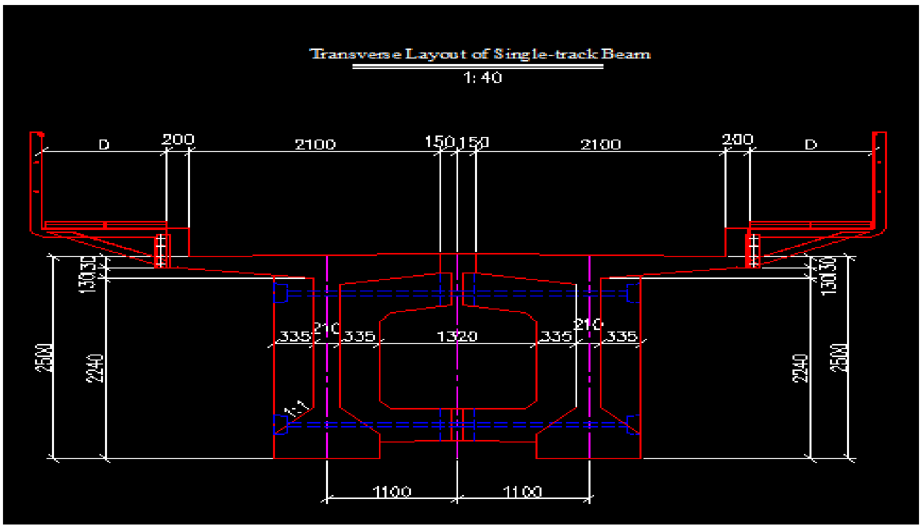



**Figure 4-1: Sebeta-Meisso rail way line project single track bridge section layout**

The quality of concrete bridge and sleeper is C-35, the rail is 50kg/m and train axle load is 25 tone. The concrete, rail, railpad and sleeper pad materials parameter are listed in Table 4.1. Stiffness and damping property of fasteners are ignored in this model because of very small effect relative to rail pad and sleeper pad.

**Table 4-1: Material parameters for the concrete bridge and sleeper**

| Material | Notation | Parameter | Value | Unit |
|---|---|---|---|---|
| **Concrete Bridge and sleeper** | E | Elastic modulus | $35x10^9$ | Pa |
| | P | Density | 2,600 | Kg/m3 |
| | V | Poisson's ratio | 0.2 | - |
| **Rail** | E | Elastic Modulus | $210x10^9$ | Pa |
| | P | Density | 7800 | Kg/m3 |
| | V | Poisson's ratio | 0.3 | - |
| **Rail pad and sleeper pad** | Kp | Stiffness | 100 | MN/m |
| | Cp | Damper | 60 | KN. s/m |

## 4.3 Finite Element Modeling Procedure

Dynamic numerical modeling is created using ABAQUS software. ABAQUS software is a wide range finite element program that excels in solving linear and non-linear spatially distributed field problems.

Most models created in ABAQUS/CAE are assembled from different parts. It always starts with creating different parts separately in the parts module. Different parts may need different material properties, which are defined in the property module. The model then is assembled in the assembly model, by combing the different instances originates from different parts. In the step module, the analysis is divided in different analysis step, such as static and dynamic analyses. These can be combined in a way to resemble the physical problem that is to be analyzed. The instances in the model will not interact with each other until they have been connected in the interaction module. The loads acting on the model are defined in the load module, as well as boundary conditions. The load and boundary conditions can be defined to vary over time as well as over different steps. The whole model then meshes in the mesh module. And finally, analyze the model [5], [25].

Slab track bridge modeling is constituted by a simple supported T-Girder bridge, rail, train wheel and sleeper group parts. They are all created in two-dimension (2D) and interacted using dashpot and/or normal contact. To introduce damping to the model the ABAQUS input material property referred to as viscous damping was used for railpad and sleeper pad. The entire section of the simple supported T-Girder Bridge and the rail are modeled as a 2D by Timoshenko beam elements while the sleeper is by 2D planar solid elements. The basic outline of the model can be seen in Figure 4.2.

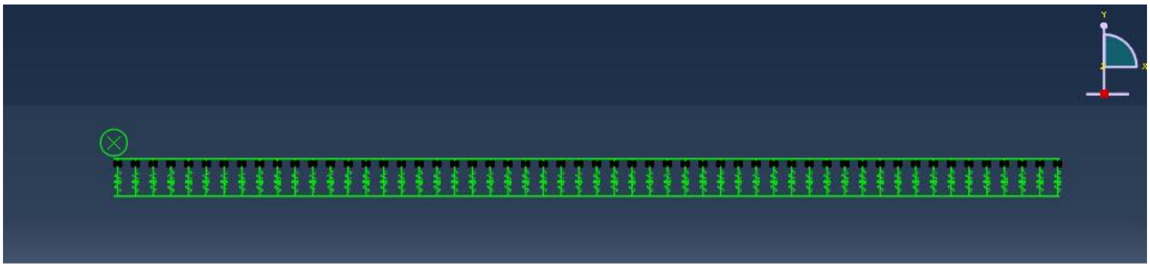


**Figure 4-2: The basic outline of a 2D ABAQUS model of a slab track on T-Girder Bridge**

## 4.4 Finite element Analysis Results and Discussion

Finite element dynamic explicit analysis and steady-state dynamic analysis result of the T-Girder Bridge with and without sleeper pad resilient material include displacement, velocity, acceleration and stress on the bridge. All the results are presented in comparative form using graph based on time and frequency domain for dynamic explicit and steady state analysis respectively.

The dynamic explicit analysis, which considers 25 tons of axle load and 120 km/hr. the speed of a train, the result shows that sleeper pad reduces the vertical acceleration at mid-span of the bridge by half (~50%) as compared with the slab bridge without sleeper pad. However, the analysis result of bridge stress, vertical displacement, and vertical velocity has no significant change between the bridge with sleeper pad and without sleeper pad. From Figure 4.3 to Figure 4.6 shows the dynamic explicit result of acceleration, velocity, displacement, and stress of the bridge with and without sleeper pad in the time domain.

The steady state dynamic analysis, which considers 0Hz-1800Hz frequency, the result shows that the sleeper pad globally reduces the acceleration, displacement and stress by 21.6%, 48.88% and 41.5% respectively in a given frequency range. At low frequency (i.e.

frequency less than 15Hz) the dynamic impact on bridge displacement, velocity and stress at mid-point are high. The acceleration becomes peak at the frequency range of 150Hz to 300Hz. Figure 4.7 to Figure 4.10 shows steady state dynamic analysis result of slab track bridge acceleration, velocity, displacement and stress in a given frequency domain.

