ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EXPERIMENTAL STUDY ON MECHANICAL AND DYNAMIC PROPERTIES OF CONCRTE WITH WASTE TYRE RUBBER AS PARTIAL REPLACEMENT OF COARSE AGGREGATE

A Thesis in structural engineering

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A Thesis

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

The undersigned have examined the thesis entitled '**Experimental Study On Mechanical And Dynamic Properties Of Concrete With Waste Tyre Rubber As Partial Replacement Of Coarse Aggregate**.' presented by **Maru Sete**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled "**Experimental Study On Mechanical And Dynamic Properties Of Concrete With Waste Tyre Rubber As Partial Replacement Of Coarse Aggregate**." 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.

Maru Sete

ABSTRACT

Concrete is one of the most popular construction materials**,** due to this reason production of sustainable concrete and trying to increase its properties, uses and applications is the most crucial factor to be considered in construction fields. The utilization of waste tyre rubber can mitigate the problematic issues of normal concrete which are brittleness, cracks and shrinkage, and low energy absorption. This research primarily focused on finding the best way of producing concrete with highly energy dissipation capacity by use of waste tyre rubber as a component material. On the other hand the management of waste tyre rubber is a major ecological and environmental problem in the world. The use of waste tyre rubber into the concrete can reduce this global problem. In this study, the performance of shredded waste tyre rubber as partial replacement of coarse aggregates in C-25 grade of concrete mix at different ratios and its effect on concrete properties like compressive strength, flexural strength split tensile strength and dynamic properties were investigated. The shredded waste tyre rubber was used to partially replace at ratios of 5%, 10% ,15% , 20%, and 25% the volume of coarse aggregate in concrete mix.

Results from laboratory tests indicated that the replacement of waste tyre rubber in the concrete as coarse aggregate showed the reduction on strength of concrete (compressive strength, split tensile strength, flexural strength); workably and dry density of rubberized concrete below the nominal concrete mixtures with the increasing of waste tyre rubber ratio. On the other hand, replacing coarse aggregate with waste tyre rubber can improve dynamic properties of concrete. It was observed that the damping ratio increased with an increase in applied string and impact load as well as with an increase in waste tyre rubber content in concrete mix.

Keywords: waste tyre rubber; rubberized concrete; damping ratio; aggregate replacement; strength of concrete

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LIST OF ABBREVIATIONS

CM-0	=	C25 concrete with 100% coarse aggregate
CM-5	=	C25 concrete with 90% coarse aggregate + 5% tyre rubber
CM-10	=	C25 concrete with 90% coarse aggregate + 10% tyre rubber
CM-15	=	C25 concrete with 85% coarse aggregate + 15% tyre rubber
CM-20	=	C25 concrete with 80% coarse aggregate + 20% tyre rubber
CM-25	=	C25 concrete with 75% coarse aggregate + 25% tyre rubber
ERA	=	Ethiopian Roads Authority
FFT	=	Fast Fourier Transform
FM	=	Fineness Modulus
MC	=	Moisture content
MR	=	Modulus of Rupture
NC	=	Normal Concrete
UTM	=	Universal Testing Machine
Dps	=	Degree per second

LIST OF SYMBOLS

A	=	cross sectional area
b	=	width of the specimen
C	=	damping coefficient
Ccr	=	Critical damping coefficient
d	=	depth of the specimen
D	=	diameter of the cylinder in mm.
E	=	Young's modulus (MPa)
f	=	Fundamental natural frequency of vibration (Hz)
Fb	=	flexural strength in MPa,
Fc	=	compressive stress in MPa.
Fct	=	split tensile strength in MPa,
G	=	Shear modulus or modulus of rigidity
k	=	stiffness
L	=	length
m	=	mass
P (t)	=	external force
P y	=	Load causing yielding of the tensile steel (kN)
t	=	Time (sec)
T	=	Period
Y_1	=	Maximum amplitude on the response
Y_n	=	Displacement amplitude after *n* number of cycles
ξ	=	Damping ratio
ωd	=	damped natural frequency
ωn	=	natural frequency

CHAPTER ONE INTRODUCTION

1.1 General

In a building construction, concrete is used for the construction of structural or non-structural elements. Concrete technology deals with study of properties of concrete and its practical applications. Buildings built on earthquake prone areas, have to meet the requirement of earthquake resistance structure such as having lightweight material, having high ductility and being able to dissipate more of earthquake energy.

Properties of aggregate that may affect the properties of the concrete, each of the properties of lightweight aggregates may have some bearing on the properties of the fresh and hardened concrete. The increased usage of processed lightweight aggregates is evidence of environmentally sound planning, as these products require less trucking and use of materials that have limited structural applications in their natural state, thus minimizing construction industry demands on finite resources of natural sands, stones, and gravels (ACI 213 2003).

Another problem that is topical in today's world is environment pollution. The activities of humans create a lot of different waste every year. The used car tyres are one of frequent problems. The quantity of waste tire worldwide is increasing highly which becomes a significant problem to be solved. It has been a major problem for managing waste for a few decades and in some cases has involved serious environmental pollution. All over the world, the amount of rubber waste has gradually increased in the recent years. Every year the number of used tires grows very quickly for example in Ethiopia, According to Matador Addis Tyre Factory market demand prediction of annual tyre demand is estimated at around one million pieces. And it is believed that every three years at least one million tires will be discarded resulting in a little over ten thousand tons of waste tires annually (Misgana Berhanu 2020).

The use of waste tyre as a coarse aggregate in concrete mix is the major concern of this paper. This study aiming to improve the ability of concrete materials in dissipating earthquake energy have been widely carried out by way of increasing the damping ratio of the material and to form lightweight concrete by partially replacing waste tyre rubber as a coarse aggregate in concrete. Incorporation of waste tyre rubber in concrete will also have an additional advantage of conserving natural resources (mineral aggregate used in concrete production) which are becoming increasingly scarce. This finding is expected to give an interesting solution for new researches to carry out the experiment.

1.2 Objectives of the study

1.2.1 General Objective

The main objective of this research is to study mechanical and dynamic properties of concrete with waste tyre rubbers partially replace as a coarse aggregate.

1.2.2 Specific Objectives

1. To study fresh and hardened properties of rubberized concrete by variation in percentage of waste tyre rubber
2. To investigate the effect of waste tyre rubber on compressive strength, split tensile and flexural strength of rubberized concrete.
3. To measure the percentage increase or decrease of damping ratio of rubberized concrete when the percentage of replacement of waste tyre rubber increases.
4. To investigate the effect of replacement ratio of waste tyre rubber in natural frequency of rubberized concrete.

1.3 Research Significance

Results obtained from this study are expected to contribute to the efforts made to characterize the mechanical and dynamic properties of rubberized concrete and more over to open new concrete application in the Ethiopian construction industry by replacing waste materials.

Rubberized concrete can be used on account of the advantage of increased energy absorbing characteristics and better fatigue strength. Rubberized concrete could have an important role to play in modern concrete technology. Therefore the possible application areas for the study are listed as follows:

- It can commonly be used in industrial floors to reduce damage due to abrasion and impact.
- It can be applied in place where vibration damping is needed, such as in foundation pad for rotating machinery and in railway stations.
- It can be applied for trench filling and pipe bedding, pile heads, and paving slabs.
- It can be used in heavy machinery foundations to minimize damage due to vibration and dynamic load.
- Rubberized concrete because of its light unit weight, can be used for architectural applications such as nailing concrete, false facades stone backing and interior construction.
- The tyre factories will have definitely benefit from this study. It will also provide sustainable markets for waste tyre rubber and it will encourage material recovery of large amounts of tyres.

1.4 Organization of the thesis

This thesis is organized in to five chapters. The title and the aims of each chapter are described as follows;

Chapter One: Introduction. The introduction part consists of general, objectives of the research, research significance and organization of the research.

Chapter Two: Literature review, the literature review part consists of introduction to the literature, classification of the scrap tyres, different conclusion given by different researchers on effect of waste tyre rubber on mechanical properties of concrete (compressive strength, split tensile strength, flexural strength, workability, unit weight , impact resistance, creep and shrinkage, durability, thermal properties) and reviews on previous research on dynamic properties of concrete with waste tyre rubber , conclusion of researchers on modules of elasticity and also dynamic test set up for specimens.

Chapter Three: Experimental Investigation. This chapter consists of physical tests of ingredients of concrete such as specific gravity of Waste Scrap Tyre Rubber, coarse and fine aggregates, moisture Content of coarse and fine aggregates, absorption of coarse and fine aggregates, unit weight of coarse and fine aggregates and silt content of sand and proportioning of ingredients of concrete and methodology of compressive, split tensile and flexural strength test as well as dynamic test.

Chapter Four: Result and Discussion. This chapter consists from the test result of slump, compressive, split tensile and flexural strength of concrete and discussion on effect of Waste tyre rubber on mechanical properties of concrete based on the experimental result obtained. Similarly soft ware output which present the results in graphical form, as well as summarizing the outcomes of the dynamic tests and discussing on the effect of Waste tyre rubber on dynamic properties of concrete.

Chapter Five: Conclusion and Recommendation. This chapter summarizes the findings that were drawn from the experimental test results and recommends a few study areas that should be investigated further.

CHAPTER TWO LITERATURE REVIEW

2.1 Introduction

Earthquake is a natural phenomenon that occurs due to sudden movement of plate tectonics from the earth's outermost crust. Earthquakes mostly occur when the fault at the edge of plate tectonic collide into each other or slide past each other. During earthquake, a building experiences dynamic motion because it is subjected to inertia force which is acting in an opposite direction towards earthquake acceleration and this inertia force is known as seismic loading and is assumed to be an external force to the building.

Each building has its own natural period or frequency which is dependent on the height of the building. The natural period of the ground motion is dependent on the type of soil. However, natural period of common building is within the range of ground motion period. The structure should be designed and detailed to possess the required ductility capacity and deformation capacity. The story ductility demands for multistory building vary over its height and differ from the allowable ductility used in defining the design spectrum and computing the story yield strengths. Ductility demand may vary considerably over the building height, depending on the building height and on the relative values of story strengths, and these demands on some stories may exceed the allowable ductility. The deviation of story ductility demands from the allowable ductility increases for taller buildings Chopra (1995).

Modern structures are flexible and lightly damped due to high strength materials and the development of new building technique and also reduced the cost of structures. High-rise buildings are inherently sensitive to earthquake or wind excitation. Consequently, induced oscillations of structures due to wind and earthquake may cause failure of some structures and human discomfort. To reduce undesirable structural vibrations under wind and earthquake loading must ensure functional performance of structures. To achieve this goal different possibilities exist such as structural control, aerodynamic modification and structural modification. Vibration control of structural system in order to provide safety and functionality against induced vibration has always been considered as major relevant technological challenges for the designers.

Basic principles of dynamics can be maintained by taking under the control, modifying and changing the characteristics of both restoring-force when affected by seismic forces, and damping of the building, and also the mass of the building and seismic forces that affect the building. As it is known, the equation of motion of a building that is subjected to the ground motion depends on mass, stiffness, and energy damping nature of the building, as well as on external seismic forces affecting the building. The characteristics of response forces can be controlled, by changing stiffness of the building. When stiffness of the building is decreased, the response acceleration also decreases and displacements increase. On the other hand, response of acceleration and displacement can be decreased, by increasing the damping effect of the building. Various kinds of dampers and their combinations can be placed in the building. The dynamic characteristics of the structural system might be varied, by changing total mass and the distribution of the mass within the system Torunbalci (2004).

Energy dissipation control system can generally be divided into three, accordance to their operation principles, which is active control system passive control system and hybrid systems. Provide a continuous energy from outside is supplied to operate the mechanism for active control system. Due to that the cost of setting up these systems is high. Active control systems can control acceleration of the structure. These systems are composed of electronic device such as computer, actuator, and starter. The design of active control systems is independent from the intensity of the ground motion. There are three types of active control system, which are active mass damper, active variable stiffness, and active passive composite tuned mass damper Torunbalci (2004).

The passive damper does not use any energy from outside. Due to that the cost of the system is less in comparison with active systems. In this system, the certain limit of displacement can be controlled because the system was designed according to a certain earthquake magnitude. The system is composed of dampers, isolators and other devices that can easily be found. The utilization of all the system is based on material that absorb energy at the certain level, either individually or combination with the other. There are different types of passive damper such as irreversible displacement system, plastic system, elastic system, viscous system, kinematical system, Steel hysteretic system and e.t.c Torunbalci (2004).

Generally, the purposes of dampers are earthquake prevention of buildings to provide the structural safety and comfort by controlling the internal forces and displacement within the particular limits. Another method for protection of the structures against the earthquake is to isolate the building from the ground and/or to install seismic energy dissipating elements at the appropriate places of the building. So both isolation and structural control can be reduced the effect of the earthquake, the building damage will also be reduced, but isolation damper installation is one of long-term reliability and high costs in maintenance. Therefore, innovations have been made to improve the passive damper by material replacement compared to active damper, which is usually compact and non-invasive to architectural spaces, improve cost-effective design, building construction and maintenance.

Additionally production of waste tire is one of the main problems faced by most countries the quantity of waste tire worldwide is increasing highly which becomes a significant problem to be solved. It has been a major problem for managing waste for a few decades and in some cases has involved serious environmental pollution. Moreover, it is known that waste materials have to be controlled properly to control environmental pollution. Using a waste tire rubber has a significant role in reusing the material as a row construction ingredient. In Ethiopia, waste tires are retreaded as a form of other products like shoes Misgana Berhanu (2020).

Therefore, the innovation of using waste tyre rubber can be utilized in concrete mixture and it could improve the concrete properties especially damping properties, thus reducing the environmental problem caused by excessive production of waste tyres.

2.2 Classification of the scrap tyres

In most of the researches performed, usually three broad categories of discarded tyre rubber have been considered such as chipped, crumb and ground rubber:

1) Shredded or chipped rubber to replace the gravel. Particles of about with 13 - 76 mm in dimensions are produced and are called “shredded particles”.

2) Crumb rubber that replaces for fine aggregate, is manufactured by special mills in which big rubbers change into smaller pieces. Particles are made with a high irregularity in the range of 0.425 - 4.75 mm.

3) Ground rubber that may replace cement is dependent upon the equipment for size reduction. The processed used tyres are typically subjected to two stages of magnetic separation and screening. Various size fractions of rubber are recovered in more complex procedures. In micro–milling process, the particles made are in the range of 0.075 - 0.475 mm Ganjian, *et al.* (2012).

2.3 Research on application of waste tyre rubber in concrete

Concrete with waste tyre rubber as partial aggregate has effect on the properties of concrete in a wide spectrum. Among construction materials concrete is one of the most popular. Due to this reason, the construction industry is always trying to enhance its properties, uses and applications. In general, concrete has low tensile strength, low energy absorption, and low ductility. Concrete also tends to crack and shrink during the hardening and curing process. To overcome these limitations researchers are introducing and testing new aggregates and admixtures. The introduction of waste tyre rubber to the concrete mix may be one of such method.

2.3.1 Compressive Strength

The compressive strength of concrete is most commonly considered property of concrete. Aggregates generally occupy 60% to 75% of the concrete volume (70% to 85% by mass) and strongly influence the property. Concrete properties are highly influenced by the Aggregate type used in the concrete mix. Due to this, many researches had conducted on the effect of partial replacement of aggregate on compressive strength of concrete. Conclusions given by different researchers are presented on partial replacement of waste tyre rubber in concrete as follows:

Joseph Olawale *et al.* (2016) had conducted a research work on production of lightweight concrete from waste tire rubber crumb and effect of waste tire rubber on compressive strength of Concrete. The study discovered that the compressive strength of crumb rubber concrete decreased as rubber content was increased. The systematic reduction of ultimate strength in tire rubber concrete might restrict the use of tire rubber concrete, with tire rubber concentrations exceeding 8%, in structural applications. There reduction in compressive strength can be attributed to the decrease in adhesive strength between the surface of the waste rubber and the cement paste.

Results from Dubravka *et al.* (2011) compared the compressive strength test results for mixes with varying rubber content from 10 to 40% and nominal mix and also compared to the mixture without mineral admixtures, mainly silica fume. The compressive strength values obtained from their tests decreased as they varied the content of rubber from 10 to 40%. They also observed that waste tyre rubber concrete has certainly reason for reduction of compressive strength. Cement paste containing rubber particles is much softer than hardened cement paste without rubber. Besides that, lack of proper bonding between rubber and the cement paste is certainly one of the major reasons for reduction of compressive strength. Large pore between rubber particle and cement matrix in hardened concrete taken by optical microscope is shown Figure 2.1.

Figure 2.1 Bonding between cement paste and rubber particle.(Dubravka et al. 2011)

Kudzai *et al.* (2018) had conducted a research work on study of the effects of truck tyre crumb rubber particle size, as fine aggregate, on the compressive strength, shrinkage and creep behavior of structural rubberized concrete. For this concrete cubes of having 100mm x 100mm x 100mm size were cast using three tyre crumb rubber sizes (2.36, 1.18 and 0.425 mm) were used to replace 10% by volume of fine mineral aggregates to produce concrete with a target strength of 30 MPa. The study reveals rubberized concrete has lower compressive strength than the control concrete mix for all crumb rubber sizes. Crumb rubber size has an effect on the strength of concrete, as the crumb rubber becomes smaller compressive strength decreases. (Mohamed *et al.* 2016) further observed that in as much as compressive strength was showed a reduction reached up to 29.7% Inclusion of 15% crumb rubber in self-consolidating rubberized concrete mixtures. Several authors Stergios and Ataria (2016); Amedeo *et al.* (2019); Farhad Aslani, (2012) reported the compressive strength results of rubberized concrete. Results of various studies indicate that the size, proportions and surface texture of rubber particles noticeably affect the compressive strength of rubberized concrete. These researchers reveal that the compressive strength of rubber concrete decreased as rubber content was increased.

Sibiyone and Sundar (2017) had conducted a research work on Study of compressive strength of rubberize concrete using rubber waste as partial replacement of coarse aggregate in M20 concrete mix. Concrete samples of 150 mm x 150 mm x 150 mm were cast using rubber waste for different partial replacements of flap rubber (10, 20, 30 and 40%) by volume of coarse aggregate are cast and test for compressive strength. These specimens result were observed at 7^{th} and 28^{th} day with various percentages of rubber by universal testing machine. The study revealed that the compressive strength increases with increasing percentage of rubber. 10% addition of rubber into the concrete shows maximum benefits in compressive strength the replacement over 10% is show is a reduction in all type of strength for flap rubber mixture, Even 40% addition of rubber into the concrete gives more strength than the nominal concrete.