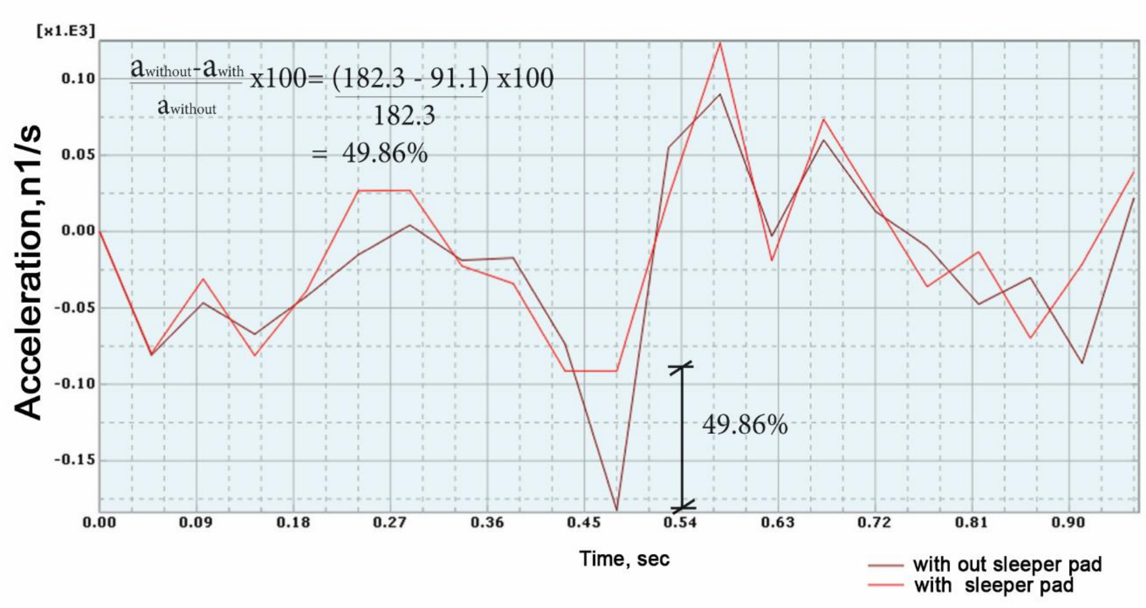



**Figure 4-3: Vertical acceleration of the bridge with and without resilient sleeper pad**

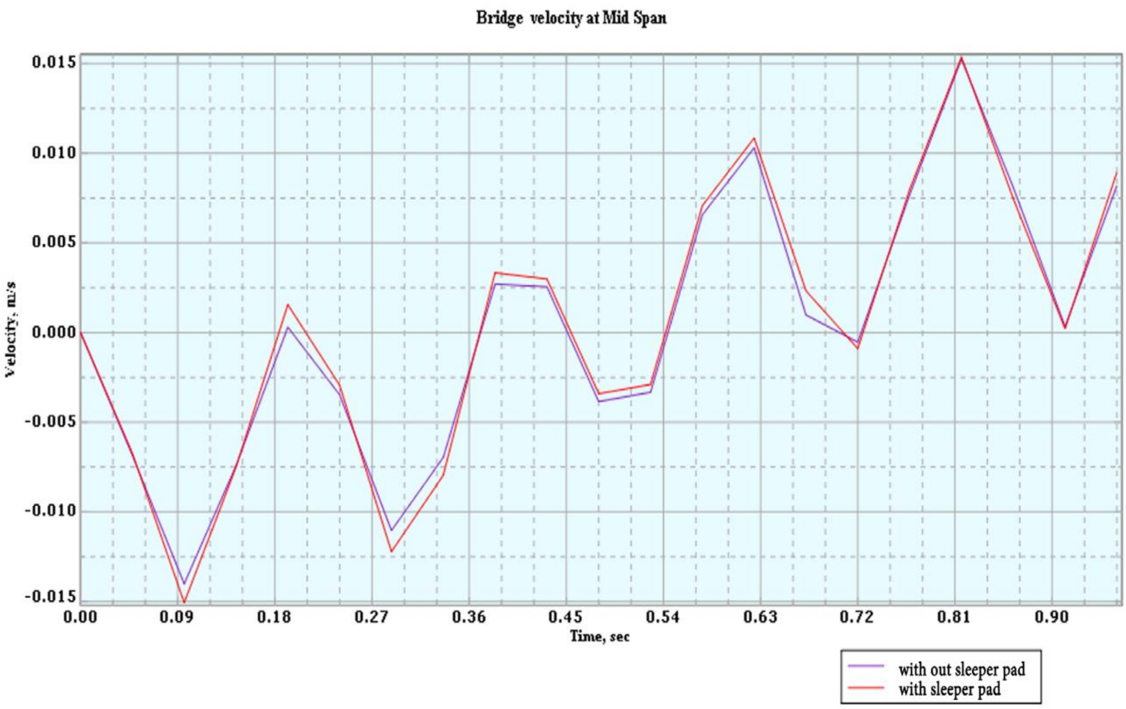



**Figure 4-4: Vertical Velocity of the bridge with and without resilient sleeper pad**

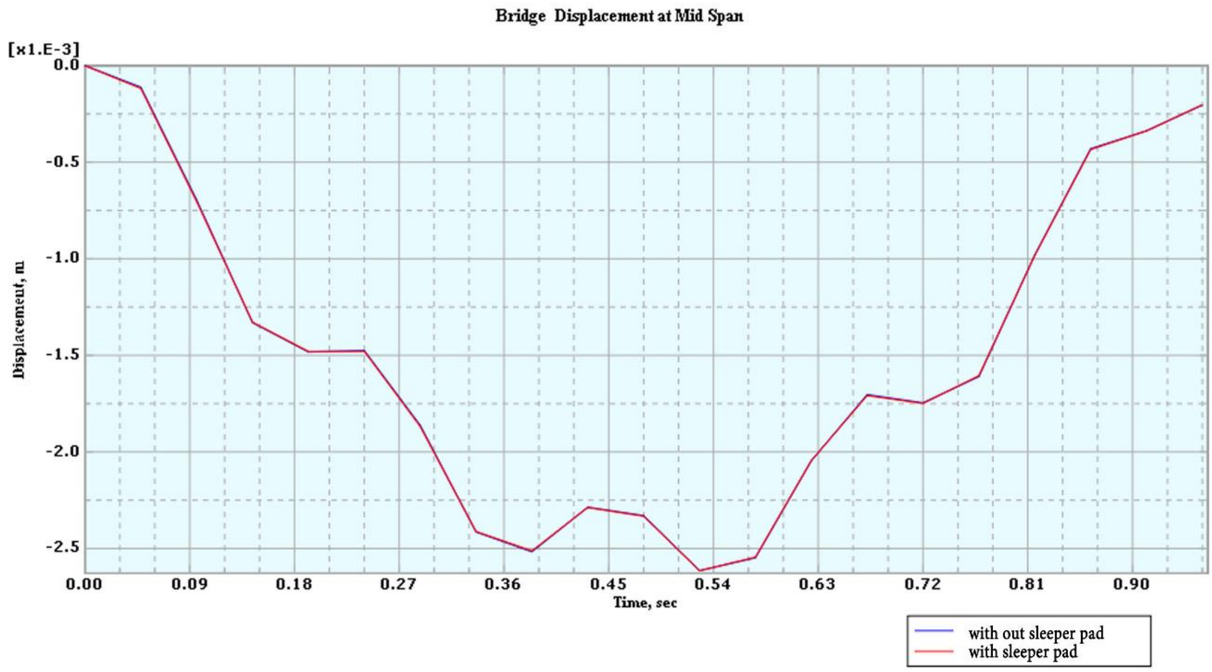



**Figure 4-5: Vertical displacement of the bridge with and without resilient sleeper pad**

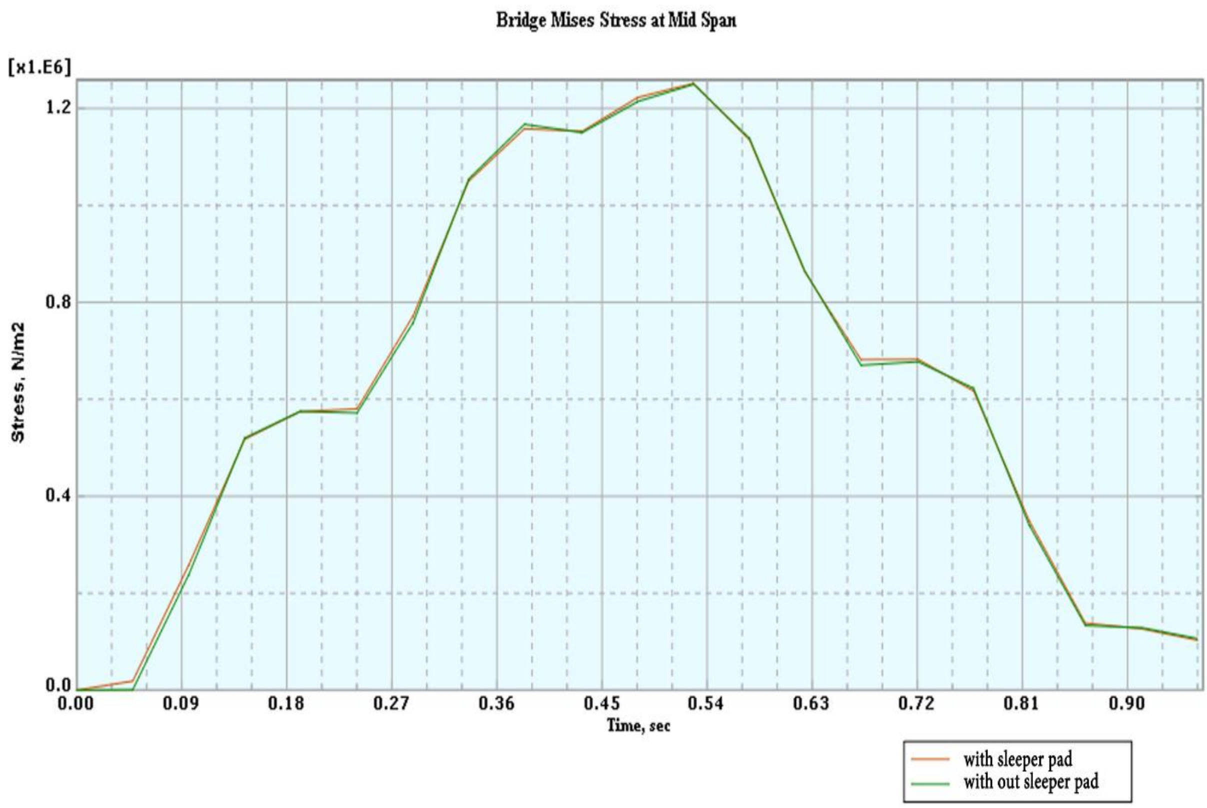



**Figure 4-6: Stress of the bridge with and without resilient sleeper pad**

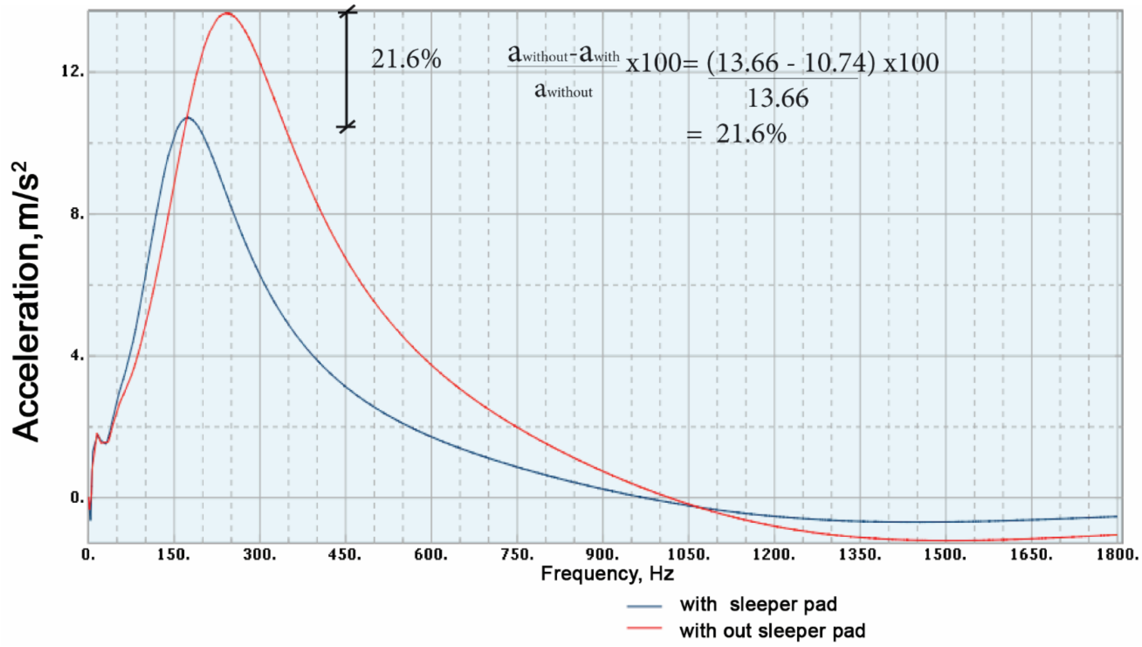



**Figure 4-7: Vertical acceleration of the bridge with and without resilient sleeper pad**

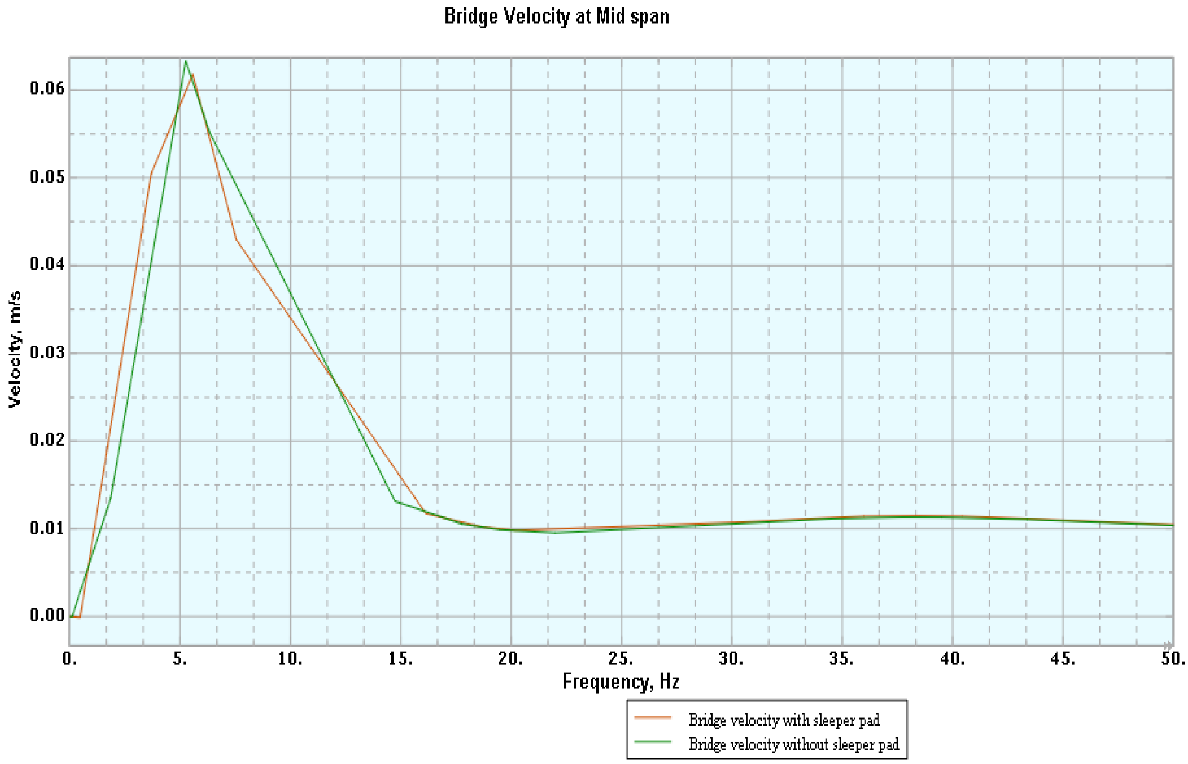



**Figure 4-8: Vertical velocity of the bridge with and without resilient sleeper pad**

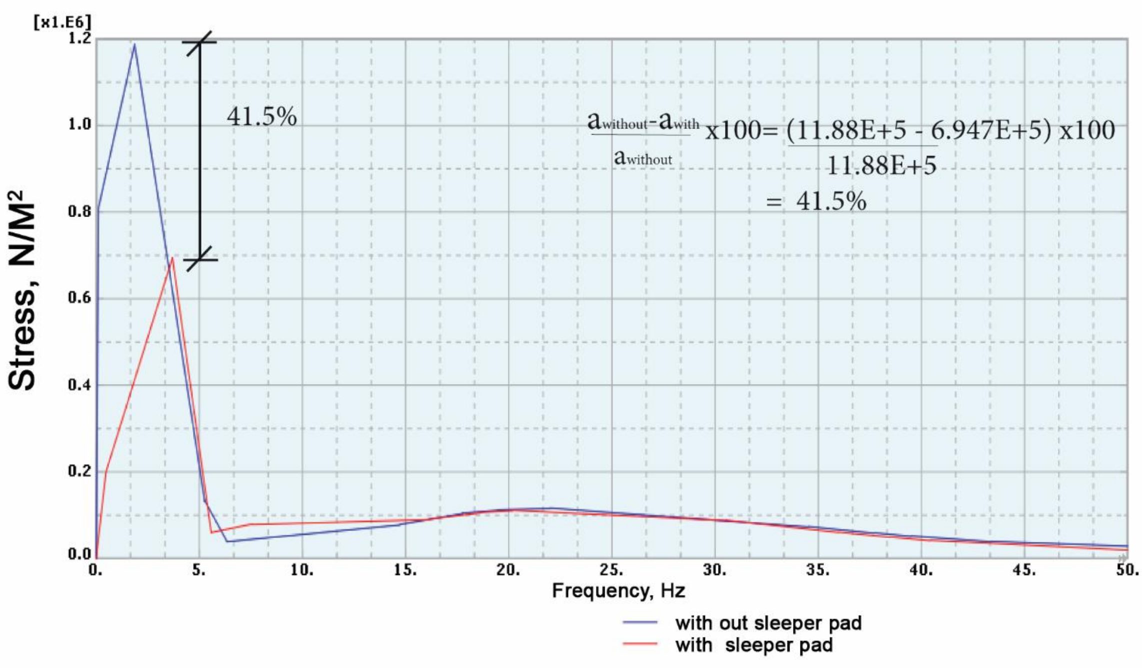



**Figure 4-9: Stress of the bridge with and without resilient sleeper pad**

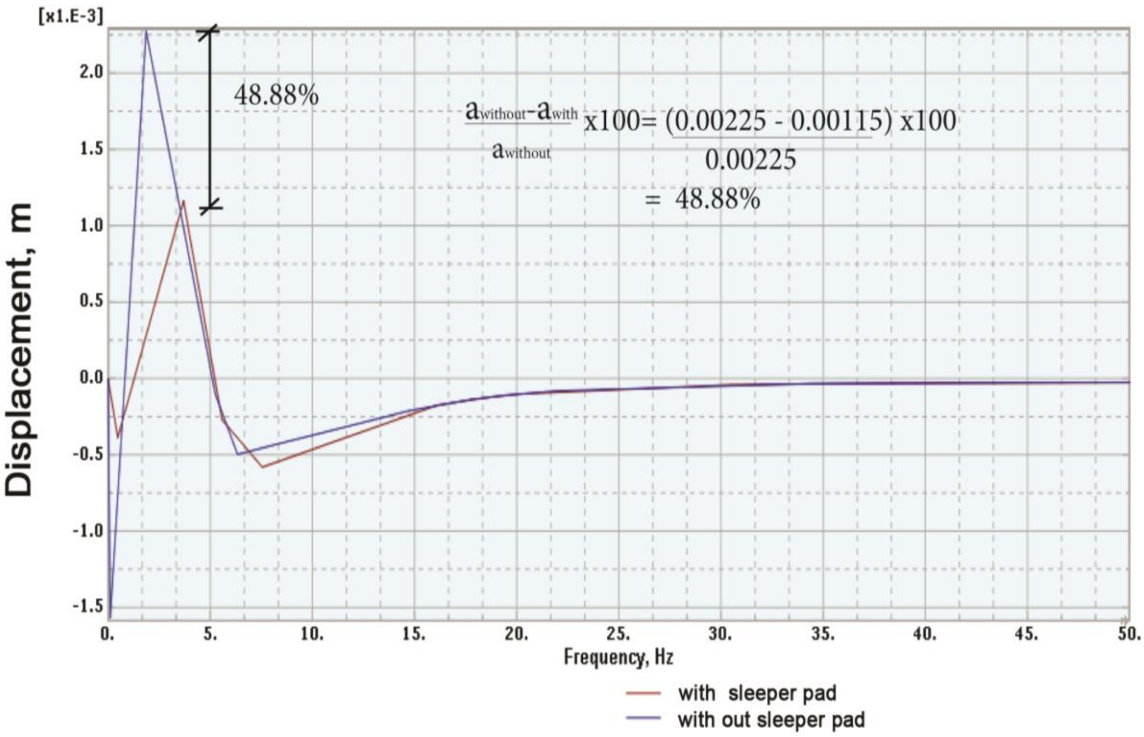



**Figure 4-10: Vertical displacement of the bridge with and without resilient sleeper pad**

# CHAPTER 5
# CONCLUSIONS AND RECOMMENDATION

## 5.1 Conclusions

In railway industry especially in slab track, the emission of a high amount of vibration and structure born noise disturbs the surrounding environment and the rail track structure due to dynamic impact of the train on rail materials. In order to reduce these impact, we should have to use the resilient material on the rail track as ballast mat, sleeper pad and rail pad as an optional solution. These resilient materials can potentially be produced from recycled rubber material /end of life tyre. In the thesis, two fundamental objectives are addressed.

The first is giving contribution for the preparation of the rubber rail pad which is a potential material for the intended purpose in our country. Moreover, a new composite material has been developed which is produced using recycling rubber as one ingredient. During material composition up to 50PHR (Parts per Hundred of Rubber) of recycled rubber material is applied. In economy point of view, almost 10% reduction of material cost of rubber pad is achieved. As a general, rubber railpad material composition and production technology are adopted.