To conclude the researchers showed that the compressive strength increases when the percentage of waste tyre rubber increases in concrete mix [Sibiyone and Sundar (2017)], and the compressive strength of concrete decrease when the percentage of waste tyre rubber increases in concrete mix [Amedeo *et al.* (2019); Farhad Aslani, (2012)]. So there is no clear conclusion on the effect of partially replace of waste tyre rubber on the compressive strength of concrete. Due to this the effect of partial replacement of waste tyre rubber as a coarse aggregate on the compressive strength of concrete was investigated again.

2.3.2 Split tensile strength

Joseph Olawale *et al* (2016) reached a conclusion from tests that, the tensile strength reduces when rubber crumbs added to the concrete as a partial replace of fine aggregate at 0, 4, 8, 12, and 16% ratio. The reduction in tensile strength can also be attributed to the weak interfacial adhesive force between the cement paste and the elongated surface of the rubber crumb which encourages micro voids within the concrete material; these voids are potential weak points for the tensile stresses generated during the application of tensile forces on the concrete samples, the more voids within the concrete samples the less tensile strength. Mohamed et al. (2016) further observed that in as much as tensile strength was showed a reduction reached up to 31% inclusion of 15% crumb rubber in self-consolidating rubberized concrete mixtures. Other researchers Sofi (2017); Abubaker *et al*. (2017) also had conducted a research work on the effect of waste tyre rubber on tensile strength of concrete. These outers reveal that the tensile strength of rubber concrete decreased as rubber content was increased.

Sibiyone and Sundar (2017) had aimed to achieve the use of rubber waste as partial replacement of coarse aggregate to produce rubberized concrete. Different partial replacements of flap rubber (10, 20, 30 and 40%) by volume of coarse aggregate are cast. The concrete cylinder of size 150 x 300 mm were cured at 7and 28 days and tested for split tensile strength. The study concludes that the tensile strength increases with increasing percentage of rubber. 10% addition of rubber into the concrete shows maximum benefits in tensile strength, the replacement over 10% is show is a reduction in all type of strength for flap rubber mixture; Even 40% gives more strength than the nominal concrete.

The researchers give different conclusions. The first conclusion said that the tensile strength increases when the percentage of waste tyre rubber increases in concrete mix, the second conclusion said that the tensile strength of concrete decrease when the percentage of waste tyre rubber increases in concrete mix. So there is no clear conclusion on the effect of partially replace of waste tyre rubber on the tensile strength of concrete. Due to this the effect of partial replacement of waste tyre rubber as a course aggregate on the tensile strength of concrete was investigated again.

2.3.3 Flexural strength

Sibiyone and Sundar (2017) had conducted a research work on study of flexural strength of rubberize concrete using rubber waste as partial replacement of coarse aggregate. Prismatic specimen of size 100 x 100 mm cross section and 500 mm length were cast using rubber waste for different partial replacements of flap rubber (10, 20, 30 and 40%) by volume of coarse aggregate are cast and test for flexural strength. The study reveals that the flexural strength increases with increasing percentage of rubber. 10% addition of rubber into the concrete shows maximum benefits in flexural strength the replacement over 10% is show a reduction in all type of strength for flap rubber mixture, Even 40% gives more strength than the nominal concrete.

Addition of crumb rubber has been showed a slight reduction of the flexural capacity about 2.67% of nominal mix Mohamed *et al*. (2016). Stergios and Ataria (2016); had observed the result, that of decreased in flexural strength by 16% when 15% incorporated of rubber particles by volume of the total coarse aggregates in concrete mix. And the study reveals, the reduction in compressive strength is more than the flexural strength, for 15% replacement of coarse aggregates with rubber particles in concrete, the reduction in compressive strength is 57.8% more than the flexural strength. In addition, Mohamed *et al*. (2016), Abubaker et al. (2017), and Sofi (2017) noted that flexural strength gradually decreased as the amount of crumb rubber increased.

The researchers give different conclusions. The first conclusion said that the flexural strength increases when the percentage of waste tyre rubber increases in concrete mix, the second conclusion said that the flexural strength of concrete decrease when the percentage of waste tyre rubber increases in concrete mix. So there is no clear conclusion on the effect of partially replace of waste tyre rubber on the flexural strength of concrete. Due to this the effect of partial replacement of waste tyre rubber as a course aggregate on the flexural strength of concrete was investigated again.

2.3.4 Workability

The slump test is the most commonly used method of measuring the consistency or workability of concrete which can be employed either in the laboratory or on site Joseph

Olawale, *et al* (2016) reached a conclusion from tests that the slump value decreases as the percentage of rubber increases in the concrete mix, but in general, the rubberized concrete specimens have acceptable workability in terms of ease of handling, placement, and finishing. The very low slump especially in all the rubberized samples can be attributed to the absorption of water by the rubber particles in the concrete mixture; since the rubber crumb was dry, it affinity with water was high within the concrete environment hence the almost dry concrete obtained. Mavroulidou and Figueiredo (2010) discovered that with increase of rubber content there was decreased workability of concrete for both fine and coarse aggregate replacements with tire rubber. The concrete mixtures with finely ground rubber particles were found to be more workable than those with the coarse aggregate-sized rubber chips. Kudzai *et al.* (2018) reached a conclusion from tests that there is an improvement in workability of the concrete with the incorporation of rubber particles. The general increase in slump can be attributed to the low water absorption of tyre rubber when compared to mineral aggregates.

The researchers give different observations about workability of concrete and water absorption capacity of tyre rubber. It is difficult to attribute this behavior to a particular tyre rubber particle since the increase and decrease does not seem to follow a certain trend based on size and moisture. To properly evaluate the influence of the rubber content on the workability, it will be necessary to perform the slump tests of fresh rubberized concrete.

2.3.5 Unit weight

Addition of rubber has been observed to lower the unit weight of the concrete, due to the rubber having a lower specific gravity than the other typical solid components. Kaloush, *et al.* (2005) observed that the unit weight of crumb rubber concrete decreased approximately 6 pcf for every 50 lbs per cubic yard of crumb rubber added. Osama and Saleem (2010) concluded that the density of concrete decreased in general as the percent replacement by crumb rubber increased. Mavroulidou and Figueiredo (2010) concluded that the density reduces by the addition of rubber aggregates whether these are fine or coarse.

Cavalline *et al.* (2021) had conducted a research work on study of influence of lightweight aggregate concrete materials on building energy performance. The study reveals in use of sand lightweight concrete resulted in prediction of 15–17% heating energy savings and 10% cooling energy savings, while use of all lightweight concrete resulted in prediction of approximately 35–40% heating energy savings and 30% cooling energy savings. Joseph Olawale *et al.* (2016) also concluded the decrease in bulk density with increase in the amount of rubber crumbs in all concrete samples showed and the rubber crumbs in concrete encourage the formation of voids within the concrete interface and thus lead to the lightweight characteristics of the rubberized concrete.

2.3.6 Impact resistance

Sallam *et al.* (2008) investigated the impact resistance of a control concrete mixture and rubber concrete mixtures. They reported that the presence of crumb rubber of small size in concrete increased the resistance of concrete to crack initiation under impact load. Wakchaure and Channa (2018) also had conducted a research work on the effect of waste tyre rubber on impact resistance of concrete. They reported that the difference between numbers of blow for ultimate failure and first crack increases significantly with the increase in replacement level of crumb rubber, which indicates the reduction in brittleness of concrete or increase in ductility of waste tyre crumb rubber concrete .

2.3.7 Creep and shrinkage

Kudzai *et al.* (2018) had conducted a research work on Study of shrinkage and creep tests of concrete made using crumb rubber. For these concrete prisms were cast using mould sizes of 710 x 100 x 100 mm for the shrinkage and creep tests. After approximately 20 days of curing, each concrete beam was cut into three 100 mm x 200 mm prisms using a diamond saw and faced. The concrete prisms were cured in a water-curing tank for a total of 28 days before they were set up in the loading frames and the load is applied by a hydraulic flat jack. The study shows an increased in the shrinkage and creep deformation of the concrete when crumb rubber is added. Sallam *et al* (2008) also had concluded that the presence of crumb rubber of small size in concrete increased the resistance of concrete to crack initiation under impact load.

2.3.8 Durability

Ganjian *et al.* (2012) had noted that permeability is the most effective internal factor in concrete durability. A reduction in permeability of concrete would improve its other characteristics including durability against environmental conditions like freezing and thawing cycles, reduction in corrosion of concrete and steel bars exposed to aggressive minerals and or acids. And the study reveals that replacement of rubber increased water permeability depth in the concrete mixtures and increases the water absorption. Dubravka *et al.* (2011) also had conducted a research work on the effect of waste tyre rubber on durability of concrete. The investigation confirmed that presence of rubber particles in concrete induces improvement of durability properties.

2.3.9 Thermal properties

Osama and Saleem (2010) concluded that thermal insulation increased was achieved as crumb rubber percent increased Kaloush *et al.* (2005) reached a conclusion from tests that crumb rubber concrete showed more resistance to thermal changes. This study showed that rubber concrete has favorable coefficient of thermal expansion values, with reduced thermal effects of heating and cooling on the concrete. The addition of crumb rubber of 27.2 kg per cubic meter reduced the thermal expansion values by about 29% when compared to the control mix. These results indicate that the crumb mixes are more resistant to thermal changes.

2.4 Dynamic properties of concrete with waste tyre rubber

Some of the concrete structures like road foundations and other infrastructural facilities are subjected to vibration forces such as impact loading or dynamic shock of moving vehicles. The induced vibration in a given structures depending on structural type and dynamic load applied, varies in amplitude and in frequencies with excitation source.

The dynamic properties of concrete material system include three primary parameters: dynamic modulus of elasticity, natural frequency, and vibration damping. These three properties interact with each other. Damping is the characteristic of energy dissipation of the material; dynamic modulus is a characteristic on the dynamic response of the material;

and natural frequency is a characteristic associated with the material and structure system. Damping of a system can be manifested in the form of the decay of free vibrations. Vibration damping is valuable for structures because it mitigate hazards whether due to accidental loading, wind, ocean waves, or earthquakes, increases the comfort of people who use the structures, and enhances the reliability Zheng *et al* (2008).

Zheng *et al* (2008) concluded that the Dynamic Properties of concrete increased as rubber replacement increased. The study revealed the vibration reduction requires high vibration damping capacity as well as high stiffness of materials. The rubberized concrete damping ratio increased considerably with the increase of rubber content and the dynamic modulus elasticity of rubberized concrete was lower than that of plain concrete. Rubber content had significant effects on both dynamic and static modulus of elasticity of concrete.

2.4.1 Modules of elasticity

Ganjian *et al* (2012) discovered that modulus of elasticity decreased with an increase in the rubber content. Reduction in modulus of elasticity was 17 to 25 percent in the case of 5 to 10 percent aggregate replacement by chipped rubber and the corresponding reduction for powdered rubber was 18 to 36 percent. Osama and Saleem (2010) concluded that the modulus of elasticity decreased as crumb rubber replacement increased. Generally, samples showed relatively higher strain with the increase in crumb rubber replacement. Zheng *et al.* (2008) had concludes that dynamic modulus elasticity of rubberized concrete was lower than that of plain concrete. Sofi (2017) also had concluded that modulus of elasticity of concrete was reduced with the replacement of rubber for aggregate or cement.

2.4.2 Dynamic test set up

This is the simplest test to measure the damping properties of concrete material using a simple and easy method to do. A test to investigate damping properties of the beam specimen was done by generating the free vibration on the beam and then recording it using a sensor. The beam specimen was placed in a clamped position at one end and free on the other end. After the position was determined, the load was hung on the free end by a string and kept stable. The string was cut to generate a free vibration on the beam which was recorded by a sensor installed on the free end of the beam connected by a dewe-43 universal data acquisition instrument. The dewe43 was connected by Dewesoft program installed in the computer to convert the form of vibration data from analogue into digital signals and to transform them into frequency domain (FFT) as shown in Figure 2.2 Faizah and Aminullah (2020).

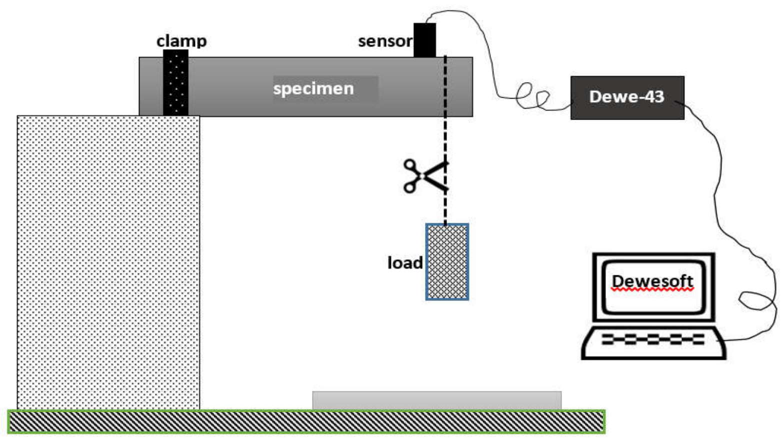


Figure 2.2: Experimental set-up of simple laboratory, (Faizah and Aminullah 2020)

This test can identify the frequency fundamental of the beam and the vibration caused by cutting of the load-string. The clamp arrangement was also prepared for clamping one end of the specimen as illustrated in Figure 2.3. It was made from iron material by 3 mm thickness in order to bind the specimen firmly. Faizah and Aminullah (2020)

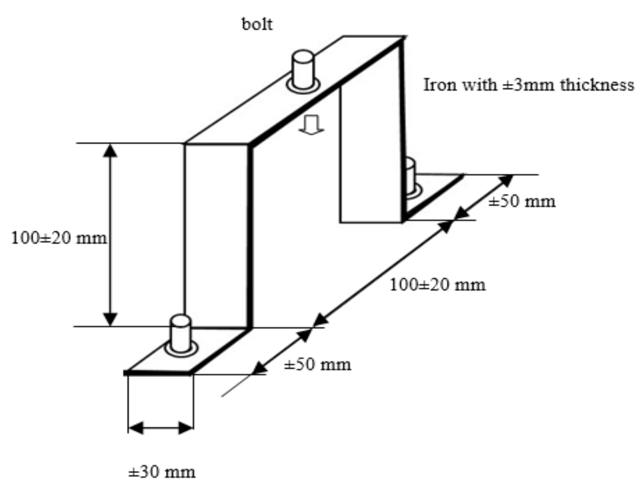


Figure 2.3: Sketch of the clamp, (Faizah and Aminullah 2020)

CHAPTER THREE MATERIALS AND METHOD

3.1 MATERIALS

3.1.1 Cement

Cement is material which generally use for bonding in concrete in construction industries. Ordinary cement (OPC) with grade of 42.5R fabricated from Dangote cement has been used.

3.1.2 Fine aggregate

The river sand was used as fine aggregate. The river sand was washed and screened, to eliminate unwanted deleterious material and over size particles. The test for determination of particle size distribution and silt content was carried out. The surface dry aggregate were used for test. These properties of aggregate are necessary to decide proportions of the concrete mix.

3.1.2.1 Silt content of sand

Silt content is a fine material which is less than 150 micron. It's unstable in the presence of water. If we use silty sand for bonding, it will reduce the strength. The clay and silt content may usually not exceed 6%.To determine silt content of sand, put the sand into transparent jar, add water up to 50% above the sand level and shake the jar strongly for at least 30 seconds. Then Place the jar on a table at least one hour, when the water is clear, measure the thickness of the silt layer (A) and the thickness of the total material layer (B).

Silt (%) = $\frac{A}{B} \times 100$

Silt (%) = $\frac{8}{300} \times 100$

Silt (%) = 2.666%

3.1.2.2 Sieve analysis of Sand

In the construction industry of Ethiopia the manuals used for the sieve analysis and other laboratory tests are AASHTO and ASTM, therefore I used these manuals for particle size distribution of aggregates. River sand is used and sieve analysis was carried out to whether it meets the AASHTO or BS standards and the result is given in table 3.1 below.

Table 3.1: Particle size distribution of natural sand AASHTO M 6-93 Or ASTM C 136

Sieve Size (mm)	Weight Retained (kg)	Percentage Retained	Cumulative Passing (%)	AASHTO M-6 Standard Passing (%)
9.5	0	0	100	100
4.75	0	0	100	95-100
2.36	0.04	8	92	80-100
1.18	0.12	24	68	50-85
0.6	0.18	36	32	25-60
0.3	0.12	24	8	10—30
0.15	0.03	6	2	2—10
Pan	0.01	2	0	
Total	0.5	100		

F.M = 2.98%

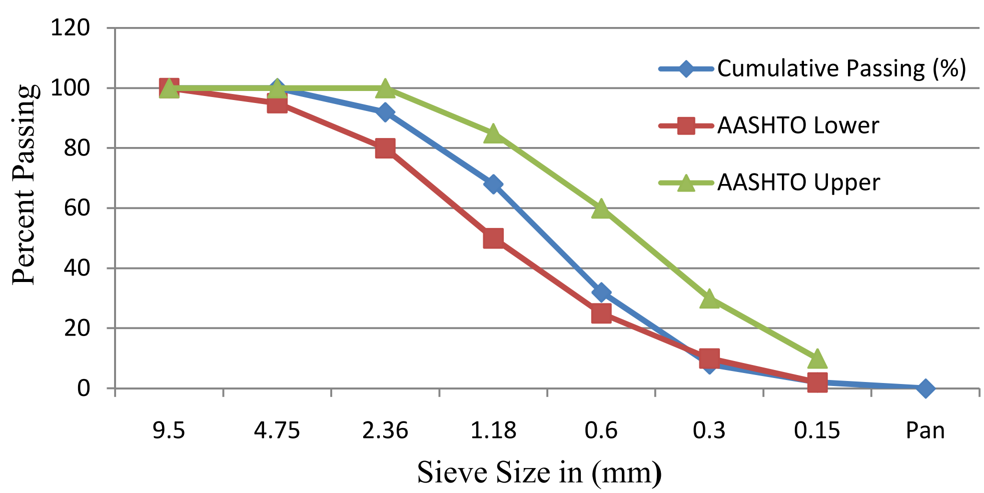


Figure3.1: Particle size table distribution of natural sand

3.1.2.3 Specific gravity of fine aggregates

The specific gravity of a substance is the ratio between the weight of the substance and that of the same volume of water. Specific gravity = 2.51,

3.1.2.4 Absorption of fine aggregate

Moisture content % = 0.73% and most it's recommended to be less than 3%.

3.1.3 Coarse aggregate

The coarse aggregate from crushed rock are used. The aggregates were free from injurious amount of disintegrated pieces, vegetable matter and other deleterious substances. Typically coarse aggregate sizes are larger than 4.75mm.