The second aspect is a determination of the sleeper pad effect on 32m span T-Girder Bridge during dynamic loading analysis. For this case, using dynamic explicit and steady-state dynamic analysis, the bridge with and without sleeper pad is modeled and compared. As a result, the dynamic explicit analysis shows, sleeper pad reduces the bridge acceleration at mid-span almost by half. From steady-state dynamic analysis, sleeper pad reduces the acceleration, displacement and stress of the slab track bridge in different frequency range significantly.

## 5.2 Recommendation

End-of life-tires and plastics have an enormous environmental impact. By recycling plastic and end of life tyres, reduction of a pollutant can be achieved. For Ethiopian railway industry, domestic companies have potential to do the rubber rail pad, sleeper pad, ballast mat or any resilient material and plastic mold.

In addition to rail pad, Rubber Resilient materials like sleeper pad should be introduced in slab Truck Bridge and tunnel in order to reduce vibration and structure born noise.

Further study must be extended for practical application by performing the following studies:

1) The study presented in this thesis should be extended to different span length and for other types of bridges like continuous bridges, frame bridges, composite bridges, steel bridges, etc. to see the difference in the results between sprung mass model and moving load model.
2) Railpad field tests should be made to verify the results obtained from this laboratory test.
3) 2D Modeling results of this thesis could be compared with a 3D modeling and analysis result.

# REFERENCE


[1] Konstantinos Tzanakakis. The Railway Track and Its Long-Term Behavior. A Handbook for a Railway Track of High Quality, Springer-Verlag Berlin Heidelberg. 2013.

[2] Coenraad Esveld. Modern Railway Track. Second Edition, Delft University of Technology. 2001.

[3] Clifford F. Bonnett. Practical Railway Engineering. 2nd Edition, Imperial College Press. 2005.

[4] Georgios Michas. Slab Track Systems for High-Speed Railways. Master's degree project, Royal Institute of Technology. 2012.

[5] Huan Feng. 3D-models of Railway Track for Dynamic Analysis. Master Degree Project, Royal Institute of Technology. 2011

[6] Sakdirat Kaewunruen, Alex M Remennikov. Dynamic Properties of Railway Track and Its Components. A state-of-the-art review, University of Wollongong Research Online. 2008.

[7] Lichtberger B. Track compendium. second edition, Eurail Press. 2011.

[8] Ing. Concetta Onorii. Mechanical Behaviour of Traditional and Antivibration Railway Tracks with Recycled Rubber Materials. Elastomer Engineering Guide, www.jameswalker.biz/pdf_docs

[9] RECYTRACK Project. Elastomeric Eco-friendly Material Based on End-of-Life Tires Blended with Organic Bind Resin for Railway Applications. Journal of Mechanics Engineering and Automation. 2012.

[10] D. K. Singh. Failure analysis and critical study of provisions in specifications of Grooved Rubber Sole Plate (GRSP). IRICEN Journal of Civil Engineering. 2011.

[11] Standard of People's Republic of China Railway Industry. TB/T 2626. 1995.

[12] Landislov Fryba, Dynamics of railway bridges. 1996.

[13] Shuhbaz Rashid. Parametric study of bridge response to high speed trains, Stockholm Sweden. 2011.

[14] Y.B Yang. Vehicle bridge interaction Dynamics with application to high speed railway. world scientific publishing. 2004.

[15] Mareike Hess. Devulcanization as an opportunity to recycle rubber. German Institute for rubber Technology. 2009.

[16] Svajus Asadausakas. Devulcanizing agent for production of reclaim rubber powder. Devulco.Uab, 2014.

[17] Bureau of Indian standards. Reclaimed rubber specification. ICS 83.060. 1997

[18] Debapria De. Meghnad. Processing and material characteristics of a reclaimed ground rubber tire reinforced styrene-butadiene rubber. Saha Institute of technology, India. 2011.

[19] C. Kumnuantip. Effect of reclaimed rubber content in NR/carbon black vulcanizates using microwave irradiation system. School of energy and materials, Thailand, 2005.

[20] John Wiley & Sons. Fundamental of modern manufacturing. 2nd edition.2002.

[21] Indian railway standard specification. Grooved rubber sole plates for placing beneath rails. Serial No.T-47. 2006.

[22] Australian standard of Railway track material. AS1085. 2001.

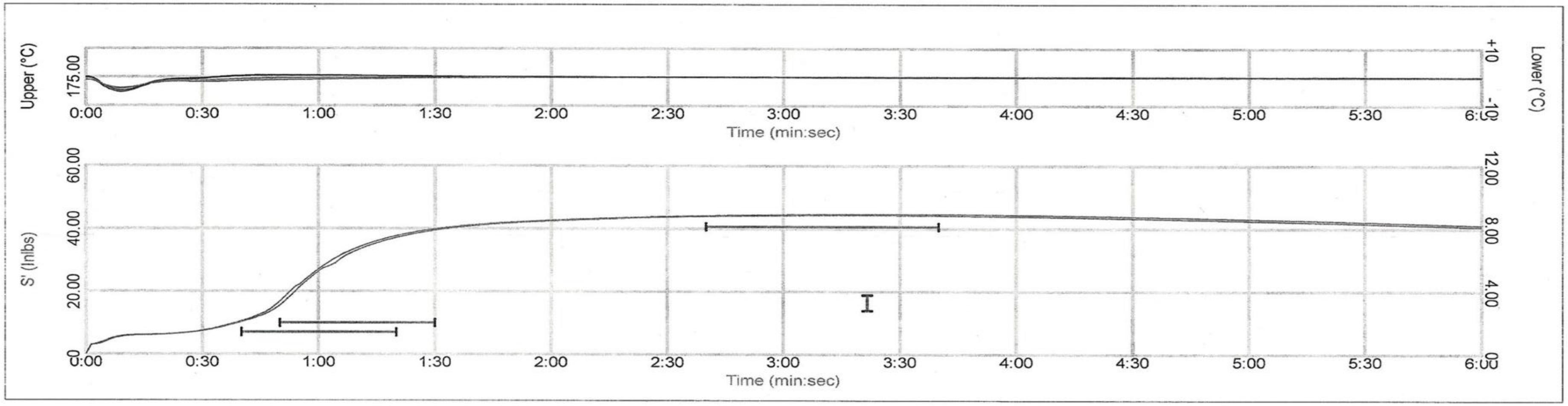
[23] Joakim Kylen. 2D-model of a portal frame Railway Bridge for dynamic analysis. 2010.

[24] ABAQUS version 6.12.1 Documentation Library.

# APPENDIX A

Rail pad experimental analysis result, which include Rheo-line, Testo-meter and Abrasion test results

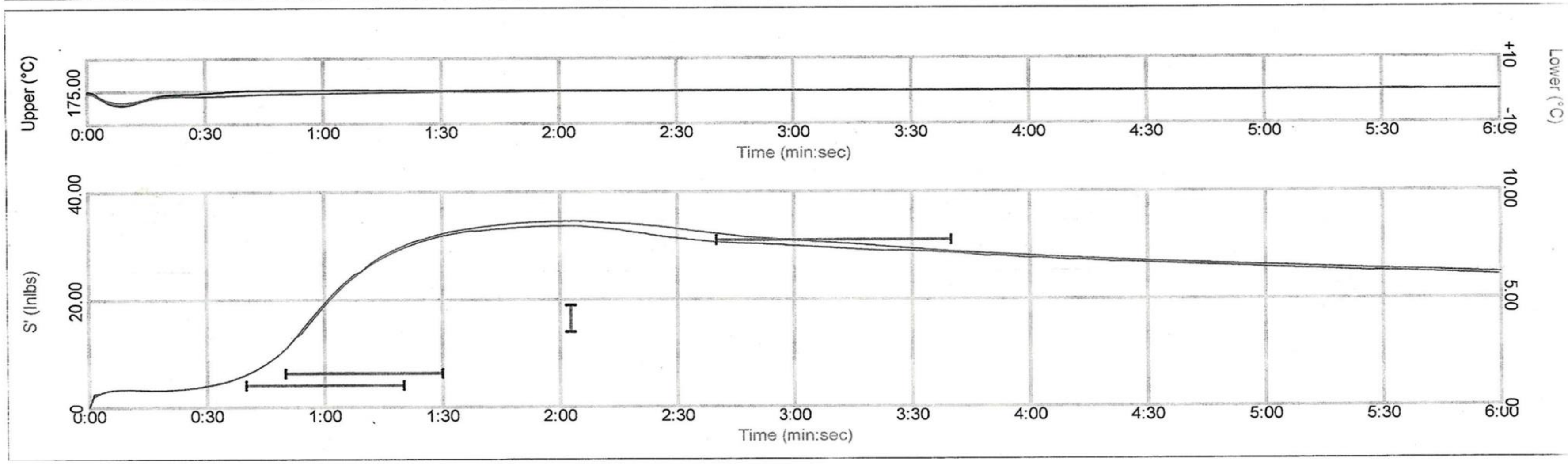
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-2-02 | Result 1 | 6/2/2015 11:32:50 AM | | 6.11 | 6.11 | 44.39 | 40.66 | 0:28 | 0:39 | 0:59 | 1:37 |
| pad test-2-01 | Result 1 | 6/2/2015 11:26:14 AM | | 6.08 | 6.08 | 44.73 | 41.20 | 0:27 | 0:39 | 0:58 | 1:37 |
| | Mean | | | 6.09 | 6.09 | 44.56 | 40.93 | 0:28 | 0:39 | 0:59 | 1:37 |
| | Std Dev.(P) | | | 0.02 | 0.02 | 0.17 | 0.27 | 0:00 | 0:00 | 0:00 | 0:00 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 4.81 | 0.00 | 24.72 | 17.89 | 0.00 | 50.65 |
| | Cpk | | | 0.00 | 0.00 | -49.15 | 0.00 | -15.32 | -9.94 | 0.00 | -106.76 |

**Figure A-1: Rheo-meter test result, and Torque VS Time graph of compound type – 2**

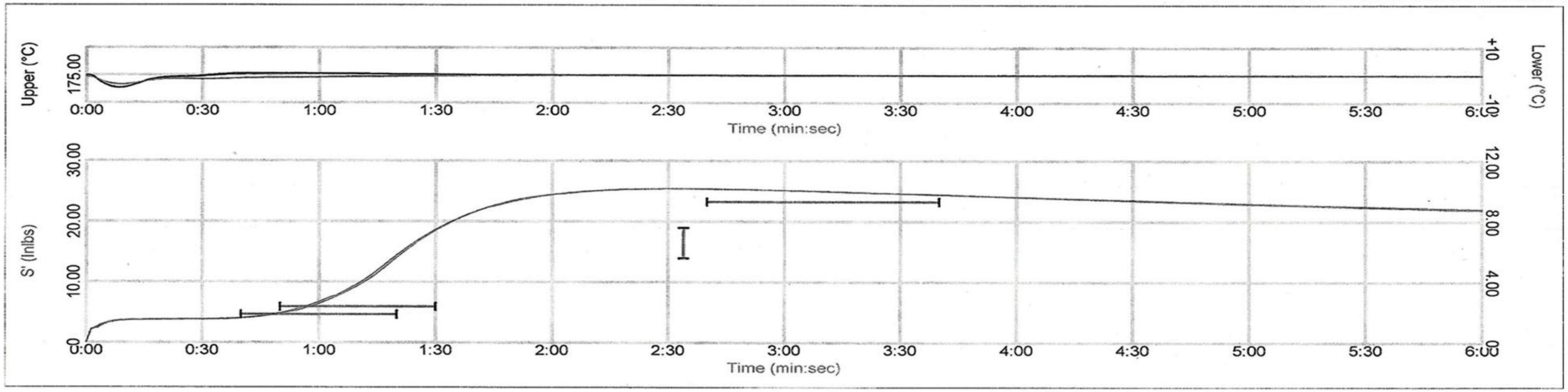
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-3-3 | Result 1 | 6/2/2015 3:26:32 PM | | 3.31 | 3.17 | 33.68 | 24.30 | 0:31 | 0:41 | 0:59 | 1:24 |
| pad test-3-1 | Result 1 | 6/2/2015 3:12:59 PM | | 3.31 | 3.18 | 34.57 | 24.78 | 0:30 | 0:41 | 0:59 | 1:26 |
| | Mean | | | 3.31 | 3.18 | 34.13 | 24.54 | 0:31 | 0:41 | 0:59 | 1:25 |
| | Std Dev.(P) | | | 0.00 | 0.00 | 0.44 | 0.24 | 0:00 | 0:00 | 0:00 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 1.88 | 0.00 | 19.05 | 66.35 | 0.00 | 9.24 |
| | Cpk | | | 0.00 | 0.00 | -11.35 | 0.00 | -8.76 | -31.05 | 0.00 | -23.12 |