3.1.3.1 Sieve analysis of aggregates

The aggregates were free from injurious amount of disintegrated pieces, vegetable matter and other deleterious substances. Typically coarse aggregate sizes are larger than 4.75mm and maximum size 25mm is used. A crushed aggregate is proportioned to meet the AASHTO or ERA standards and the result is given in table 3.2 below.

Table 3.2: Particle size distribution of crushed aggregate

Sieve Size (mm)	Weight Retained (kg)	Percentage Retained	Cumulative Passing (%)	Standard Passing
37.5	0	0	100	95-100
25	0	0	100	95-100
19.5	1.89	37.8	62.2	30-70
12.5	1.51	30.2	32	25-60
9.5	0.43	8.6	23.4	10—35
4.75	1.16	23.2	0.2	0-5
Pan	0.01	0.2	0	
Total	5	100		

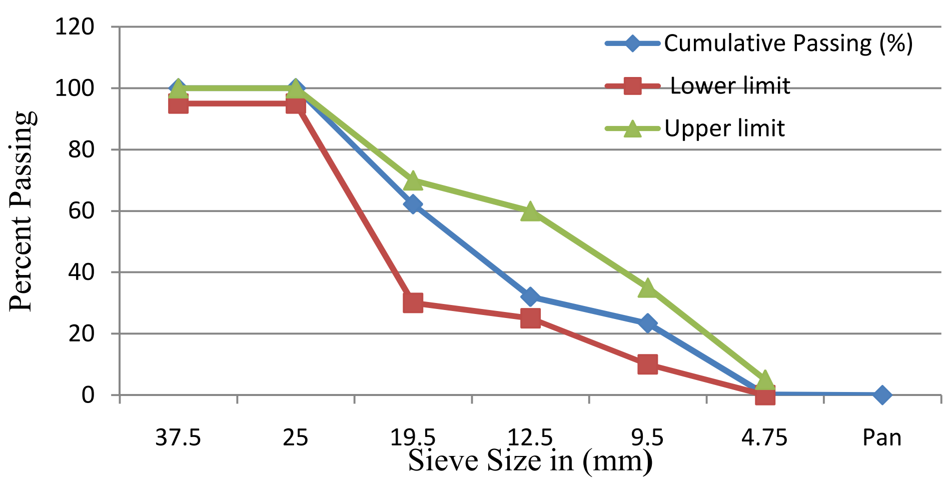


Figure 3.2: Particle size distribution of aggregate

3.1.3.2 Specific gravity of coarse aggregate

Specific gravity is defined as the ratio of the weight of aggregate in air to the weight of equal volume of water displaced by saturated surface dry aggregate. Specific gravity of coarse aggregate = 2.715,

3.1.3.3 Absorption of coarse aggregates

The water absorption of aggregates ranges from 0.1 to 2% of its dry weight. Moisture content % of coarse aggregate = 1.05% and its between allowable range of 0.1 = MC = 2.

3.1.4 Waste scrap tyre rubber:

Tyre may be divided into two types – car and truck tyres. Car tyres are different from truck tyres with regard to constituent materials (e.g. natural and synthetic rubber).

Figure 3.3: Rubber samples (Before Cutting)

The chipped rubber samples were obtained by cutting the tyre manually. The scrap tyre rubber chips passing through the 25 mm sieve size were used in the study. Rubber samples before cutting are as shown in Figure. 3.3. After Cutting Chipped Rubber Samples are shown in Figure. 3.4.

Figure 3.4: Chipped rubber samples

3.1.4.1 Particle size distribution of waste tyre rubber

Waste tyre rubber particles were partially replaced as coarse aggregate, so the size of the particle treated as coarse aggregate. The actual grading requirements depend on the shape and surface characteristics of the particles. Extending the grading of aggregate to a larger maximum size lowers the water requirement of the mix, so that, for a specified workability and cement content, the water/cement ratio can be lowered with a consequent increase in strength. In structural concrete of usual proportions, there is no advantage in using aggregate with a maximum size greater than about 25 or 40mm when compressive strength is a criterion. Particle size distribution of an aggregate is determined using sieve analysis. Usually the grading and grading limits are expressed in terms of percentage of material passing through each sieve. The particle size distribution and fineness modulus (FM) of the tyre rubber is checked as per the aggregate requirement. After taking two representative samples of the rubber aggregate, sieve analysis was conducted and an average value of the samples was taken as particle size distribution of the rubber aggregate.

Table 3.3 Particle size distribution of waste scrap tyre rubber

Sieve Size (mm)	Weight Retained (kg)	Percentage Retained	Cumulative Passing (%)
37.5	0	0	100
25	0.01	0.5	99.5
19.5	0.615	30.75	68.75
12.5	0.72	36	32.75
9.5	0.325	16.25	16.5
4.75	0.33	16.5	0
Pan	0	0	0
Total	2	100	

3.1.4.2 Specific gravity of waste tyre rubber

Specific gravity: - the specific gravity of Waste Scrap Tyre Rubber indicates the density relative to that of the water. We know that the specific gravity of water is 1000kg/m³. So the first thing is find the mass of waste tyre sample which is 9.6g but the volume of the sample was not determined. The displacement method was used to determine the volume of the tyre sample, firstly the sample was wrapped by the small string around it and immersed in water then displaced amount of water was counted and it equal to the volume of tyre rubber sample. The scale was show the mass of water displaced, and mass of the water displaced was 8.5g. Since the density of water is one that means 8.5cm³ have been displaced it equals the volume of waste tyre sample so the density of waste tyre sample is

Mass=9.6g

Volume=8.5cm³

Density= $\frac{\text{mass}}{\text{volume}} = \frac{9.6\text{g}}{8.5\text{cm}^3}$ =1.129 g/cm³ = 1129kg/m³

3.1.5 Mix design

There were six type of mix considered: which of one control mixture CM-0 (without rubber) was designed as per ACI Standard Specification ACI-2111_91, the consideration of mix design are presented in Appendix A. The other five concrete mixes were made by replacing the coarse aggregates with 5%, 10%, 15%, 20% and 25% of discarded tyre rubber by volume; the details mixture proportions are given in Table 3.4

Table 3.4: Mix Considered for rubberized concrete

Mix Identity	Mix proportions by volume
CM-0	C25 concrete with 100% coarse aggregate
RCM-5	C25 concrete with 95% coarse aggregate and 5% tyre rubber
RCM-10	C25 concrete with 90% coarse aggregate and 10% tyre rubber
RCM-15	C25 concrete with 85% coarse aggregate and 15% tyre rubber
RCM-20	C25 concrete with 80% coarse aggregate and 20% tyre rubber
RCM-25	C25 concrete with 75% coarse aggregate and 25% tyre rubber

3.2 Methods

3.2.1 Problem of statement

Discarded waste tyre rubber is chosen as a natural aggregate to replace by 5%, 10%, 15%, 20% and 25% volume of coarse aggregate. And comparing in C-25 grade plain cement concrete and rubberize concrete with various amount of rubber content for compressive, split tensile, flexural and dynamic properties

3.2.2 Compressive strength

The most common test for hardened concrete involves taking a sample of fresh concrete and putting it into a special cube molds so that, when hard, the cubes can be tested to failure in a special machine in order to measure the strength of concrete. The results obtained from compression tests on hardened concrete cubes are used to check that its strength is above the minimum specified and to assess the control exercised over the production of concrete. Compressive test were carried out on cubes of dimensions 150 × 150 × 150 mm after 7 days and 28 days. For each test date and for each mix three specimens were tested. The compressive strength of each cube was determined according to ACI Standard by using Universal Testing Machine (UTM) at a load rate of 180 kN/min. The compressive strength test setup for cubes is shown in Figure 3.5.

Figure 3.5: Compressive strength test set up for cubes

3.2.4 Split tensile strength

In this test, a concrete cylinder is placed with its axis horizontal between a plates of the testing machine, and the load is applied until failure by indirect tension in the form of splitting along the vertical diameter takes place. However, immediately under the load a high compressive stress would be induced and, in practice, narrow strips of packing material, such as plywood are interposed between the cylinder and the plates. During vibration of fresh concrete filled in cylindrical molds, rubber discarded in concrete was flow on the upper part of the concrete. To keep homogeneity of the concrete the layer of concrete was stroked by using the tamping rod. Add two further layers of equal height and rodding each layers allowing the rod to penetrate through in to the layer below.

Figure 3.6: Roding the layer of concrete using the tamping rod

Cylindrical specimens of 150 mm long and 300 mm diameter were tested in accordance to ACI Standard. The split tensile strength was computed using the expression

$$\text{Fct} = \frac{2\text{p}}{\pi \text{ld}}$$

Where, Fct is the split tensile strength in MPa,

P is the maximum compressive load on the cylinder (in Newton),

l is the length of the cylinder in mm, and

d is the diameter of the cylinder in mm.

The split tensile strength test setup is shown in Fig. 3.7.

Figure 3.7: Split tensile test set up for cylinders

3.2.5 Flexural strength

Flexural strength is measured by loading (100×100 mm) concrete beams with a span length at least three times the depth which is 500 mm in this research. The flexural strength is expressed as modulus of rupture (MR) in (MPa) and is determined by standard test methods third-point loading or center point loading. However, the best correlation for specific materials is obtained by laboratory tests for given materials and mix design. For a bending force applied downward on a member supported simply at its two ends, the part of members above the neutral axis are, generally, subjected to compressive stresses and those below the neutral axis to tensile stresses. For this load and support system, portion of the member near the supports are subjected to relatively higher shear stresses than tensile stresses. In this test the concrete member to be tested is supported at its ends and loaded at its two interior locations as show in Figure 3.9 by a gradually increasing load to failure. The prism molds were filled with concrete by using the scooping fill and vibrated in order to remove air bubbles, during vibration rubber discarded was flow on the upper part of the concrete. To keep homogeneity of the concrete, the layer of concrete was stroked by using the tamping rod.

Figure 3.8: Rodding the concrete using the tamping rod

After rodding the test was performed on prisms of dimensions 100 × 100 × 500 mm. The flexural strength was determined by the two point loading technique and computed by using the expression

$$F_b = \frac{\mathrm{pl}}{\mathrm{bd}^2}$$

Where F_b is the flexural strength in MPa,

P is the maximum applied load in Newton,

L is the span length in mm,

b is the width of the specimen in mm, and

d is the depth of the specimen in mm.

The test setup for flexural strength of prisms is as shown in Figure 3.9.

Figure 3.9: Flexural strength test set up for prisms by third point loading using UTM

3.2.6 Dynamic properties

The testing programs in order to apply a simple laboratory test were conducted in the Material Laboratory of Civil and Environmental Engineering Department of Addis Ababa University. Fresh concrete was molded in the mold with the dimension of 100 x 100 x 500 mm. After the concrete beam was removed from the mold it was cured by immersing under water to keep its moisture. The concrete beam was tested at the age of 28 days. Damping properties of concrete material can be investigated by a simple laboratory test. The investigation applied impulse technique with a concrete beam as the specimen requiring dynamic test laboratory equipment (Figure 3.10) including Arduino uno board universal data acquisition instrument (Figure 3.10A), Arduino soft program installed in computer (Figure 3.10B) and MPU6050, sensor (Figure 3.10C).

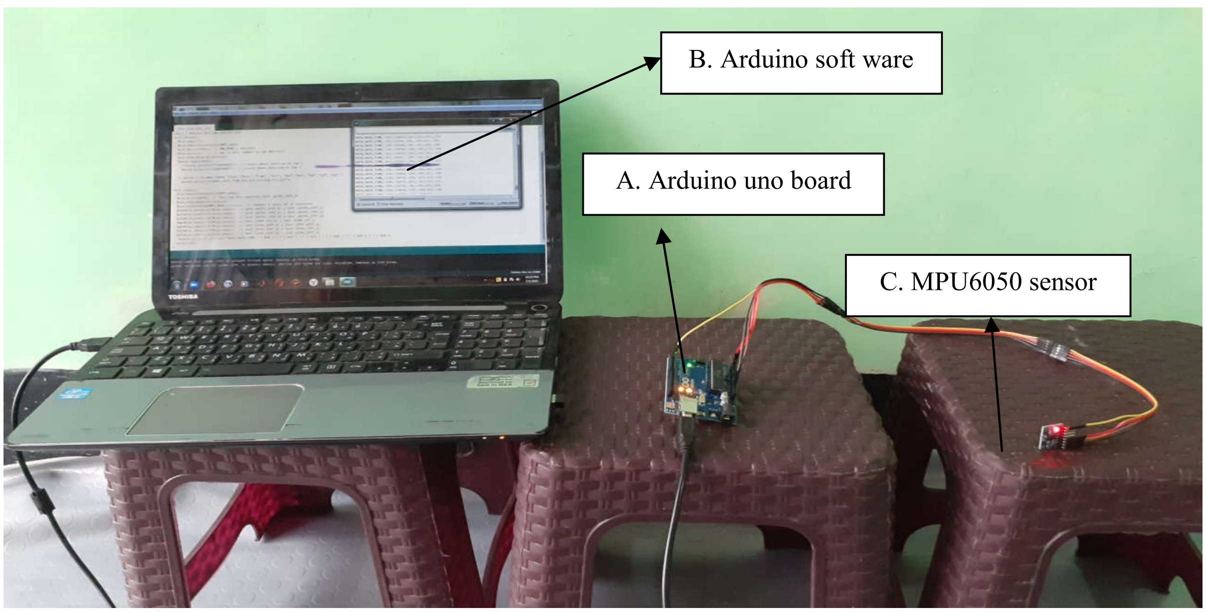


Figure: 3.10 Dynamic test laboratory equipment

3.2.6.1 Purpose and scope of MPU6050 sensor

The MPU6050 sensor eliminates the package-level gyroscope and accelerometer cross-axis misalignment associated with discrete solutions that devices provide the world's first integrated 6-axis motion processor solution. The device has a combine of a 3-axis accelerometer and a 3-axis gyroscope on the same silicon die together. The MPU-6050 features a user programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g.

The parts also have a user-programmable gyroscope full-scale range of ±250, ±500, ±1000, and ±2000°/sec (dps). The MPU-6000 family is comprised of two parts, the MPU-6000 and MPU-6050. The MPU-6050 supports I2C communications at up to 400 kHz. The figure of MPU6050 sensor is available on Appendix B

3.2.6.2 Clamp

The clamp equipment was also prepared for clamp one end of the specimen by dimension illustrated in Figure 3.11. It was made from iron material by ±3mm thickness in order to bind the specimen firmly.

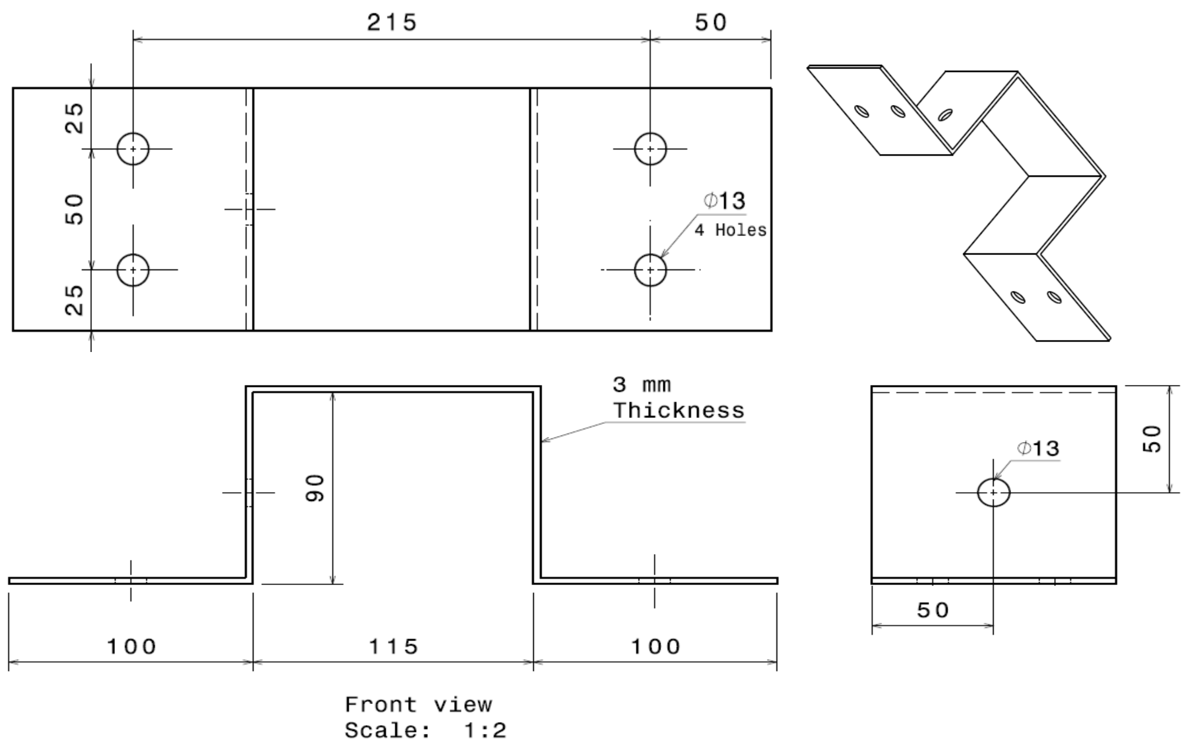


Figure 3.11: Sketch of the clamp

3.2.6.3 Preparing specimens

The test specimen was a concrete beam with a specific characteristic adapting the research objective. There were various mixing methods and material variations to make the beam with a dimension of 100 x 100 x 500mm³ as shown in Figure 3.12. The prism molds were filled with concrete and vibrated for 30 s using vibrator in order to remove air bubbles, during vibration rubber discarded was flow on the upper part of the concrete. To keep homogeneity of the concrete the layer of concrete was stroked by using the tamping rod. After being molded, the specimen was cured for 28 days to get their full strength and they were ready for the test. However, the beam can also be tested on 28 days old to investigate the dynamic properties.