**Figure A-2: Rheo-meter test result and Torque VS Time graph of compound type – 3**

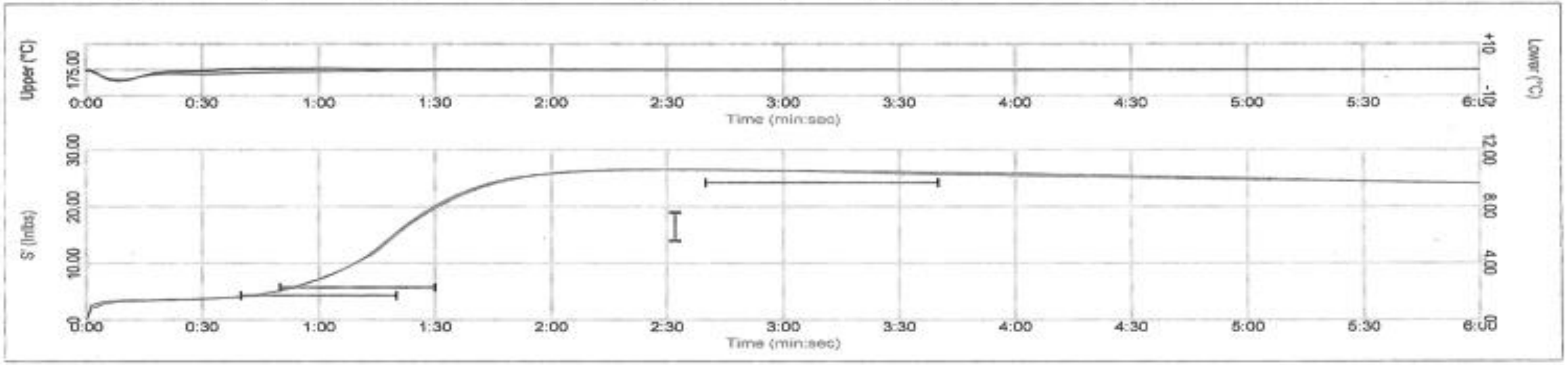
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-4-2 | Result 1 | 6/8/2015 1:22:46 PM | | 3.72 | 3.72 | 25.45 | 21.91 | 0:49 | 0:58 | 1:21 | 1:50 |
| pad test-4-1 | Result 1 | 6/8/2015 1:14:07 PM | | 3.78 | 3.78 | 25.45 | 22.07 | 0:48 | 0:57 | 1:20 | 1:49 |
| | Mean | | | 3.75 | 3.75 | 25.45 | 21.99 | 0:49 | 0:57 | 1:21 | 1:49 |
| | Std Dev.(P) | | | 0.03 | 0.03 | 0.00 | 0.08 | 0:00 | 0:01 | 0:00 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 818.36 | 0.00 | 76.89 | 12.85 | 0.00 | 18.22 |
| | Cpk | | | 0.00 | 0.00 | -2110.36 | 0.00 | 32.86 | 4.57 | 0.00 | -30.85 |

**Figure A-3: Rheo-meter test result and Torque VS Time graph of compound type – 4**

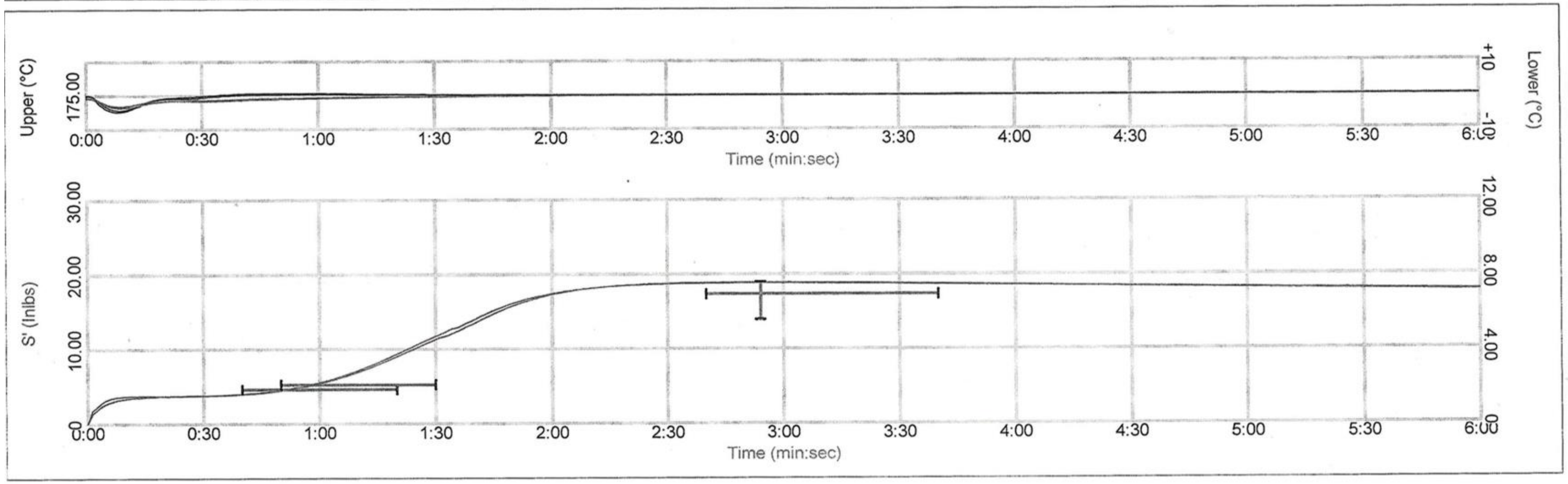
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-5-2 | Result 1 | 6/8/2015 2:01:46 PM | | 3.37 | 3.37 | 26.52 | 24.11 | 0:42 | 0:53 | 1:20 | 1:46 |
| pad test-5-1 | Result 1 | 6/8/2015 1:55:08 PM | | 3.45 | 3.45 | 26.60 | 24.02 | 0:43 | 0:53 | 1:19 | 1:45 |
| | Mean | | | 3.41 | 3.41 | 26.56 | 24.07 | 0:43 | 0:53 | 1:20 | 1:45 |
| | Std Dev.(P) | | | 0.04 | 0.04 | 0.04 | 0.04 | 0:00 | 0:00 | 0:00 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 21.94 | 0.00 | 30.28 | 1251.25 | 0.00 | 19.33 |
| | Cpk | | | 0.00 | 0.00 | -66.37 | 0.00 | 3.99 | 201.25 | 0.00 | -35.15 |

**Figure A-4: Rheo-meter test result and Torque VS Time graph of compound type- 5**

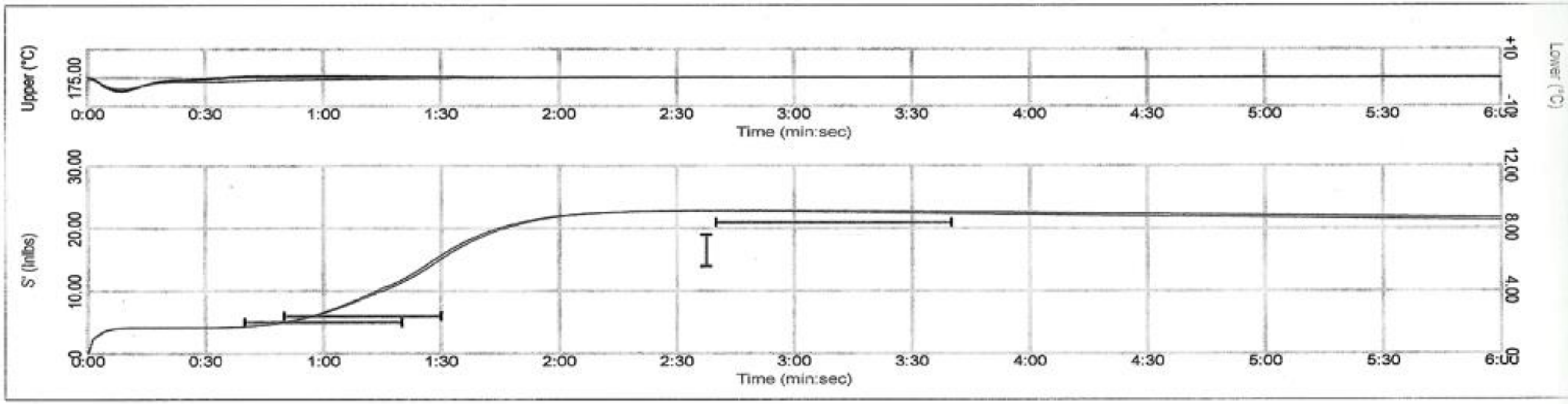
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-7-2 | Result 1 | 6/9/2015 10:11:20 AM | | 3.69 | 3.69 | 18.84 | 17.77 | 0:51 | 0:57 | 1:28 | 1:59 |
| pad test-7-1 | Result 1 | 6/9/2015 10:04:48 AM | | 3.74 | 3.74 | 18.93 | 17.89 | 0:52 | 0:59 | 1:30 | 2:01 |
| | Mean | | | 3.71 | 3.71 | 18.88 | 17.83 | 0:52 | 0:58 | 1:29 | 1:60 |
| | Std Dev.(P) | | | 0.03 | 0.02 | 0.05 | 0.06 | 0:01 | 0:01 | 0:01 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 18.36 | 0.00 | 7.80 | 8.88 | 0.00 | 10.16 |
| | Cpk | | | 0.00 | 0.00 | 0.88 | 0.00 | 4.54 | 3.57 | 0.00 | -13.63 |