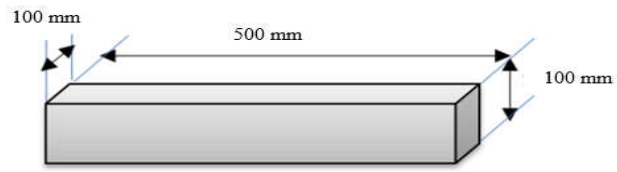


Figure 3.12: The beam specimen of concrete

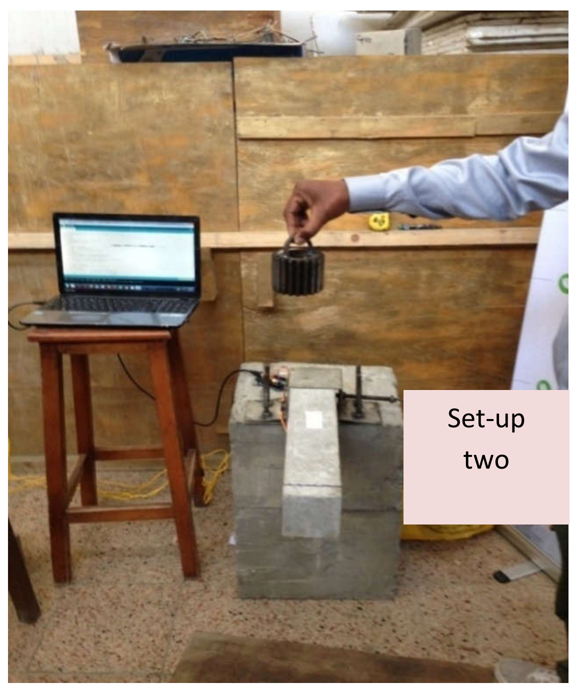
3.2.6 .4 Experimental procedures

A simple experiment to investigate damping properties of the beam specimen was done by generating the free vibration on the beam and then recording it using a MPU6050 sensor. The beam specimen of 100 x 100 x 500 mm³ was placed in a clamped position at one end and free on the other end. After the position was determined, there were two types test set-ups, as shown in the experimental set-up on Figure 3.13A and Figure 3.13B.

In the first test set up the load was hung on the free end by a string and kept stable. The experiment was carried out with four loading variations, 10, 15, 20 and 35 N, for the same beam, then, the string to which the loads were hung was cut to generate a free vibration which was recorded by a MPU6050 sensor installed on upper the free end of the beam. In the second test set-up the experiment was done with applying impact load by fall of two steel balls with height of fall 50cm and steel ball of weight 10N and 20N where the free vibration was generated due to fall of steel balls on the beam. The free vibration was recorded by sensor MPU6050 installed in lower part of the beam at free end.

For both cases free vibration was recorded by a sensor installed on the free end of the beam connected to an Arduino uno board universal data acquisition instrument. The Arduino uno board was connected to Arduino soft program installed in the computer to record the data and convert the form of vibration data from analogue into digital signals and also transform them into frequency domain (FFT). Picture of sensor type (MPU6050), and Arduino board and also coding of Arduino soft to connect PLQDX soft are presented in appendix B and appendix C. Damping ratio of the specimen was analyzed by logarithmic decrement method. After the value of maximum and a half-magnitude of the wave (Y_1 and Y_n) and number of cycles between Y_1 and Y_n (j) was determined from the body of the wave, the damping ratio could be counted. The peak amplitude of the response did not always occur in the first cycle, but instead some peaks occurred in the second or third cycle. Therefore, all analyses in this study started from the peak of the vibration rather than from the first cycle. In the logarithmic decrement method, the resulting damping ratio varies depending on the number of cycles and their amplitudes. The mean value resulting from 10 cycles is generally acceptable, But for small deformation as Faizah and Aminullah (2020) damping ratio was estimated by using nearly half magnitude of peak amplitude of the response. In this paper, the experimental result mostly shows the half of maximum amplitude occurs within 3 cycles so the damping ratio was estimated by taking the value resulting from 3 response cycles and by using the first (peak) amplitude Y_1 and the fourth (nearly half of peak) amplitude Y_4, where Y_1 is the maximum magnitude of the wave and Y_4 is nearly the half of Y_1 magnitude approximately ($Y_4 \sim 0.5Y_1$). The number of cycles between Y_1 and Y_4 is also calculated and included in the estimation of the damping ratio using equation. 25.

A) Test set-up of string load



B. Test set-up of impact load

Figure 3.13: Experimental set-ups of dynamic testing program

3.2.6 .4 .1 Connecting MPU 6050 sensor with Arduino

The Arduino communicates with the MPU 6050 through the I2C protocol. The GND of the MPU 6050 is connected to the GND of the Arduino. The pin labeled as INT on the MPU 6050 was Connected Arduino's digital pin 2 (interrupt pin 0). To set up the I2C lines, the Arduino's analog pin 4 (SDA) was connected with the pin labeled SDA on the MPU 6050 , and the pin labeled as SCL on the MPU 6050 connected to the Arduino's analog pin 5 (SCL). The MPU 6050 was connected to Arduino uno as shown in the Figure 3.14

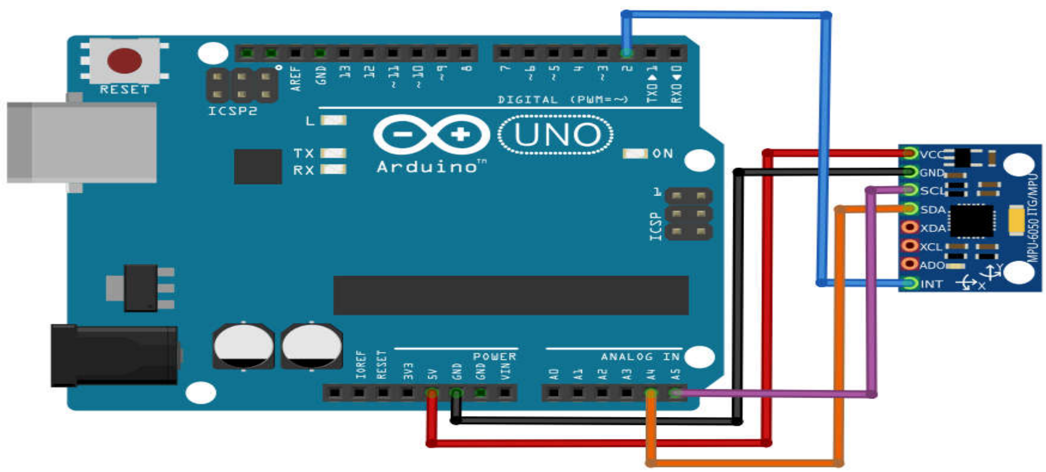


Figure 3.14: Arduino uno and MPU 6050 connections

3.2.6 .4 .2 programming Arduino to communicate with Excel using PLX DAQ

PLX DAQ is a program used to establish an easy communication between Microsoft Excel on a Windows Computer and any device that supports serial port protocol. It was intentionally written to allow communication between Arduino and Excel. To work PLX DAQ soft correctly Arduino needs to send special formatted commands. All commands need to be sending from Arduino to the PC using the `Serial.println` commands. These commands can include parameters, variables and functions to send to as well. These parameters need to be separated by commands. These different categories of commands are presented in Appendix C.

3.2.6.5 The analysis of damping ratio

Damping properties of the beam is expressed by damping ratio (ξ) which can be calculated by analyzing the wave using the logarithmic decrement method, for a single degree of freedom system, with mass (*m*), stiffness (*k*) and damping (*c*), the power equation can be expressed as follows:

$$m\ddot{x} + c\dot{x} + kx = p(t) \tag{1}$$

Considering the response with a nonzero damping coefficient c≠ 0, the homogenous solution of the differential equation becomes;

$$x(t) = e^{at} \tag{2}$$

$$\dot{x}(t) = ae^{at} \tag{3}$$

and the acceleration is given by

$$\ddot{x}(t) = a^2 e^{at} \tag{4}$$

Using equations (2), (3) and (4) in equation (1) and making the external force function $p(t)$ equal to zero for substituting free vibration we obtain

$$e^{at}[ma^2 + ca + k] = 0 \tag{5}$$

Solving for a we have

$$a_{1,2} = \frac{-c \pm \sqrt{(c^2) - 4km}}{2m} \tag{6}$$

Defining the critical damping coefficient as

$$C_{cr} = \sqrt{4km} \tag{7}$$

And the damping ratio as

$$\xi = \frac{c}{Ccr} \tag{8}$$

We can rewrite equation (6)

$$a_{1,2} = -\xi\omega n \pm i\omega n\sqrt{1-\xi^2} \tag{9}$$

Defining the damped natural frequency as

$$\omega d = \omega n\sqrt{1-\xi^2} \tag{10}$$

Equation (9) can be rewritten as

$$a_{1,2} = -\xi\omega n \pm i\omega d \tag{11}$$

Thus, the solution for the differential equation of motion for a damped unforced system is

$$x(t) = Ae^{-\xi\omega nt}e^{-i\omega dt} + Be^{-\xi\omega nt}e^{i\omega dt} \tag{12}$$

or

$$x(t) = e^{-\xi\omega nt}(Ae^{-i\omega dt} + Be^{i\omega dt}) \tag{13}$$

Using Euler's formula and rewriting equation (13) yields

$$e^{-iat} = \cos(at) + i\sin(at) \tag{14}$$

$$x(t) = e^{-\xi\omega nt}(C\cos(\omega d)t + D\, i\sin(\omega d)t \tag{15}$$

The difference is in the presence of the term $e^{-\xi\omega nt}$ this term forces the response to be shaped with an exponential envelope as shown in Figure 3.14.

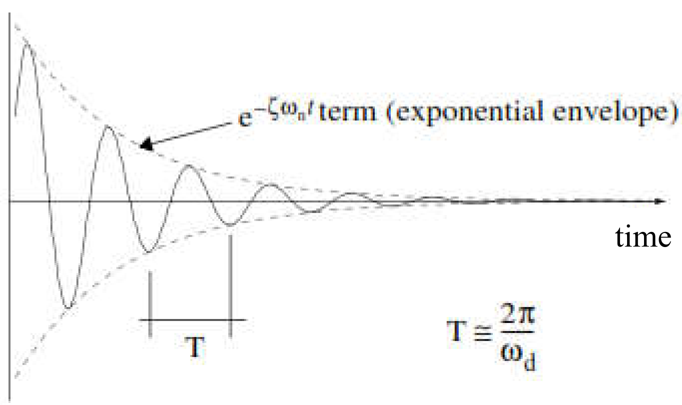


Figure 3.15: Free vibration of damped structures.

Using free vibration data of the acceleration of the structure one may obtain the damping ratio. Figure 3.15 shows a free vibration record of a structure. The logarithmic decrement, δ, between two peaks is defined as

$$\delta = \left(\ln\frac{Y_1}{Y_2}\right) \tag{16}$$

Where Y_1 and Y_2 are the amplitudes of the peaks.

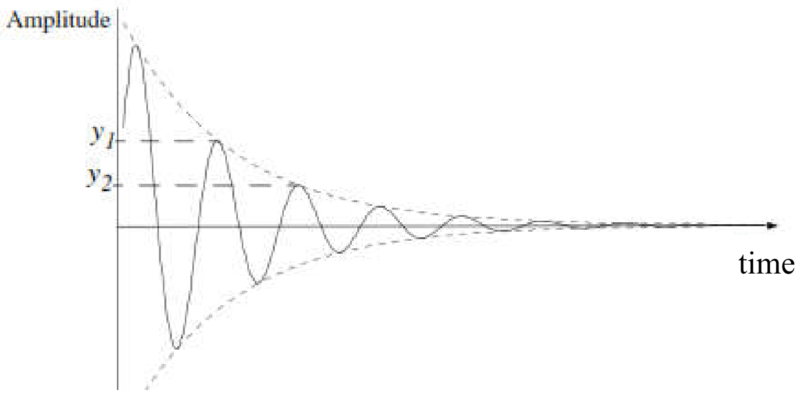


Figure 3.16: The logarithmic decrement signal at the free end of the beam

From the solution of the damped system (equation (15)) we can say that Y_1 and Y_2 can be written as

$$Y_1 = Ce^{-\xi\omega nt} \tag{17}$$

$$Y_2 = Ce^{-\xi\omega n(t+T)} \tag{18}$$

Where the constant C includes the terms of the sine and cosines in equation (15), and T is the period of the system. Using equations (17) and (18) in equation (16)

$$\delta = \left(\ln\frac{Y_1}{Y_2}\right) = \ln\left(\frac{Ce^{-\xi\omega nt}}{Ce^{-\xi\omega n(t+T)}}\right) = \xi\omega nT \tag{19}$$

And when the damping ratio is small, can be approximated as

$$\delta \cong 2\pi\xi \tag{20}$$

Solving the damping ratio ξ of the structure using the amplitude of the signal at two consecutive peaks in a free vibration record of acceleration is

$$\xi = \delta\times\frac{1}{2\pi} = \frac{1}{2\pi}\left(\ln\frac{Y_1}{Y_2}\right) \tag{21}$$

The decay of motion is slow as in the case for lightly damped systems; it is desirable to relate the ratio of two amplitudes several cycles apart, Instead of successive amplitudes. The damping ratio over j cycles the motion decreases from Y_1 to Y_{j+1}. The ratio is

$$\left(\frac{Y_1}{Y_{j+1}}\right) \tag{22}$$

There fore

$$\xi = \frac{1}{2\pi\times j}\left(\ln\frac{Y_1}{Y_{j+1}}\right) \tag{23}$$

$$\xi_{10} = \frac{1}{2\pi \times 10}\left(\ln \frac{Y_1}{Y_{10+1}}\right) \tag{24}$$

$$\xi_3 = \frac{1}{2\pi \times 3}\left(\ln \frac{Y_1}{Y_{3+1}}\right) \tag{25}$$

The free vibration of the system was measured by accelerometers MPU6050, The wave analysis was obtained from Arduino soft program and the damping ratio of the specimen can be determined by the logarithmic decrement method. Figure 3.16 shows the curve of a free-vibration wave, where Y_i is the amplitude of the ith cycle, T_i is the time point corresponding to Y_i and T_d is the fundamental period of the vibration wave. If j cycles are considered the equation for the damping ratio and the damping ratio (ξ) with several cycles apart amplitudes can be calculated by equation.23,

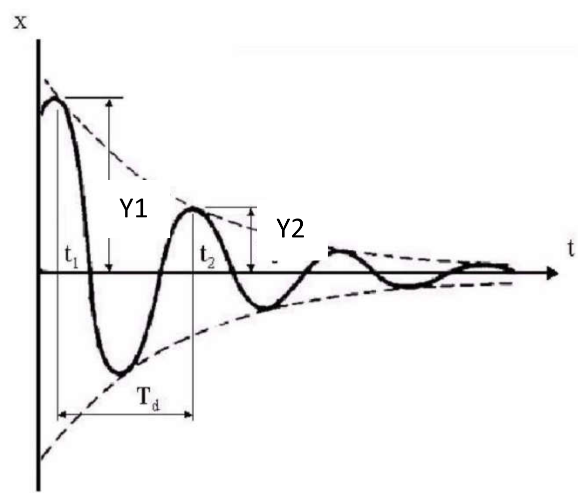


Figure 3.17 Free-vibration Wave Curve

CHAPTER FOUR RESULT AND DISCUSSION

4.1 Introduction

The fundamental component of this research was conducting laboratory experiments or tests to study the effect of waste tyre rubber on the mechanical and dynamic properties of concrete when partially replace the coarse aggregate in concrete mix. Mechanical strength test were tested in accordance to ACI Standard. The dynamic properties, such as the damping ratio and natural frequencies of rubberized concrete were tested by dynamic test structure, the first and second set of tests were carried out by changing the load type (string and impact) and magnitude. Once the better effect of the rubberized concrete was obtained on the damping ratio tests were carried out by string and impact load.

4.2 Workability

The replacement of coarse aggregate by scrap tyre rubber effects on the workability of the concrete. The results of the slump test are shown in Figure 4.1.

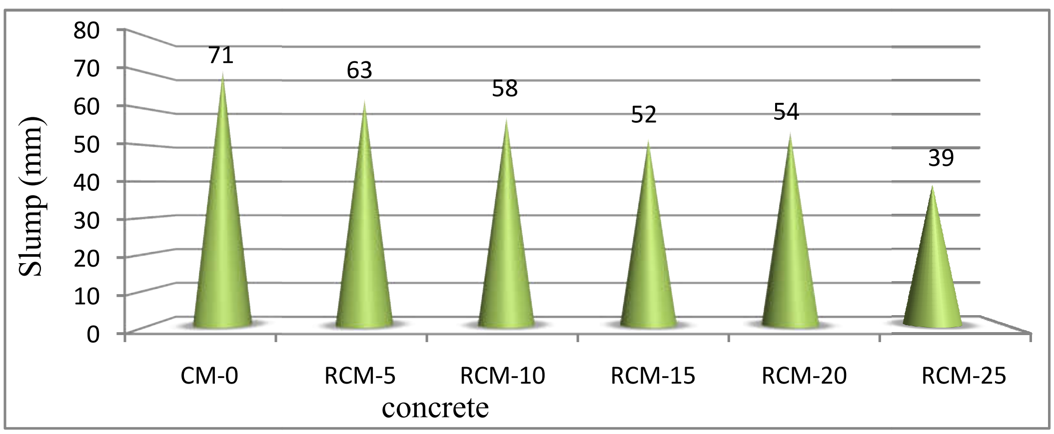


Figure 4.1: Effect of Aggregate Replacement Ratio on Slump of Rubberized Concrete

According to the results the slump values are decreasing with increasing content of waste tyre. This reduction can be reasoned to the fact that some particles like string in rubber particle are absorb the water due that workability was decrease with increase of waste tyre rubber content of total aggregate volume. Mixes RCM-5, RCM-10, RCM-15, RCM-20 and RCM-25 shows workability reduction of 11%, 18%, 27%, 24% and 45% respectively in comparison with the control mix

4.3 Dry density

This test measured for the cubes taking from curing water basin just prior to compression strength, which represent the mean of dry density of 3 cubes of each age.

Table 4.1: Dry Density values rubberized concrete.

Mix Identity	density at 7 days curing age (kg/m³)	density at 28 days curing age(kg/m³)	reduction in density at 7 days %	reduction in density at 28 days %
CM-0	2406.8	2408.8		
RCM-5	2325.3	2367.1	3.4	1.7
RCM-10	2317.9	2325	3.7	3.5
RCM-15	2250.9	2275.8	6.4	5.5
RCM-20	2199.4	2220.1	8.6	7.8
RCM-25	2157	2166.2	10.3	10

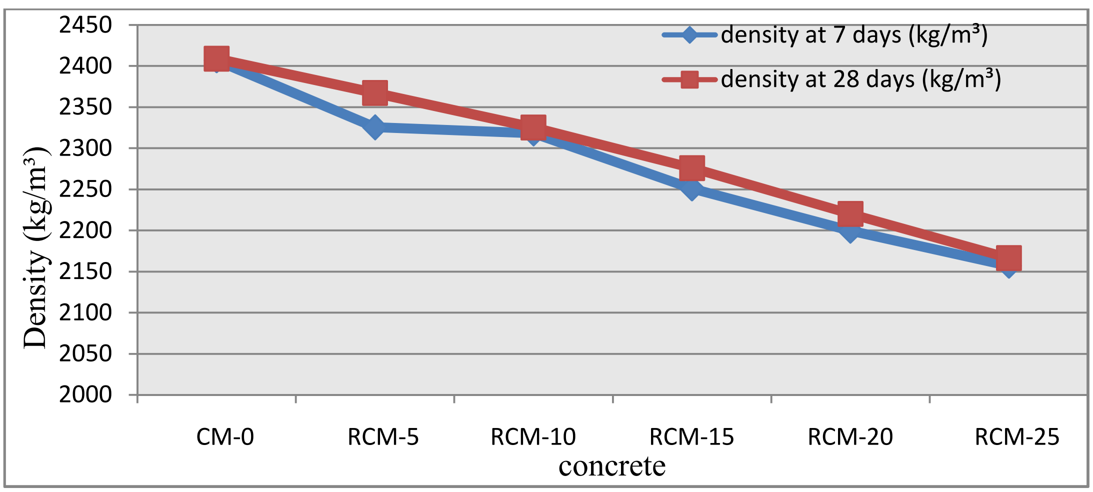


Figure 4.2: Dry density of rubberized concrete

The result of density of RCM-25 was not in range of light weight concrete according to British standard (800–2000 kg/m³) however the dry densities at each curing age tend to decrease with the increase of waste tire rubber ratio in each concrete mixture. The dry density of rubberized concrete increased with age for each concrete mixture.

4.4 Compressive strength

Compression test according to ACI Standard was carried out on these cubes. The specimens were loaded at a constant strain rate until failure. The compressive strength is decreased with an increase in the percentage of the tyre rubber chips. The results of compressive strength of cubes for 7 days and 28 days are as shown in Figure 4.3.

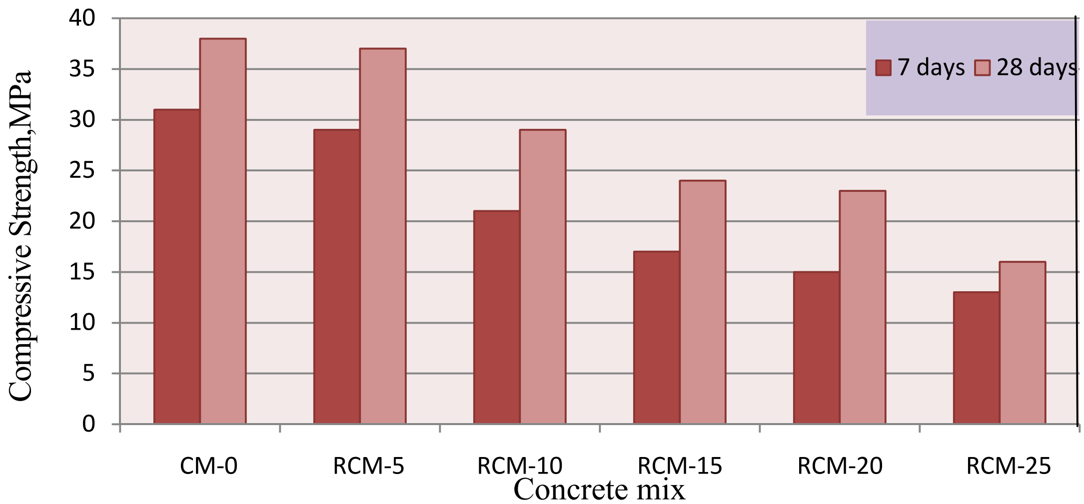


Figure 4.3: Compressive strength of rubberized concrete in 7 and 28 Days

It can be seen from the Figure 4.3 that the average compressive strength of specimens at 7 days is 31MPa for CM-0. Mixes RCM-5, RCM-10, RCM-15, RCM-20 and RCM-25 shows reduction of 6%, 32%, 45%, 52% and 58% respectively in comparison with the control mix (CM-0). Similarly the compressive strength of the concrete samples at 28 days is 38 MPa for control mix (CM-0). While MCR-06, RCM-5, RCM-10, RCM-15, RCM-20 and RCM-25 show reduction of 22%, 37%, 39% and 58% respectively in comparison with the control mix (MC-0).

Dubravka *et al.* (2011) suggested that, the compressive strength of rubberized concrete was reduced for many reason as large pore between rubber particle and cement matrix. The bond between the tyre rubber and concrete is very weak. With the increase in void content of the concrete there will be corresponding decrease in strength. The reduction in strength was also due to the fact that tyre rubber is more elastically deformable than the matrix, and produced high internal stresses that are perpendicular to the direction of applied load.

4.5 Split tensile strength

Split tensile strength test were tested in accordance to ACI Standard. The tensile strength was reduced with the increase in percentage of rubber particles in concrete mix. The results of split tensile strength test of cylinder for 7 days and 28 days are as shown in Figure 4.4.

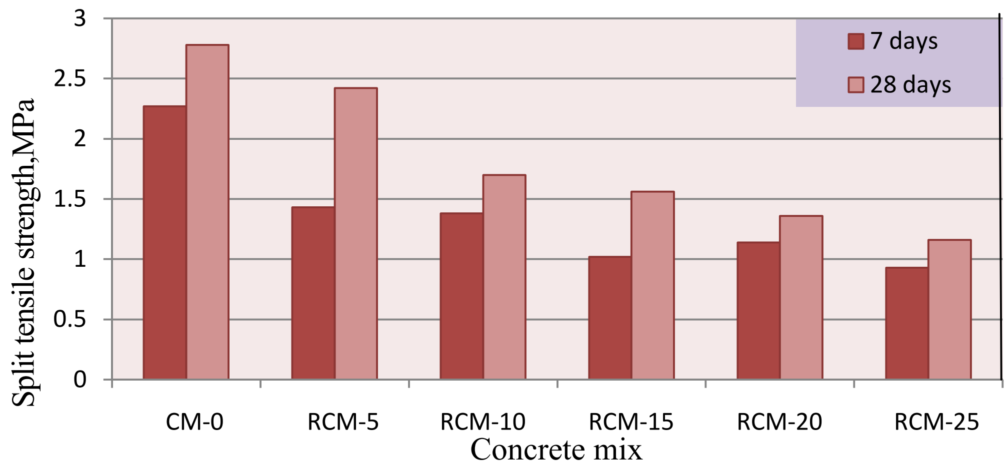


Figure 4.4: Split tensile strength of rubberized concrete in 7 and 28 days.

Figure 4.4 shows that the split tensile strength at 7 days curing for control mixture (CM-0) is achieved 2.27 MPa. The mixes RCM-5, RCM-10, RCM-15, RCM-20 and RCM-25 shows reduction of 36.69%, 39.29%, 55.17%, 49.89% and 59.12% strength respectively, in comparison with the control mix MC-0. Similarly it can be seen that from Figure 4.4 that the split tensile strength at 28 days of curing for control mixture (CM-0) is achieved 2.78 MPa. The mixes RCM-5, RCM-10, RCM-15, RCM-20 and RCM-25 shows reduction of 12.8%, 38.94%, 43.98%, 50.89% and 58.07% strength respectively, in comparison with the control mix CM-0. The use of 20% tyre rubber gives better results than the use of 15%.

The significant decrease in strength of rubberized concrete is due to weak bonding between rubber and cement paste. Ganjian *et al.* (2012), also stated the following reasons for the reduction in tensile strength i.e. Due to weak bonding between rubbers and cement the interface zone acts as a micro-crack.

4.6 Flexural strength

Prismatic specimens 100 × 100 × 500 mm were tested according to ACI. The result of flexural strength of prisms for 28 days is as sown in Figure 4.5.

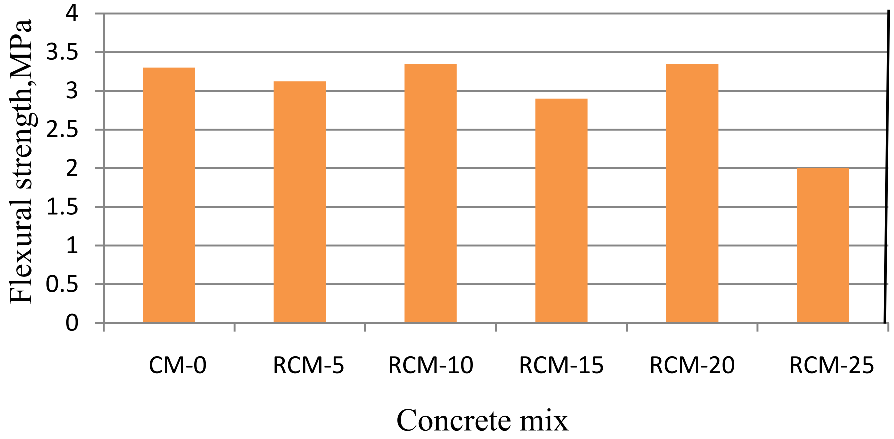


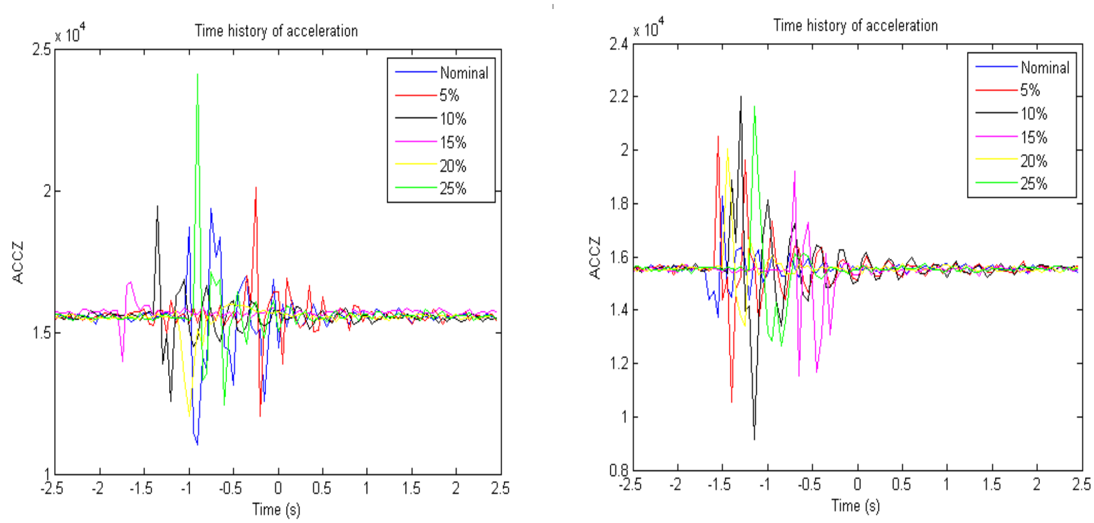
Figure 4.5: Flexural strength of rubberized concrete at 28 days

Similarly it can be seen that from Figure 4.5, that the flexural strength at 28 days curing for control mixture (CM-0) achieved 3.3 MPa. The use of 20% and 10% tyre rubber gives better results than the control mix. The mixes RCM-5, RCM-15 and RCM-25 shows reduction of 5.3%, 12.12%and 39.39% strength respectively, in comparison with the control mix CM-0. The significant decrease in strength of rubberized concrete is due to weak bonding between rubber and cement paste. Ganjian *et al.* (2012) is also concluded that reducing the flexural strength was lack of good bonding between rubber particles and cement paste, even so tyre rubber as a soft material can act as a barrier against crack growth in concrete. Stergios Mitoulis (2016) also found that the reduction of the compressive strength is higher than that of the flexural strength. This leads to the findings that rubberized concrete perform better under bending than in compression.

4.7 Damping properties

4.7.1 Natural frequency of rubberized concrete with string load

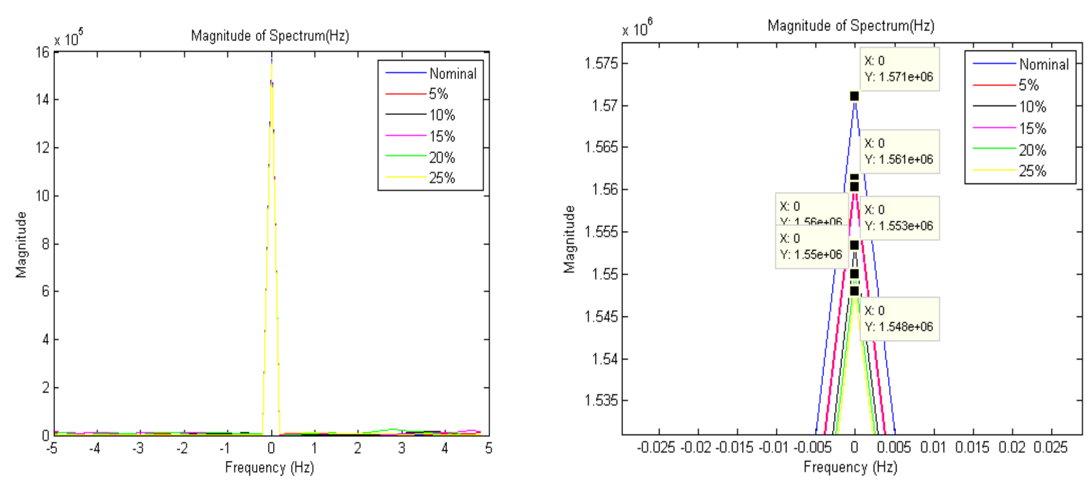
In order to demonstrate the dynamic properties of rubberized concrete such as the natural frequencies and damping ratio, the tests were carried out by changing the load type magnitude and rubber content in concrete. Time history of acceleration response and Single sided magnitude spectrum of the acceleration response was obtained from MATLAB R2013a program output are available on Appendix B, as example some program output shown in Figure 4.6. and Figure 4.7, Including the Time history of acceleration response of samples with 10 N string load (Figure 4.6a), Time history of acceleration response of samples with 20 N string load (Figure 4.6b),



a) Samples with 10 N string load b) samples with 20 N string load

Figure 4.6: Time history of acceleration response of rubberized concrete with 10 N and 20 N string load

Figure 4.6 shows The time history response of translational free vibration in the Z - Direction by string load shows a rapid decrease in acceleration when the rubber content of samples increase and relatively more rapid when rubber content more increase to the previous translational time history graphs. This shows that the rubber content has effect on frequency of the structure and the frequency of the simply supported beam decreased with the increase of rubber content.



a) Single-sided magnitude spectrum b) Peak reduction detail of spectrum

Figure 4.7: Single-sided magnitude spectrum of the acceleration response for 10N string load

Figure 4.7 shows that the string loads provide a high level of attenuation to the peak when the rubber content was zero or control mix. The peak is reduced by 0.64% when the mix contains 5% rubber as an aggregate, by 0.7% when the mix contains 10% rubber, by 1.15% when the mix contains 15% rubber, by 1.34% when the mix contains 20% rubber and by 1.46% when the mix contains 25% rubber.

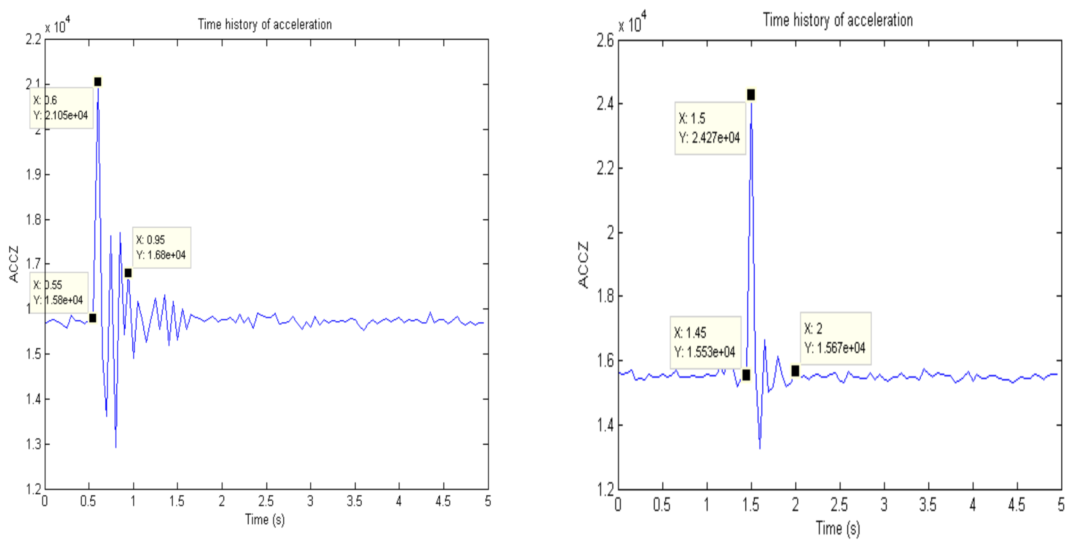
Table 4.2: the reduction of peak mix of rubberized concrete by string load

Mix identity	load(N)	Peak	percentage reduction
CM-0	10	1.571	
RCM-5		1.561	0.64
RCM-10		1.56	0.7
RCM-15		1.553	1.15
RCM-20		1.55	1.34
RCM-25		1.548	1.46
CM-0	15	1.585	
RCM-5		1.581	0.25
RCM-10		1.556	1.83
RCM-15		1.545	2.52
RCM-20		1.541	2.78
RCM-25		1.54	2.84
CM-0	20	1.558	
RCM-5		1.558	0
RCM-10		1.556	0.13
RCM-15		1.555	0.19
RCM-20		1.554	0.26
RCM-25		1.545	0.84
CM-0	35	1.586	
RCM-5		1.578	0.5
RCM-10		1.559	1.7
RCM-15		1.559	1.7
RCM-20		1.542	2.77
RCM-25		1.542	2.77

Table 4.2 shows the result from the string load testing response of the different mix at 28 days. The peak magnitude decreases depending on percent of rubber. The results show that the natural frequency of the simply supported beam decreased with the increase of rubber content.

4.7.2 Applied string load vs. damping ratio

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens was test by applied 10 N and 15 N, 20 N and 35 N string load. The wave analysis and calculation of damping ratio was performed for each mix type as discussed in section 3.2.6.4 but the result and outputs are generally as follow, The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (nominal mix and 25% tyre rubber replacement mix) program output shown in Figure 4.8. Including the logarithmic decrement signal of nominal mix with 35 N string load (Figure 4.8a), logarithmic decrement signal of 25% tyre rubber replacement mix with 35 N string load (Figure 4.8b), the peak amplitude was calculate by subtracting initial magnitude from peak magnitude mostly first cycle, and the half of peak amplitude was calculate by subtracting the initial magnitude from the there'd cycle. After calculating the peak and the half of the peak amplitude the damping ratio (ξ) can be calculated by equation 25.



a) CM-0 with 35N string load   b) CM-25 with 35N string load

Figure 4.8: The logarithmic decrement signal of samples with string load

Figure 4.9 shows the result from the string load testing response of the rubberized concrete at 28 days. The peak amplitude varied depending on the impulse force. The results show that damping ratio increased with increasing the magnitude of string load in a logarithmic trend.