**Figure A-5: Rheo-meter test result and Torque VS Time graph of compound type – 7**

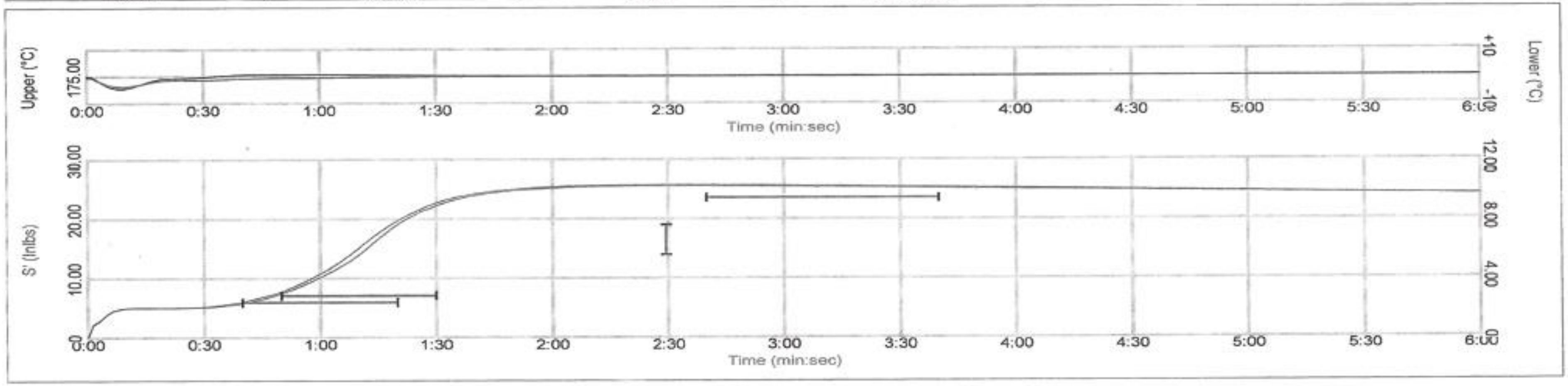
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-8-2 | Result 1 | 6/9/2015 2:41:39 PM | | 4.12 | 4.10 | 22.79 | 21.34 | 0:50 | 0:57 | 1:25 | 1:50 |
| pad test-8-1 | Result 1 | 6/9/2015 2:33:57 PM | | 4.09 | 4.08 | 22.90 | 21.72 | 0:50 | 0:57 | 1:26 | 1:52 |
| | Mean | | | 4.10 | 4.09 | 22.85 | 21.53 | 0:50 | 0:57 | 1:25 | 1:51 |
| | Std Dev.(P) | | | 0.01 | 0.01 | 0.05 | 0.19 | 0:00 | 0:00 | 0:01 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 16.51 | 0.00 | 60.35 | 29.22 | 0.00 | 10.00 |
| | Cpk | | | 0.00 | 0.00 | -25.40 | 0.00 | 29.37 | 10.33 | 0.00 | -16.41 |

**Figure A-6: Rheo-meter test result and Torque VS Time graph of compound type – 8**

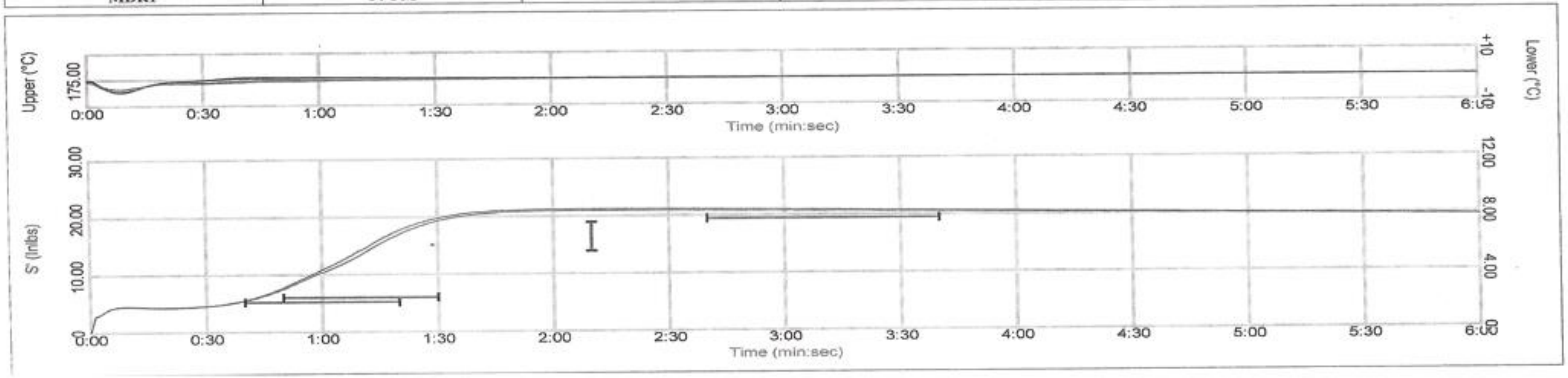
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pad test-9-2 | Result 1 | 6/11/2015 1:02:32 PM | | 5.06 | 5.02 | 25.54 | 24.10 | 0:41 | 0:48 | 1:13 | 1:36 |
| pad test-9-1 | Result 1 | 6/11/2015 11:52:58 AM | | 5.03 | 5.01 | 25.74 | 24.12 | 0:39 | 0:47 | 1:10 | 1:35 |
| | Mean | | | 5.04 | 5.02 | 25.64 | 24.11 | 0:40 | 0:47 | 1:12 | 1:36 |
| | Std Dev.(P) | | | 0.02 | 0.01 | 0.10 | 0.01 | 0:01 | 0:01 | 0:01 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 8.62 | 0.00 | 6.00 | 7.79 | 0.00 | 17.27 |
| | Cpk | | | 0.00 | 0.00 | -22.89 | 0.00 | 0.01 | -1.02 | 0.00 | -37.11 |

**Figure A-7: Rheo-meter test result and Torque VS Time graph of compound type – 9**

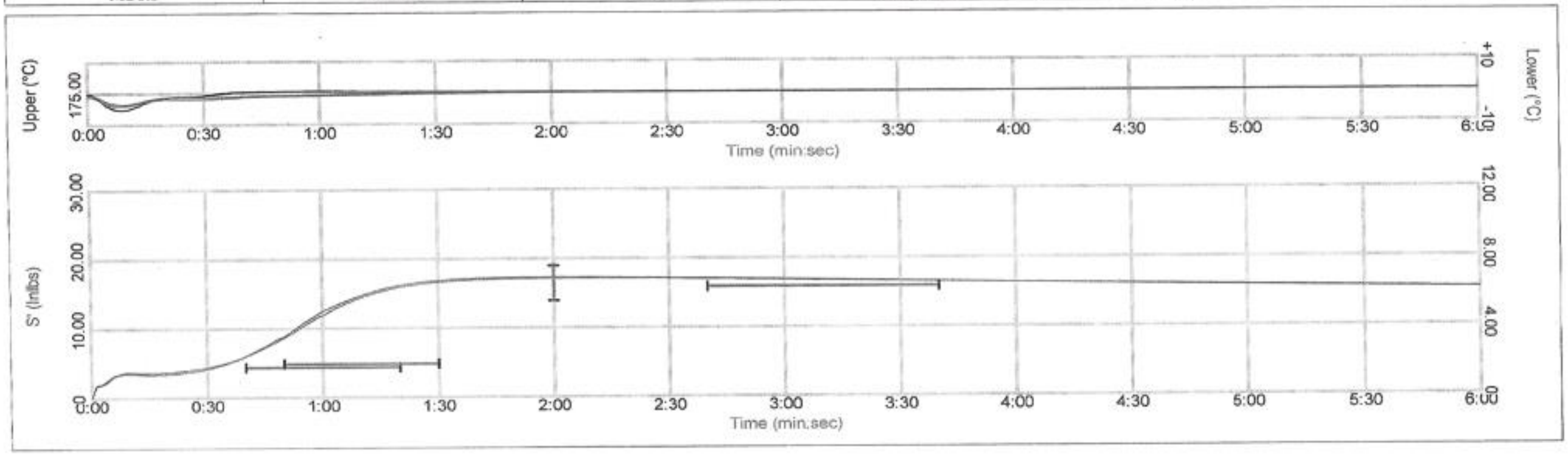
| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |




| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pad test-10-02 | Result 1 | 6/18/2015 8:53:53 AM | | 4.54 | 4.35 | 21.28 | 19.67 | 0:38 | 0:43 | 1:06 | 1:29 |
| Pad test-10-01 | Result 1 | 6/18/2015 8:46:49 AM | | 4.47 | 4.30 | 21.02 | 19.55 | 0:38 | 0:43 | 1:08 | 1:30 |
| | Mean | | | 4.51 | 4.32 | 21.15 | 19.61 | 0:38 | 0:43 | 1:07 | 1:29 |
| | Std Dev.(P) | | | 0.04 | 0.02 | 0.13 | 0.06 | 0:00 | 0:00 | 0:01 | 0:01 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 6.45 | 0.00 | 75.99 | 51.78 | 0.00 | 13.34 |
| | Cpk | | | 0.00 | 0.00 | -5.55 | 0.00 | -8.80 | -18.22 | 0.00 | -31.41 |

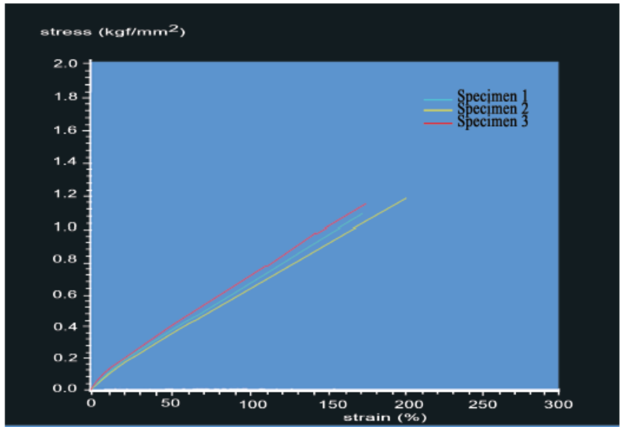
**Figure A-8: Rheo-meter test result, and Torque VS Time graph of compound type – 10**

| Instrument Type | Compound | Method | Test Length | Temperature | Arc |
|---|---|---|---|---|---|
| MDR1 | 04-FM | 04-fm | 6:00min:sec | 175.00°C | 0.5° |