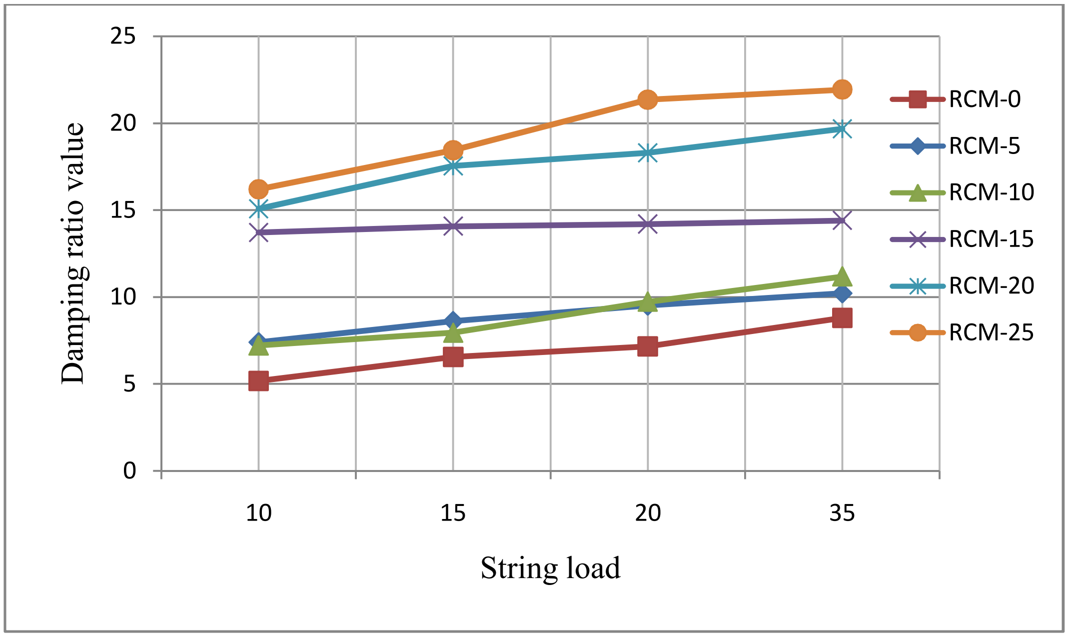


Figure 4.9: Damping ratio of rubberized concrete with string load

Figure 4.9 shows the damping ratio changed with different applied load for plain concrete, RCM-5, RCM-10, RCM-15, RCM-20, and RCM-25 rubberized concrete. It was observed that the damping ratio increased with an increase in applied string load. For example, with the increment of string load from 10 to 35N, the damping ratio of plain concrete increased from 0.052 to 0.088, with 69% augment, with the increment of string load from 10 to 35N, the damping ratio of RCM-5 rubberized concrete increased from 0.074 to0. 1, with 35% augment, with the increment of string load from 10 to 35N, the damping ratio of RCM-10 rubberized concrete increased from 0.072 to 0.11, with 52% augment, with the increment of string load from 10 to 35N, the damping ratio of RCM-15 rubberized concrete increased from 0.137 to 0.144, with 5% augment, with the increment of string load from 10 to 35N, the damping ratio of RCM-20 rubberized concrete increased from 0.15 to 0.197, with 31% augment, with the increment of string load from 10 to 35N, the damping ratio of RCM-25 rubberized concrete increased from 0.162 to 0.219, with 35% augment. The larger load might cause a greater vibration, but conversely, it causes lower frequency. In other words, energy dissipation (damping ratio) increases with the strain of amplitude increasing Shengqi *et al.* (2018). On the basis of this result, it is conclusive that the larger load causes the higher damping ratio of materials.

4.7.3 Damping ratio of rubberized concrete with string load

The experimental results that show the effect of different rubber replacement ratios in rubberized concrete of damping ratio was undertaken with four different string loads such as 10 N, 15 N, 20 N and 35 N. The peak amplitude was calculate by subtracting initial magnitude from peak magnitude mostly first cycle, and the half of peak amplitude was calculate by subtracting the initial magnitude from the there'd cycle. After calculating the peak and the half of the peak amplitude the damping ratio (ξ) can be calculated by equation.25. In each load case the results show that the damping ratio increased when the ratio of coarse aggregate replacement was increased. For some loads the increment was not linear, the results in each string load was as follow;

4.7.3.1 The specimens subjected to 10 N string load

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens were tested by applied of 10 N string load. The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (25% tyre rubber replacement mix) program output shown in Figure 4.10.

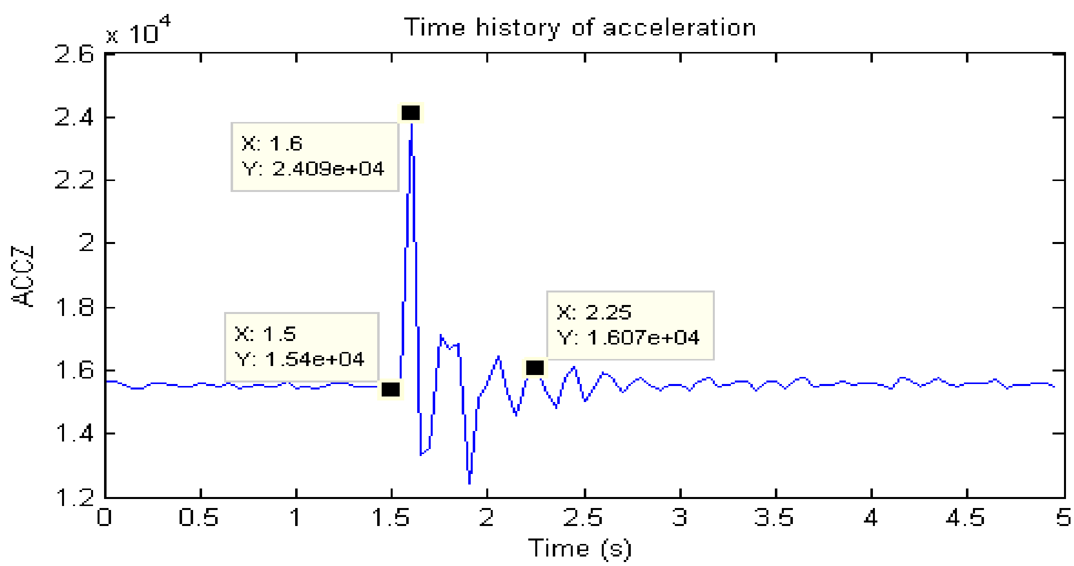


Figure 4.10: The logarithmic decrement signal of RCM-25 rubberized concrete with10 N string load

Table 4.3: Damping ratio of rubberized concrete with 10 N string load

Mix identity	load(N)	Y1(g)	Y4(g)	δ	ξ3(%)
CM-0	10	4010	1510	0.98	5.18
RCM-5		4560	1130	1.39	7.40
RCM-10		3740	960	1.36	7.21
RCM-15		1060	80	2.58	13.71
RCM-20		3430	200	2.84	15.08
RCM-25		8690	410	3.05	16.20

Table 4.3 shows The damping ratio values of rubberized concrete increased with the increase of the amount of tyre rubber, which are 5.2%, 7.4%, 7.2%, 13.7%, 15.1%, and 16.2% for tyre rubber replacement ratio of 0%,5%, 10%, 15%.20% and 25% respectively. It reveals that the relation between the damping ratio and rubber replacement ratio is significantly nonlinear, because the damping ratio when the 10% tyre rubber replacement was 7.2% it is less than 7.4%(the damping ratio when the 5% tyre rubber replacement) .The damping ratio of each specimen was divided by the damping ratio of the plain concrete specimen to obtain the damping ratio rate. In the experimental results, the RCM-20 and the RCM-25 specimens had optimal damping ratios, which were 2.88 and 3.11 times the damping ratio of the plain concrete specimen, respectively

4.7.3.2 The specimens subjected to 15 N string load

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens were tested by applied of 15 N string load. . The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (10% tyre rubber replacement mix) program output shown in Figure 4.11.

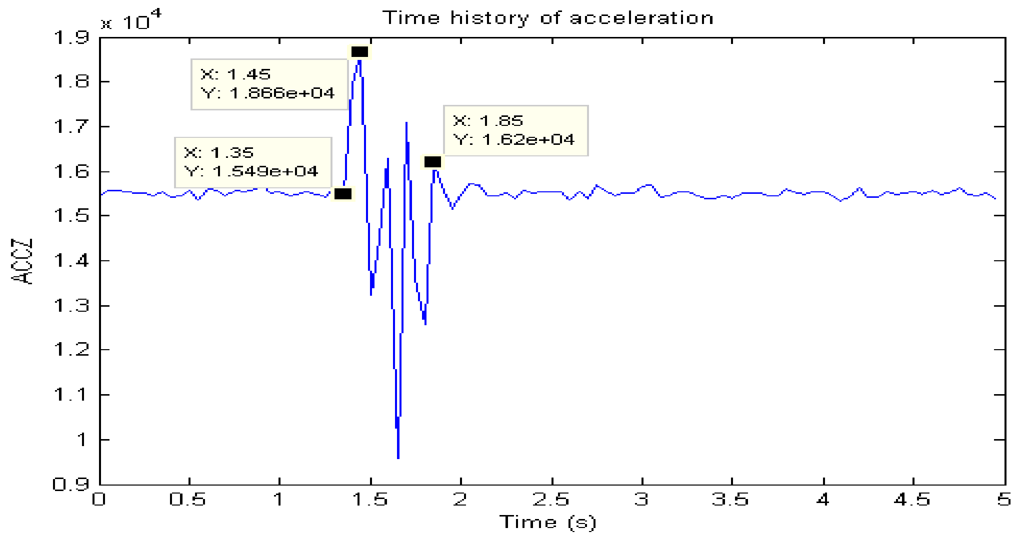


Figure 4.11: The logarithmic decrement signal of RCM-10 rubberized concrete with15 N string load

Table 4.4: Damping ratio of rubberized concrete with 15 N string load

Mix identity	load(N)	Y1(g)	Y4(g)	δ	ξ3(%)2
CM-0	15	3930	1140	1.24	6.56
RCM-5		1520	300	1.62	8.61
RCM-10		3170	710	1.50	7.94
RCM-15		1560	110	2.65	14.07
RCM-20		4640	170	3.31	17.54
RCM-25		8400	260	3.47	18.44

Table 4.4 shows The damping ratio values of rubberized concrete increased with the increase of the amount of tyre rubber, which are 6.6%, 8.6%, 7.9%, 14.1%, 17.5%, and 18.4% for tyre rubber replacement ratio of 0%,5%, 10%, 15%.20% and 25% respectively. It reveals that the relation between the damping ratio and rubber replacement ratio is significantly nonlinear, because the damping ratio when the 10% tyre rubber replacement was 7.9% it is less than 8.6% (the damping ratio when the 5% tyre rubber replacement). The damping ratio of each specimen was divided by the damping ratio of the plain concrete specimen to obtain the damping ratio rate. In the experimental results, the RCM-20 and the RCM-25 specimens had optimal damping ratios, which were 2.67 and 2.8 times the damping ratio of the plain concrete specimen, respectively

4.7.3.3 The specimens subjected to 20 N string load

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens was test by applied 20 N string load. The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (10% tyre rubber replacement mix) program output shown in Figure 4.12.

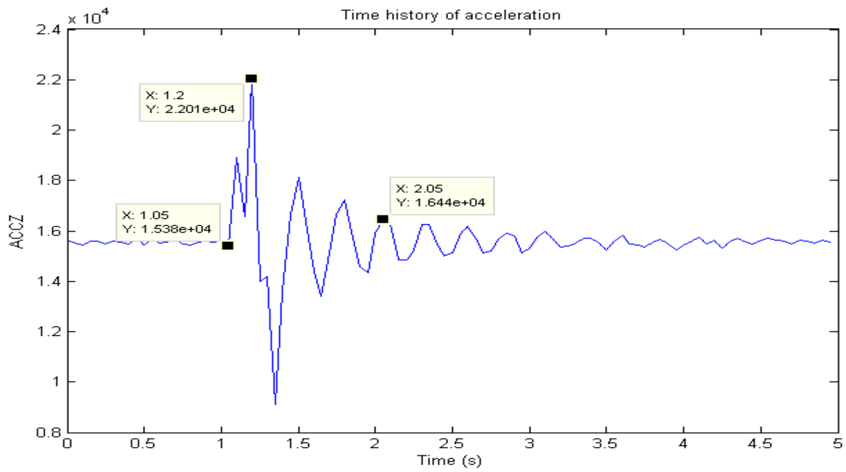


Figure 4.12: The logarithmic decrement signal of RCM-10 rubberized concrete with 20 N string load

Table 4.5: Damping ratio of rubberized concrete with 20 N string load

Mix identity	load(N)	Y1(g)	Y4(g)	δ	ξ3(%)2
CM-0	20	2700	700	1.35	7.16
RCM-5		4930	820	1.79	9.52
RCM-10		6630	1060	1.83	9.73
RCM-15		3770	260	2.67	14.19
RCM-20		4410	140	3.45	18.30
RCM-25		6150	110	4.02	21.35

Table 4.5 shows the damping ratio values of rubberized concrete increased with the increase of the amount of tyre rubber, which are 7.2%, 9.5%, 9.7%, 14.2%, 18.3%, and 21.3% for tyre rubber replacement ratio of 0%,5%, 10%, 15%.20% and 25% respectively. In the experimental results, the RCM-20 and the RCM-25 specimens had optimal damping ratios, which were 2.55 and 2.98 times the damping ratio of the plain concrete specimen, respectively

4.7.3.4 The specimens subjected to 35 N string load

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens were tested by applied of 35 N string load. The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (25% tyre rubber replacement mix) program output shown in Figure 4.13.

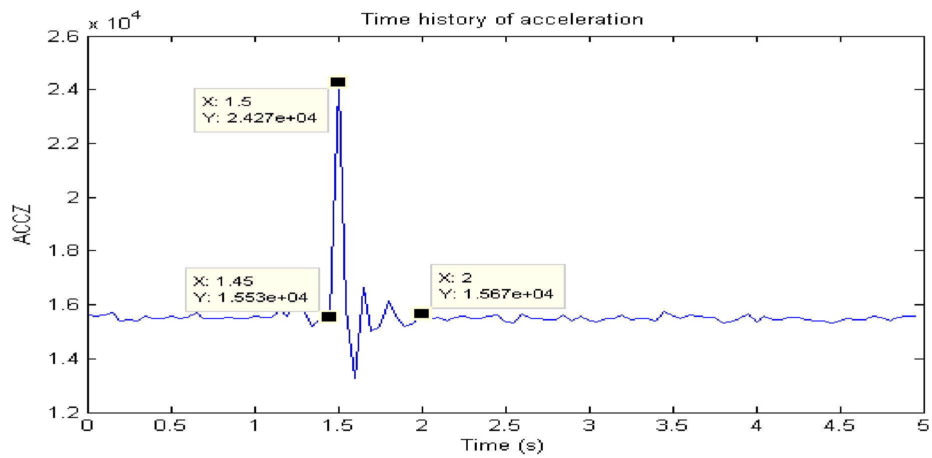


Figure 4.13: The logarithmic decrement signal of RCM-25 rubberized concrete with 35 N string load

Table 4.6: Damping ratio of rubberized concrete with 35 N string load

Mix identity	load(N)	y1(g)	y4	δ	ξ3(%)
CM-0	35	5250	1000	1.66	8.80
RCM-5		3640	530	1.93	10.22
RCM-10		11680	1420	2.11	11.18
RCM-15		7850	520	2.71	14.40
RCM-20		9810	240	3.71	19.68
RCM-25		8740	140	4.13	21.93

Table 4.6 shows the damping ratio values of rubberized concrete increased with the increase of the amount of tyre rubber, which are 8.8%, 10.2%, 11.2%, 14.4%, 19.7%, and 21.9% for tyre rubber replacement ratio of 0%,5%, 10%, 15%.20% and 25% respectively. In the experimental results, the RCM-20 and the RCM-25 specimens had optimal damping ratios, which were 2.67 and 2.8 times the damping ratio of the plain concrete specimen, respectively

4.7.3.5 Summary and conclusions

Tables 4.3, Tables 4.4, Tables 4.5 and Tables 4.6 show the damping ratios changed with different applied load for plain concrete, RCM-5, RCM-10, RCM-15, RCM-20, and RCM-25 rubberized concrete, and also Fig 4.14 show the summary of experimental results that the effect of different rubber replacement ratios in rubberized concrete of damping ratio with four different string loads such as 10 N, 15 N, 20 N and 35 N. In each load case the results show that the damping ratio increased when the ratio of replacement increased. In some loads the increment was not linear, For example, as shown in Fig 4.14 the rubber replacement ratio was increased from 5 to 10%, the damping ratio was decreased when the samples subjected to both 10 and 15 N string load.