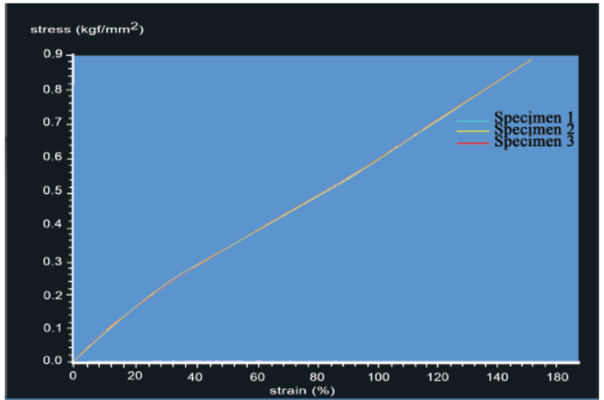

| Batch | Result Name | Date/Time | Description | S':Initial | S':Minimum | S':Maximum | S':Final | S':TS1 | S':T10% | S':T50% | S':T90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pad test-11-02 | Result 1 | 6/29/2015 9:17:21 AM | | 3.68 | 3.59 | 17.19 | 15.46 | 0:31 | 0:34 | 0:55 | 1:19 |
| Pad test-11-01 | Result 1 | 6/29/2015 9:10:31 AM | | 3.49 | 3.38 | 17.36 | 15.36 | 0:31 | 0:34 | 0:54 | 1:18 |
| | Mean | | | 3.59 | 3.49 | 17.27 | 15.41 | 0:31 | 0:34 | 0:55 | 1:18 |
| | Std Dev.(P) | | | 0.10 | 0.10 | 0.08 | 0.05 | 0:00 | 0:00 | 0:01 | 0:00 |
| | USL | | | 0.00 | 0.00 | 19.00 | 0.00 | 1:20 | 1:30 | 0:00 | 3:40 |
| | LSL | | | 0.00 | 0.00 | 14.00 | 0.00 | 0:40 | 0:50 | 0:00 | 2:40 |
| | Cp | | | 0.00 | 0.00 | 9.81 | 0.00 | 289.25 | 83.87 | 0.00 | 22.52 |
| | Cpk | | | 0.00 | 0.00 | 6.77 | 0.00 | -132.45 | -65.81 | 0.00 | -61.38 |

**Figure A-9: Rheo-meter test result, and Torque VS Time graph of compound type – 11**



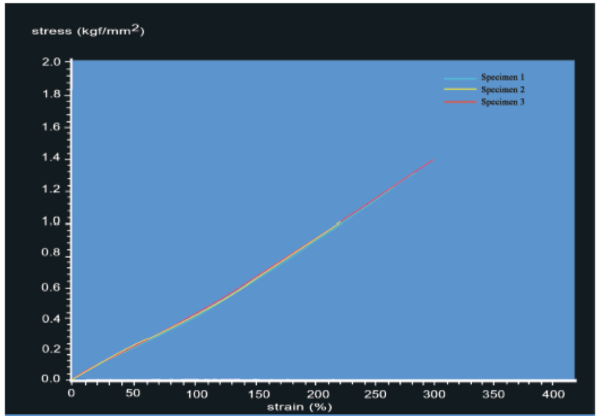

| Test No.2 | Load @ Break kgf | Stress @Break MPa | Stress @100% MPa | Stress @200% MPa | Strain @ Break % |
|---|---|---|---|---|---|
| 1 | 17 . 347 | 11 . 639 | 6 . 8354 | - | 176 . 67 |
| 2 | 21 . 099 | 12 . 741 | 6 . 4661 | 12.51 | 206 . 50 |
| 3 | 21 . 275 | 12 . 283 | 7 . 3127 | - | 178 . 45 |
| Min. | 17 . 347 | 11 .639 | 6 . 4661 | - | 176 . 67 |
| Mean | 19 . 907 | 12 . 221 | 6 . 8714 | - | 187 . 21 |
| Max. | 21 . 275 | 12 . 741 | 7 . 3127 | 12.51 | 206 . 50 |
| S.D. | 2 . 219 | 0 .553 | 0. 4245 | - | 16. . 73 |

a)




| Test No.3 | Load @ Break kgf | Stress @Break MPa | Stress @100% MPa | Stress @200% MPa | Strain @ Break % |
|---|---|---|---|---|---|
| 1 | 11.761 | 7 . 9542 | 5 . 5998 | - | 143 . 25 |
| 2 | 13.335 | 8 . 6719 | 5. 5880 | - | 156 . 27 |
| 3 | 13.312 | 8 . 6569 | 5 . 6229 | - | 156 . 93 |
| Min. | 11.761 | 7 .9542 | 5 .5880 | - | 143 .25 |
| Mean | 12.803 | 8 .4277 | 5 .6036 | - | 152 .15 |
| Max. | 13.335 | 8 .6719 | 5 .6229 | - | 156 .93 |
| S.D. | 0.902 | 0 .4101 | 0 .0178 | - | 7 .71 |

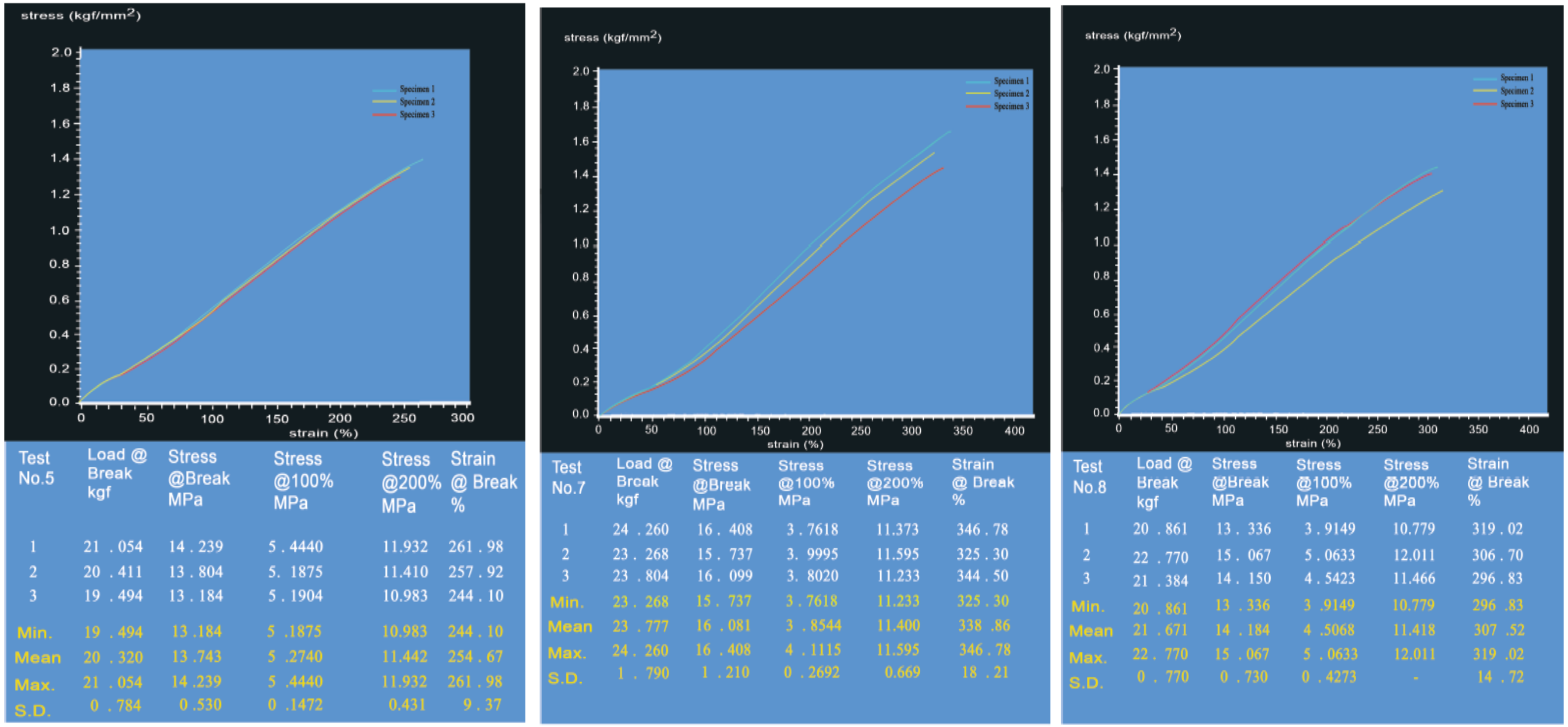
b)




| Test No.4 | Load @ Break kgf | Stress @Break MPa | Stress @100% MPa | Stress @200% MPa | Strain @ Break % |
|---|---|---|---|---|---|
| 1 | 19 . 325 | 13 . 070 | 3 . 8137 | 11.003 | 295 . 17 |
| 2 | 18 . 864 | 12 . 217 | 3. 7953 | 10.527 | 279 . 23 |
| 3 | 20 . 698 | 13 . 998 | 3 . 9445 | 11.466 | 311 . 35 |
| Min. | 18 .864 | 12 .217 | 3 .7953 | 10.527 | 279 . 23 |
| Mean | 19 . 362 | 13 .095 | 3 .8511 | 10.998 | 295 . 25 |
| Max. | 20 . 698 | 13 .998 | 3 .9445 | 11.466 | 311 . 35 |
| S.D. | 1 . 317 | 0 . 891 | 0 .0814 | 0.764 | 16 . 06 |

c)

**Figure A-10: Testometer result of Stress Vs Strain graph of compound: a) Type 2, b) Type 3 and c) Type 4**



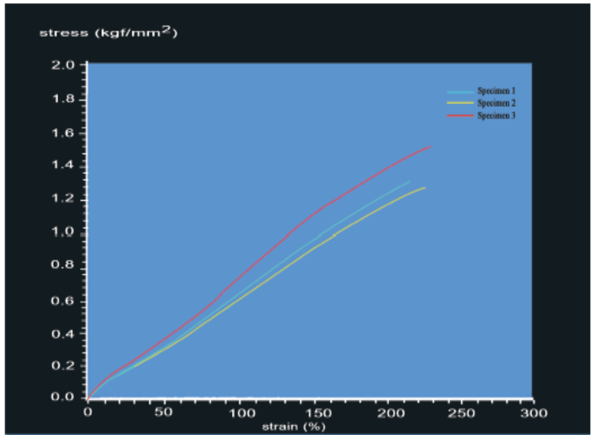

| Test No.5 | Load @ Break kgf | Stress @Break MPa | Stress @100% MPa | Stress @200% MPa | Strain @ Break % |
|---|---|---|---|---|---|
| 1 | 21 . 054 | 14 . 239 | 5 . 4440 | 11.932 | 261 . 98 |
| 2 | 20 . 411 | 13 . 804 | 5. 1875 | 11.410 | 257 . 92 |
| 3 | 19 . 494 | 13 . 184 | 5 . 1904 | 10.983 | 244 . 10 |
| Min. | 19 . 494 | 13 .184 | 5 .1875 | 10.983 | 244 . 10 |
| Mean | 20 . 320 | 13 .743 | 5 .2740 | 11.442 | 254 . 67 |
| Max. | 21 . 054 | 14 .239 | 5 .4440 | 11.932 | 261 . 98 |
| S.D. | 0 . 784 | 0 .530 | 0 .1472 | 0.431 | 9 . 37 |

| Test No.7 | Load @ Break kgf | Stress @Break MPa | Stress @100% MPa | Stress @200% MPa | Strain @ Break % |
|---|---|---|---|---|---|
| 1 | 24 . 260 | 16 . 408 | 3 . 7618 | 11.373 | 346 . 78 |
| 2 | 23 . 268 | 15 . 737 | 3. 9995 | 11.595 | 325 . 30 |
| 3 | 23 . 804 | 16 . 099 | 3. 8020 | 11.233 | 344 . 50 |
| Min. | 23 . 268 | 15 . 737 | 3 . 7618 | 11.233 | 325 . 30 |
| Mean | 23 . 777 | 16 . 081 | 3 . 8544 | 11.400 | 338 .86 |
| Max. | 24 . 260 | 16 . 408 | 4 . 1115 | 11.595 | 346 . 78 |
| S.D. | 1 . 790 | 1 . 210 | 0 . 2692 | 0.669 | 18 . 21 |

| Test No.8 | Load @ Break kgf | Stress @Break MPa | Stress @100% MPa | Stress @200% MPa | Strain @ Break % |
|---|---|---|---|---|---|
| 1 | 20 . 861 | 13 . 336 | 3 . 9149 | 10.779 | 319 . 02 |
| 2 | 22 . 770 | 15 . 067 | 5 . 0633 | 12.011 | 306 . 70 |
| 3 | 21 . 384 | 14 . 150 | 4 . 5423 | 11.466 | 296 . 83 |
| Min. | 20 . 861 | 13 . 336 | 3 .9149 | 10.779 | 296 .83 |
| Mean | 21 . 671 | 14 . 184 | 4 .5068 | 11.418 | 307 .52 |
| Max. | 22 . 770 | 15 . 067 | 5 . 0633 | 12.011 | 319 .02 |
| S.D. | 0 . 770 | 0 . 730 | 0 . 4273 | - | 14 . 72 |

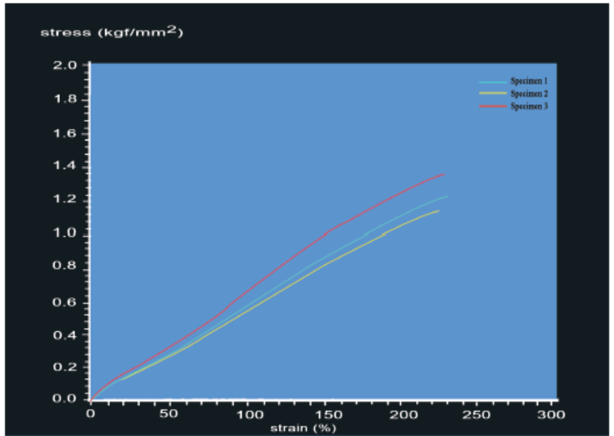
a) b) c)

**Figure A-11: Testometer result of Stress Vs Strain graph of compound: a) Type-5, b) Type-7 and c) Type-8**



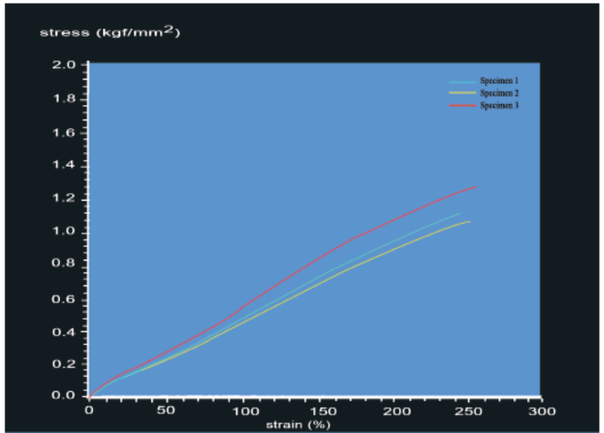

| Test No.9 | Stress @Break MPa | Strain @ Break % | Stress @100% MPa | Stress @200% MPa | Load @ Break kgf | Load @ Break kgf | Stress @300% MPa |
|---|---|---|---|---|---|---|---|
| 1 | 12.424 | 211.70 | 6.4186 | 11.962 | 17.635 | 17.635 | - |
| 2 | 15.003 | 231.77 | 7.5181 | 13.633 | 21.296 | 21.296 | - |
| 3 | 15.793 | 238.55 | 7.8387 | 14.165 | 22.417 | 22.417 | - |
| Min. | 12.424 | 211.70 | 6.4186 | 11.962 | 17.635 | 17.635 | - |
| Mean | 14.407 | 227.34 | 7.2585 | 13.253 | 20.449 | 20.449 | - |
| Max. | 15.793 | 238.55 | 7.8387 | 14.165 | 22.417 | 22.417 | - |
| S.D. | 1.762 | 13.96 | 0.7448 | 1.150 | 2.501 | 2.501 | - |

a)




| Test No.10 | Stress @Break MPa | Strain @ Break % | Stress @100% MPa | Stress @200% MPa | Load @ Break kgf | Load @ Break kgf | Stress @300% MPa |
|---|---|---|---|---|---|---|---|
| 1 | 11.736 | 220.35 | 6.1919 | 11.441 | 16.659 | 16.659 | - |
| 2 | 13.715 | 234.50 | 6.7969 | 12.403 | 19.467 | 19.467 | - |
| 3 | 12.453 | 217.62 | 6.3863 | 11.783 | 17.677 | 17.677 | - |
| Min. | 11.736 | 217.62 | 6.1919 | 11.441 | 16.659 | 16.659 | - |
| Mean | 12.635 | 224.16 | 6.4584 | 11.876 | 17.934 | 17.934 | - |
| Max. | 13.715 | 234.50 | 6.7969 | 12.403 | 19.467 | 19.467 | - |
| S.D. | 1.001 | 9.06 | 0.3089 | 0.488 | 1.422 | 1.422 | - |

b)




| Test No.11 | Stress @Break MPa | Strain @ Break % | Stress @100% MPa | Stress @200% MPa | Load @ Break kgf |
|---|---|---|---|---|---|
| 1 | 12.329 | 247.02 | 5.2833 | 10.239 | 17.500 |
| 2 | 12.435 | 255.10 | 4.8618 | 10.543 | 15.444 |
| 3 | 12.717 | 252.90 | 5.3666 | 10.867 | 18.803 |
| Min. | 12.329 | 247.02 | 4.8618 | 10.239 | 15.444 |
| Mean | 12.493 | 251.68 | 5.1706 | 10.550 | 17.249 |
| Max. | 12.717 | 255.10 | 5.3666 | 10.867 | 18.803 |
| S.D. | 1.732 | 12.96 | 0.2148 | 1.103 | 3.501 |

c)

**Figure A-12: Testometer result of Stress Vs Strain graph of compound: a) Type 9, b) Type 10 and c) Type 11**

**Table A.1: Abrasion test result of compound Type – 2 to Type-11**

| Rail pad Compound No | Test sample No | ABRASION TEST RESULT | | | |
|---|---|---|---|---|---|
| | | Before Abrasion (kg) | After Abrasion (kg) | Difference (kg) | Loss (%) |
| **Type 2** | 1 | 3.31 | 3.1 | 0.21 | 6.07 |
| | 2 | 3.29 | 3.09 | 0.2 | |
| | 3 | 3.28 | 3.09 | 0.19 | |
| | Average | 3.29 | 3.09 | 0.20 | |
| **Type 3** | 1 | 3.35 | 3.16 | 0.19 | 6.03 |
| | 2 | 3.37 | 3.14 | 0.23 | |
| | 3 | 3.36 | 3.17 | 0.19 | |
| | Average | 3.36 | 3.16 | 0.20 | |
| **Type 4** | 1 | 3.4 | 3.26 | 0.14 | 4.43 |
| | 2 | 3.39 | 3.24 | 0.15 | |
| | 3 | 3.37 | 3.21 | 0.16 | |
| | Average | 3.39 | 3.24 | 0.15 | |
| **Type 5** | 1 | 3.44 | 3.25 | 0.19 | 5.43 |
| | 2 | 3.43 | 3.24 | 0.19 | |
| | 3 | 3.41 | 3.23 | 0.18 | |
| | Average | 3.43 | 3.24 | 0.19 | |
| **Type 7** | 1 | 3.43 | 3.20 | 0.23 | 6.32 |
| | 2 | 3.42 | 3.21 | 0.21 | |
| | 3 | 3.43 | 3.22 | 0.21 | |
| | Average | 3.43 | 3.21 | 0.22 | |
| **Type 8** | 1 | 3.51 | 3.30 | 0.21 | 5.98 |
| | 2 | 3.52 | 3.31 | 0.21 | |
| | 3 | 3.51 | 3.30 | 0.21 | |
| | Average | 3.51 | 3.30 | 0.21 | |
| **Type 9** | 1 | 3.32 | 3.14 | 0.18 | 5.22 |
| | 2 | 3.34 | 3.15 | 0.19 | |
| | 3 | 3.31 | 3.16 | 0.15 | |
| | Average | 3.32 | 3.15 | 0.17 | |
| **Type 10** | 1 | 3.56 | 3.35 | 0.21 | 5.62 |
| | 2 | 3.55 | 3.36 | 0.19 | |
| | 3 | 3.56 | 3.36 | 0.20 | |
| | Average | 3.56 | 3.36 | 0.20 | |
| **Type 11** | 1 | 3.35 | 3.15 | 0.20 | 5.98 |
| | 2 | 3.34 | 3.14 | 0.20 | |
| | 3 | 3.34 | 3.14 | 0.20 | |
| | Average | 3.34 | 3.14 | 0.20 | |