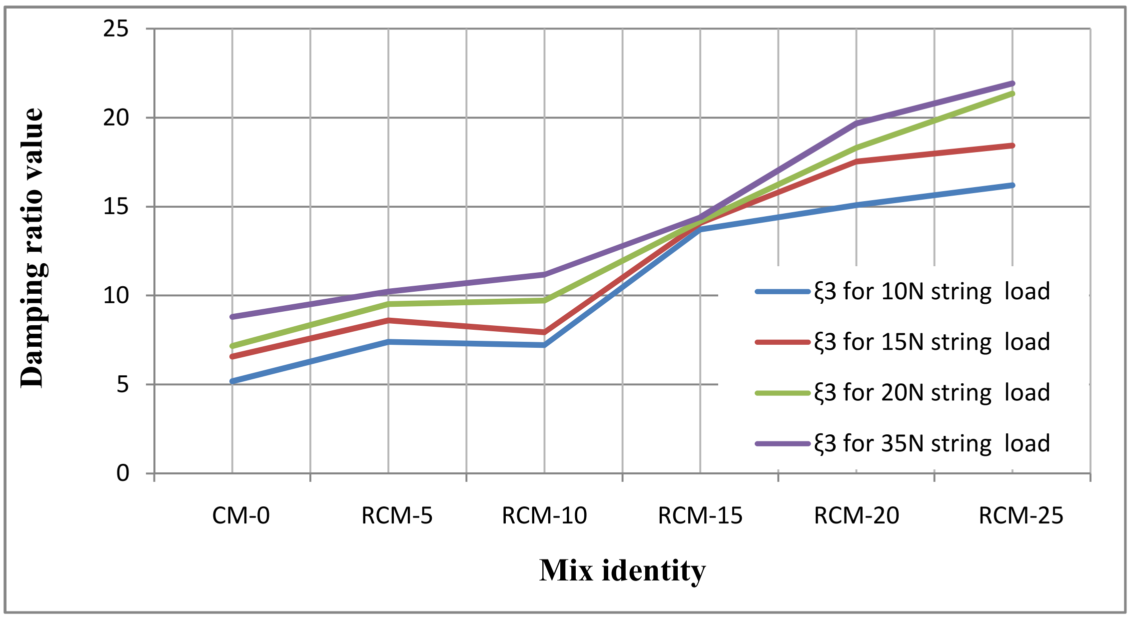
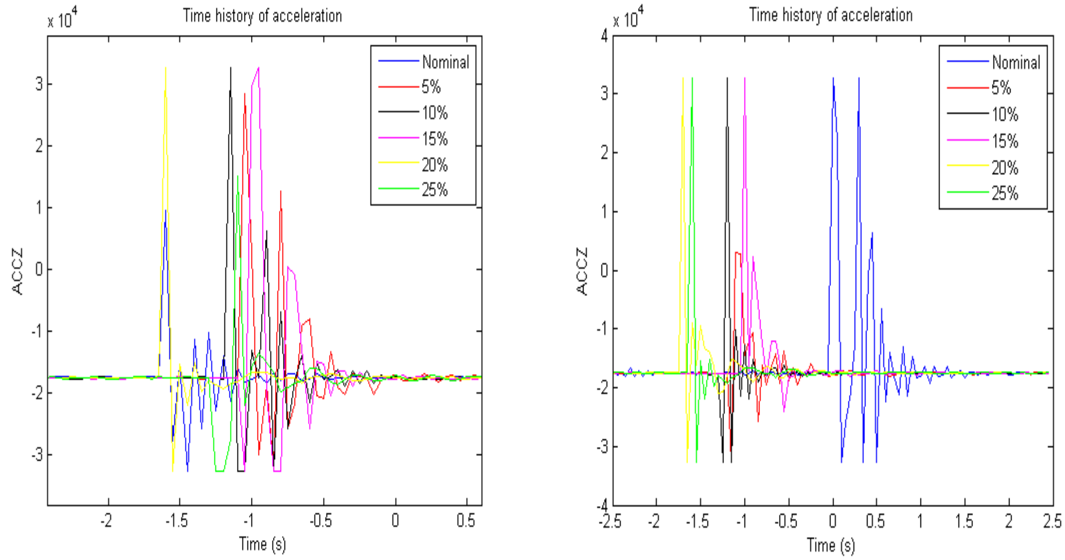


Figure 4.14: Damping ratio of rubberized concrete with string loads

4.7.4 Natural frequency of rubberized concrete with impact load

In order to demonstrate the dynamic properties of rubberized concrete such as the natural frequencies and damping ratio, the tests were carried out by changing the load type magnitude and rubber content in concrete. Time history of acceleration response and Single sided magnitude spectrum of the acceleration response was obtained from MATLAB R2013a program output shown in Figure 4.15. and Figure 4.16, Show the Time history of acceleration response of samples with 10 N impact load (Figure 4.15a), Time history of acceleration response of samples with 20 N impact load (Figure 4.15b), The time history response of translational free vibration in the Z -Direction by impact load shows a rapid decrease in acceleration when the rubber content of samples increase and relatively more rapid when it rubber content more increase to the previous translational time history graphs. This shows that the rubber content has effect on frequency of the structure and the frequency of the simply supported beam decreased with the increase of rubber content.



a). samples with 10 N impact load

b) samples with 20 N impact load

Figure 4.15: Time history of acceleration response of rubberized concrete with impact load

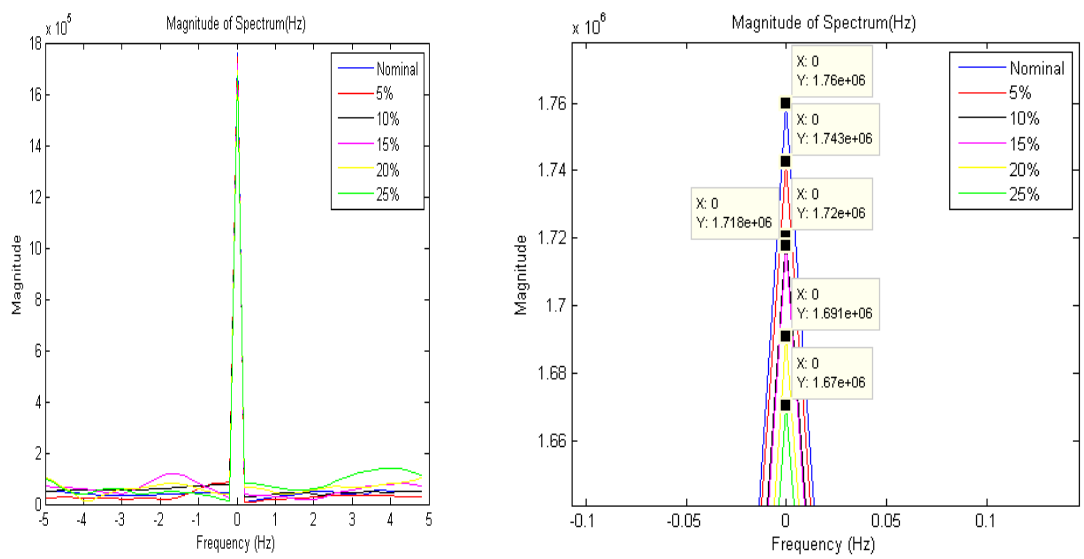


Figure 4.16: Single-sided magnitude spectrum of the acceleration response for 10 N impact load

Figure 4.16 shows that the impact load provides a high level of attenuation to the peak when the rubber content was zero or control mix. The peak is reduced by 0.96% when the mix contains 5% rubber as an aggregate, by 2.27% when the mix contains 10% rubber, by 2.39% when the mix contains 15% rubber, by 3.92% when the mix contains 20% rubber and by 5.11% when the mix contains 25% rubber.

Table 4.7: the reduction of peak mix with rubberized concrete by impact load

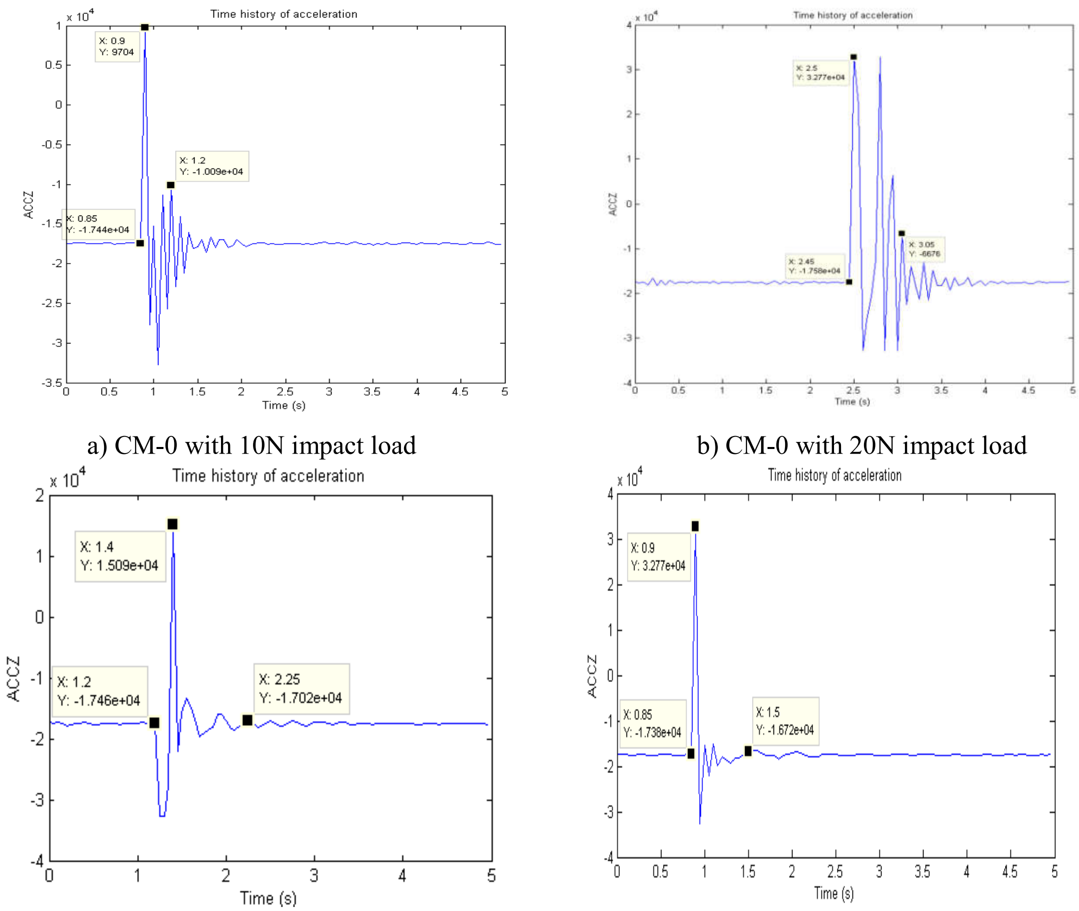
Mix identity	load(N)	Peak	percentage reduction
CM-0	10	1.76	
RCM-5		1.743	0.96
RCM-10		1.72	2.27
RCM-15		1.718	2.39
RCM-20		1.691	3.92
RCM-25		1.67	5.11
CM-0	20	1.731	
RCM-5		1.72	0.64
RCM-10		1.717	0.81
RCM-15		1.691	2.31
RCM-20		1.663	3.93
RCM-25		1.621	6.35

Table 4.7 shows the result from the impact load testing response of the different mixes at 28 days. The peak magnitude decreases depending on percent of rubber. The results show that the natural frequency of the simply supported beam decreased with the increment of rubber content.

4.7.5 Applied impact load vs. damping ratio

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens was test by applied 10 N and 20 N impact loads. The wave analysis and calculation of damping ratio was performed for each mix type as in section 3.2.6.4 but the result and outputs are generally as follow, The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (nominal mix and 25% tyre rubber replacement mix) program output shown in Figure 4.17. Including the logarithmic decrement signal of nominal mix with 10 N impact load (Figure 4.17a), logarithmic decrement signal of nominal mix with 20 N impact load

(Figure 4.17b), logarithmic decrement signal of 25% tyre rubber replacement mix with 10 N impact load (Figure 4.17c), logarithmic decrement signal of 25% tyre rubber replacement mix with 20 N impact load (Figure 4.17d), the peak amplitude was calculate by subtracting initial magnitude from peak magnitude mostly first cycle, and the half of peak amplitude was calculate by subtracting the initial magnitude from the there'd cycle. After calculating the peak and the half of the peak amplitude the damping ratio (ξ) can be calculated by equation.25.



a) CM-0 with 10N impact load

b) CM-0 with 20N impact load

c) RCM-25 with 10N impact load

d) RCM-25 with 20N impact load

Figure 4.17: The logarithmic decrement signal of nominal mix and 25% tyre rubber replacement mix with 10N and 20N impact load

Figure 4.18 shows the result from the impact load testing response of different ratio of tyre rubber replacement mix at 28 day. The peak amplitude varied depending on the impulse force. The results show that damping ratio improved with increasing the magnitude of impact load in a logarithmic trend.

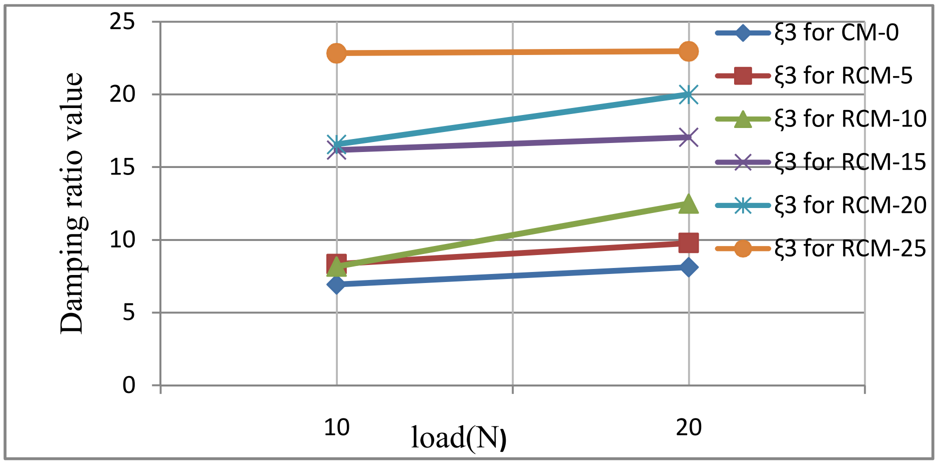


Figure 4.18: Damping ratio of rubberized concrete with impact load

Figure 4.18 shows the damping ratios changed with impact loads for rubberized concrete. It was observed that the damping ratio increased with an increase in applied impact load. For example, with the increment of impact load from 10 to 20N, the damping ratio of plain concrete increased from 0.069 to 0.081, with 17% augment, with the increment of impact load from 10 to 20N, the damping ratio of RCM-5 rubberized concrete increased from0.083 to 0.098, with 17% augment, with the increment of impact load from 10 to 20N, the damping ratio of RCM-10 rubberized concrete increased from 0.082 to 0.13, with 53% augment, with the increment of impact load from 10 to 20N, the damping ratio of RCM-15 rubberized concrete increased from 0.16 to 0.17, with 5% augment, with the increment of impact load from 10 to 20N, the damping ratio of RCM-20 rubberized concrete increased from 0.16 to 0.2, with 20% augment, with the increment of impact load from 10 to 20N, the damping ratio of RCM-25 rubberized concrete increased from 0.2283 to 0.2297 , with 1% augment**.** The larger load might cause a greater vibration, but conversely, it causes lower frequency. In other words, energy dissipation (damping ratio) increases with the strain of amplitude increasing Shengqi *et al.* (2018). On the basis of this result, it is conclusive that the larger load causes the higher damping ratio of materials.

4.7.6 Damping ratio of rubberized concrete with impact load

The experimental results that show the effect of different rubber replacement ratios in rubberized concrete of damping ratio was undertaken with two different impact loads such as 10 N and 20 N. The peak amplitude was calculate by subtracting initial magnitude from peak magnitude mostly first cycle, and the half of peak amplitude was calculate by subtracting the initial magnitude from the there'd cycle. After calculating the peak and the half of the peak amplitude the damping ratio (ξ) can be calculated by equation.25. In each load case the results show that the damping ratio increased when the ratio of replacement increased. In 10N impact load the increment was not linear, the results in each impact loads was as follows;

4.7.6.1 The specimens subjected to 10 N impact load

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens was test by applied 10N impact load. The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (15% tyre rubber replacement mix) program output shown in Figure 4.19.

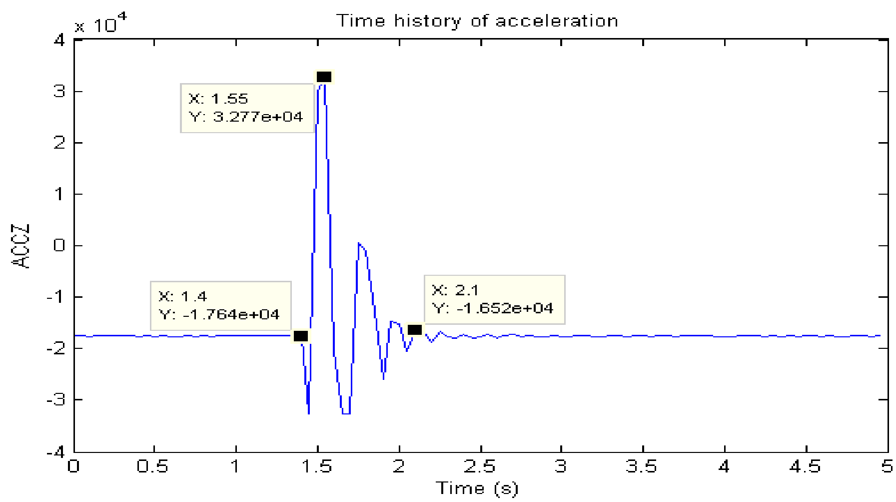


Figure 4.19: The logarithmic decrement signal of RCM-15 rubberized concrete with 10 N impact load

Table 4.8: Damping ratio of rubberized concrete with 10N impact load

load(N)	Y1(g)	Y4(g)	δ	ξ3(%)
10	27144	7350	1.31	6.93
	46140	9574	1.57	8.34
	50500	10846	1.54	8.16
	50410	2390	3.05	16.17
	50150	2210	3.12	16.56
	32550	440	4.30	22.83

Table 4.8 shows the damping ratio values of rubberized concrete increased with the increase of the amount of tyre rubber, which are 6.9%, 8.3%, 8.1%, 16.2%, 16.6%, and 22.8% for tyre rubber replacement ratio of 0%,5%, 10%, 15%.20% and 25% respectively. It reveals that the relation between the damping ratio and rubber replacement ratio is significantly nonlinear, because the damping ratio when the 10% tyre rubber replacement was 8.16% it is less than 8.3% (the damping ratio when the 5% tyre rubber replacement).The damping ratio of each specimen was divided by the damping ratio of the plain concrete specimen to obtain the damping ratio rate. In the experimental results, the RCM-20 and the RCM-25 specimens had optimal damping ratios, which were 2.39 and 3.29 times the damping ratio of the plain concrete specimen, respectively

4.7.6.2 The specimens subjected to 20N impact load

In the experiment plain concrete, 5%, 10%, 15%, 20% and 25% tyre rubber replacement concrete mix specimens was test by applied 20N impact load. The wave analysis which is obtained from MATLAB R2013a program output is available in Appendix B, as example some (10% tyre rubber replacement mix) program output shown in Figure 4.20.

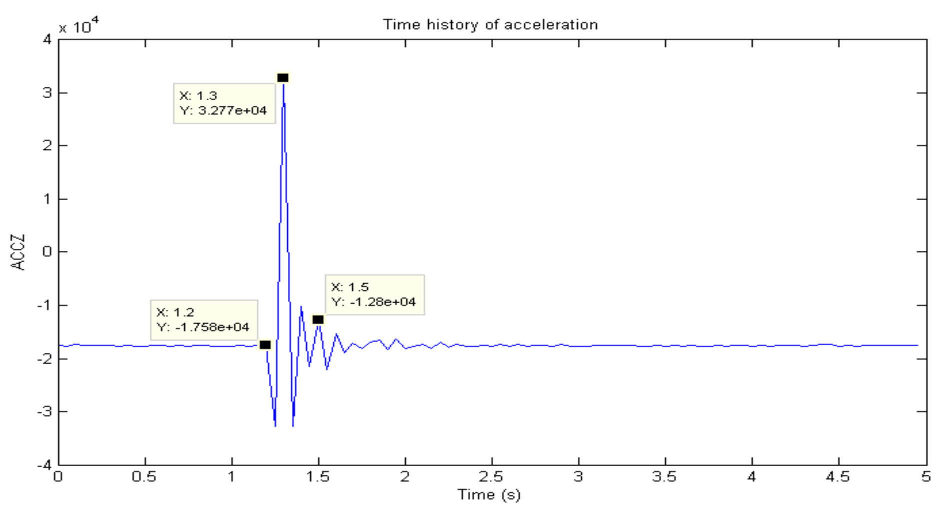


Figure 4.20: The logarithmic decrement signal of RCM-10 rubberized concrete with 20N impact load

Table 4.9: Damping ratio of rubberized concrete with 20N impact load

load(N)	Y1(g)	Y4(g)	δ	ξ3(%)
20	50350	10904	1.53	8.12
	20666	3270	1.84	9.78
	50350	4780	2.35	12.49
	50490	2030	3.21	17.05
	50250	1160	3.77	19.99
	50150	660	4.33	22.97

Table 4.9 shows that the damping ratio values of rubberized concrete increased with the increase of the amount of tyre rubber, which are 8.1%, 9.8%, 12.5%, 17.0%, 20.0%, and 23% for tyre rubber replacement ratio of 0%,5%, 10%, 15%.20% and 25% respectively. In the experimental results, the RCM-20 and the RCM-25 specimens had optimal damping ratios, which were 2.46 and 2.83 times the damping ratio of the plain concrete specimen, respectively

4.7.6.3 Summary and conclusions

Table 4.8, and Table 4.9 show the damping ratios changed with different applied load for plain concrete, RCM-5, RCM-10, RCM-15, RCM-20, and RCM-25 rubberized concrete, and also Figure 4.21 illustrates the summary of experimental results that the effect of different rubber replacement ratios in rubberized concrete of damping ratio with two different impact loads. In each load case the results show that the damping ratio increased when the ratio of rubber replacement increased.

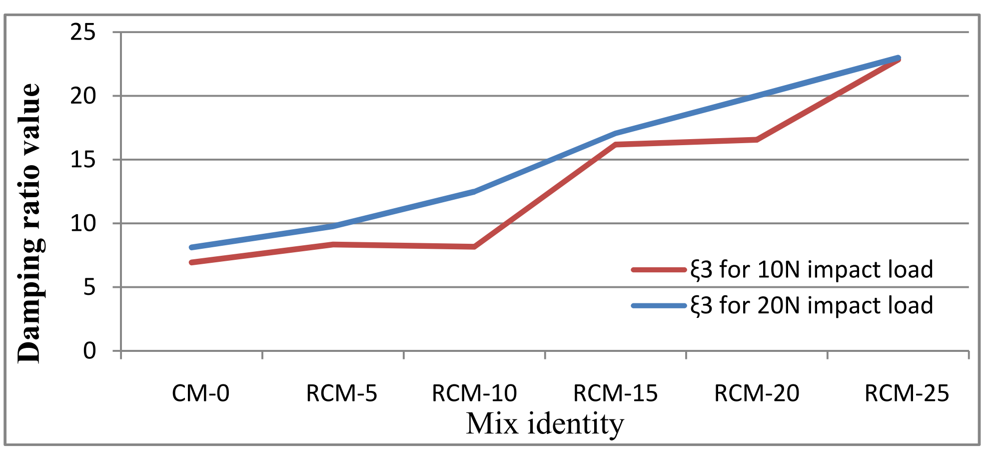


Figure 4.21: Damping ratio of rubberized concrete with impact loads

CHAPTER FIVE CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this research, the experimental work was carried out to evaluate the mechanical and dynamic properties of rubberized concrete with different replacement ratio of coarse aggregate by scrap tyre rubber is studied. On the basis of results obtained by compressive strength tests of rubberized concrete, slump tests, split tensile strength tests, flexural strength tests and dynamic tests, the following points have been concluded:

1. The presence of waste tyre rubber reduces compressive, flexural and split tensile strengths of concrete with the increased percentage of replacement. Similarly recycled rubber tyres into concrete mix leads to decrease in density and workability for the various mix samples with increase in the amount of waste tyre rubber chipped in concrete samples.
2. The addition of waste tyre rubber in concrete can improve the dynamic properties of concrete significantly, the damping ratios of rubberized concrete increased considerably with the increase of rubber content and the natural frequency of the simply supported beam decreased with the increase of rubber content.
3. It has been observed that the damping ratio increased with an increase in maximum applied load. The larger load might cause a greater vibration, but conversely, it causes lower frequency. The increment of damping ratio of rubberized concrete became larger when the maximum response amplitude was higher. The maximum response amplitude caused by larger string or impact load.
4. From the research work the 28 days compressive strength for the RCM-20 concrete mix is higher than the minimum required compressive strength used for reinforced concrete. Hence waste tyre rubber can conveniently replace coarse aggregate in concrete up to 20% for reinforced concrete and it may be suitable for architectural application, false facades, interior construction, in building as an earthquake shock wave absorber, where vibration damping is required such as in foundation pads for machinery railway station.

5.2. Recommendations

Based on the investigation made the following recommendations are forwarded for studies in purpose of future excellence.

1. The primary parameters of dynamic properties of concrete material system are dynamic modulus of elasticity, natural frequency, and vibration damping. These three properties interact with each other. Methods employing dynamic tests such as wave velocity should be used in order to attain a clearer view of the effects of tyre replacement in dynamic modulus of elasticity of rubberized concrete.
2. From the result using waste tyre rubber in concrete were reduced the compressive strength, tensile and flexural strength of concrete, it is recommended that to use steel wire as fiber in rubberized concrete to increase its strength.
3. Since mechanical properties of rubberized concrete depend, to a relevant extent, on the bond between the waste tyre rubber particles and cement paste, bond test should be carried out in order to estimate the bond strength between rubber and cement paste.
4. Studies should be carried out by replacing coarse aggregate and fine aggregate with different proportions which would give different strength values leading to optimum amount to get maximum strength.

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Appendix A

Material Preparation, ACI mix design procedure and tables

Concrete grade C-25

Cement

Type: Ordinary Pozzolana Cement

Fabrication: Derba Cement Factory

Specific Gravity: 3.15

Coarse aggregates

Specific gravity and absorption capacity

Weight of oven-dry sample in air (A) = 4934g

Weight of the sample SSD in the air (B) = 4986g

Weight of the sample SSD in water = (C)3169.2g

Bulk specific gravity = $\frac{A}{B-c} = 2.715$

Bulk specific gravity (SSD) = $\frac{B}{B-c} = 2.74$

Apparent specific gravity = $\frac{A}{A-c} = 2.796$

Absorption = $\frac{(B-A)}{A}$ =1.05%

Unit weight

Weight of aggregate = 22.88 Kg

Length = 0.28m

Diameter = 0.26m

Volume of cylinder = 0.01484m³

Compacted unit weight of aggregate = 1613.2Kg/m³

N.B:- General range unit weight of natural coarse aggregate is 1280 Kg/m³ -1440 Kg/m³

Moisture Content

Weight of Aggregate original (A) = 5000g

Weight of Oven-dried aggregate (B)= 4934g

Water content (percentage) = $\frac{A-B}{B} * 100 = 1.3\%$

Sieve Analysis for Coarser Aggregates

Sieve Size (mm)	Weight Retained (kg)	Percentage Retained	Cumulative Coarser (%)	Cumulative Passing (%)	Standard Passing
37.5	0	0	0	100	95-100
25	0	0	0	100	95-100
19.5	1.89	37.8	37.8	62.2	30-70
12.5	1.51	30.2	68	32	25-60
9.5	0.43	8.6	76.6	23.4	10--35
4.75	1.16	23.2	99.8	0.2	0-5
Pan	0.01	0.2	100	0	
Total	5	100	282.2		

Even though the 25mm and 12.5mm sieves were included in the sieve analysis, they are not included in the fineness modulus calculation. Because the total percent retained on the smaller sieve.

Sieve Size (mm)	Weight Retained (kg)	Percentage Retained	Cumulative Coarser (%)	Cumulative Passing (%)	Standard Passing
37.5	0	0	0		95-100
19.5	1.89	54.15	54.15	45.84	30-70
9.5	0.43	12.32	66.47	33.52	10--35
4.75	1.16	33.24	99.71	0.29	0-5
2.36	0.01	0.29	100	0	
1.18	0	0	100	0	
600µm	0	0	100	0	
300	0	0	100	0	
150	0	0	100	0	
Total	3.49	100	220.34		

Σ cumulative coarser = 220.34

F.M = 2.2%

Fine Aggregate

Specific gravity and absorption capacity

Weight of sand oven-dry (A) = 496.4g

Weight of pycnometer + water (B) = 707.3g

Weight of pycnometer + sample+ water (C) = 1009.8g

Bulk specific gravity = $\frac{A}{B+500-c}$ = 2.51

Bulk specific gravity (SSD) = $\frac{500}{B+500-C}$ =2.53

Apparent specific gravity = $\frac{A}{B+A-C}$ = 2.56

Absorption capacity (%) = $\frac{500-A}{A}$ =0.725%

Unit weight

Weight of aggregate = 20.88 Kg

Length = 0.28m

Diameter = 0.26m

Volume of cylinder = 0.01484m³

Compacted unit weight of aggregate = 1407Kg/m³

N.B:- General range unit weight of natural fine aggregate is 1320 Kg/m³-1680 Kg/m³

Moisture Content

Weight of Aggregate original (A) = 5000g

Weight of Oven-dried aggregate (B)= 486.5g

Water content (percentage) = $\frac{A-B}{B} * 100 =$ 2.41%

Silt Content

A = Amount of silt deposited above sand = 8mm

B = Amount of clean sand = 300mm

Silt content % = $\frac{A}{B} * 100$ = 2.666%

Sieve Analysis for Fine Aggregates

Sieve size		Percent passing by mass	
9.5 mm	(⅜ in.)	100	
4.75 mm	(No. 4)	95 to 100	
2.36 mm	(No. 8)	80 to 100	
1.18 mm	(No. 16)	50 to 85	
600 µm	(No. 30)	25 to 60	
300 µm	(No. 50)	5 to 30	(AASHTO 10 to 30)
150 µm	(No. 100)	0 to 10	(AASHTO 2 to 10)

(ASTM C-33 standard specification for fine aggregate)

Sieve Size (mm)	Weight Retained (kg)	Percentage Retained	Cumulative Coarser (%)	Cumulative Passing (%)	Standard Passing
9.5	0	0	0	100	100
4.75	0	0	0	100	95-100
2.36	0.04	8	8	92	80-100
1.18	0.12	24	32	68	50-85
0.6	0.18	36	68	32	25-60
0.3	0.12	24	92	8	10--30
0.15	0.03	6	98	2	2--10
Pan	0.01	2	100	0	
Total	0.5	100	298		

Σ cumulative coarser = 298
F.M = 2.98%

Choice of slump

Maximum slump= 100mm and minimum slump= 25mm.

Maximum size of aggregates

Sand or fine aggregates =4.75mm

Course aggregates =25mm

Estimation of mixing water and air content

Assume non air entrained concrete

From ACI standard (ACI-2111_91)s, for non-air entrained and slump of 75-100, the water in 1m^3 of concrete is 193Kg.

Water to cement ratio

Relationship between water-cement or water-cementations materials ratio and compressive strength of concrete(ACI-2111_91)

From ACI standards for C-25 and non-air entrained concrete water to cement ratio is 0.61.

Cement content calculation

For slump of 75-100

Water content = 193Kg/m³ W/C=0.61

Cement content = water content/W/c = 193/0.61 =316.3934Kg/m³

Estimation of course aggregates content

As (ACI-2111_91) standard Volume of oven-dry coarse aggregate per unit volume of concrete for different fineness modules of fine aggregate.(ACI-2111_91) for maximum size of aggregate of 25 mm and fines modules for sand =2.98 by interpolation the volume of course aggregate per unit volume of concrete is 0.652.

The required dry mass of course aggregate = 0.652*1613.2=1051.858Kg/m³.

Estimation of fine aggregates content

Content of fine aggregate (F.A) = unit weight of concrete – (C.A + cement + water)

First estimate the unit weight of fresh concretes from table as below.

From the table of ACI standards the unit weight of fresh concrete corresponding to max. Aggregate size of 25mm and non- air entrained is 2380kg/m3. Fine aggregate content = [2380 – (1051.858+316.3934+193)] = 818.748kg/m3

Moisture adjustment

Removed water from C.A = 1.34 - 1.05 = **0.29%**

Removed water from F.A = 2.41 – 0.73 = **1.68%**

Total water required = 193-[$1051.858*(0.29/100)+818.748*(1.68/100)$]

❖ The estimated ingredients for a one meter cube of concrete is therefore, summarized as follows.

Ingredients	**Weight per m3(kg/m3)**
Course aggregate	1051.858
Fine aggregate	818.748
Cement	316.3934
Water	176.2
Conc. Unit weight	**2363.2**

Compressive rubberized concrete strength at 7 days

Mix Identity	Mean weight(g)	Mean load at failure (kN)	Mean Compressive strength (MPa)	Reduction in strength %
CM-0	8123	737	31	
RCM-5	7989	653	29	6
RCM-10	7823	476	21	32
RCM-15	7597	384	17	45
RCM-20	7423	333	15	52
RCM-25	7280	288	13	58

Compressive rubberized concrete strength at 28 Days

Mix Identity	Mean weight (g)	Mean load at failure (kN)	Mean compressive strength (MPa)	Reduction in strength %
CM-0	8130	982	38	
RCM-5	7848	862	37	3
RCM-10	7847	652	29	22
RCM-15	7681	547	24	37
RCM-20	7493	513	23	39
RCM-25	7311	354	16	58

Split tensile strength of rubberized concrete at 7 days

Mix Identity	Mean weight (kg)	Mean load at failure (kN)	Split tensile strength (MPa)	reduction in strength %
CM-0	12854.66	160.63	2.27	
RCM-5	12520.33	101.53	1.43	36.69
RCM-10	12281.66	97.36	1.38	39.29
RCM-15	12117	71.9	1.02	55.17
RCM-20	11889.33	80.36	1.14	49.89
RCM-25	11574.33	65.56	0.93	59.12

Split tensile strength of rubberized concrete at 28 days

Mix Identity	Mean weight (kg)	Mean load at failure (kN)	Split tensile strength (MPa)	reduction in strength %
CM-0	12861	196.8	2.78	
RCM-5	12632	171.6	2.42	12.8
RCM-10	12324	120.16	1.7	38.94
RCM-15	12084	110.23	1.56	43.98
RCM-20	11873.66	96.63	1.36	50.89
RCM-25	11730	82.5	1.16	58.07

Damping ratio of rubberized concrete with string load

Mix identity	load(N)	Y1(g)	Y4	δ	ξ3(%)
CM-0	10	4010	1510	0.98	5.18
	15	3930	1140	1.24	6.56
	20	2700	700	1.35	7.16
	35	5250	1000	1.66	8.797
RCM-5	10	4560	1130	1.39	7.4
	15	1520	300	1.62	8.61
	20	4930	820	1.79	9.52
	35	3640	530	1.93	10.22
RCM-10	10	3740	960	1.36	7.21
	15	3170	710	1.5	7.94
	20	6630	1060	1.83	9.73
	35	11680	1420	2.11	11.18
RCM-15	10	1060	80	2.58	13.71
	15	1560	110	2.65	14.07
	20	3770	260	2.67	14.19
	35	7850	520	2.71	14.4
RCM-20	10	3430	200	2.84	15.08
	15	4640	170	3.31	17.54
	20	4410	140	3.45	18.3
	35	9810	240	3.71	19.68
RCM-25	10	8690	410	3.05	16.2
	15	8400	260	3.47	18.44
	20	6150	110	4.02	21.35
	35	8740	140	4.13	21.93

Damping ratio of rubberized concrete with impact load

Mix identity	load(N)	Y1(g)	Y4(g)	δ	ξ3(%)
CM-0	10	27144	7350	1.31	6.93
	20	50350	10904	1.53	8.12
RCM-5	10	46140	9574	1.57	8.34
	20	20666	3270	1.84	9.78
RCM-10	10	50500	10846	1.54	8.16
	20	50350	4780	2.35	12.49
RCM-15	10	50410	2390	3.05	16.17
	20	50490	2030	3.21	17.05
RCM-20	10	50150	2210	3.12	16.56
	20	50250	1160	3.77	19.99
RCM-25	10	32550	440	4.30	22.83
	20	50150	660	4.33	22.97

Flexural strength of rubberized concrete at 28 Days

Mix Identity	Mean weight (kg)	Mean load at failure (kN)	Flexural strength (MPa)	Reduction in strength %
CM-0	12056	6.6	3.3	
RCM-5	11779	6.25	3.125	5.3
RCM-10	11589.5	6.7	3.35	
RCM-15	11289	5.8	2.9	12.12
RCM-20	11139	6.7	3.35	
RCM-25	10939	4	2	39.39

Appendix B

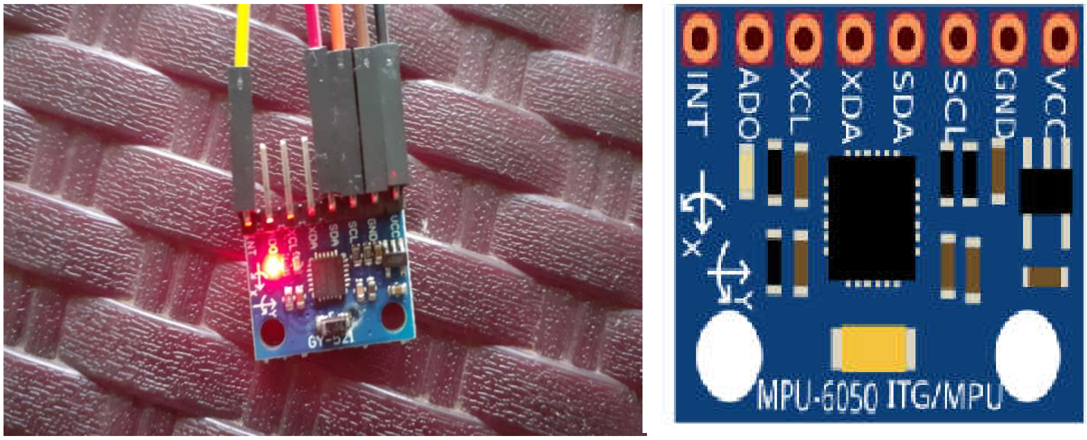
Photographs and soft ware output graphs

Sample of Flexural specimens, cylinders and cubes contains waste tyre rubber

Rubber particles distribution in concrete matrix after failure during compressive loading

Rubber particles distribution in concrete matrix after failure with tensile loading

Preparation of form work to cast the clamping system

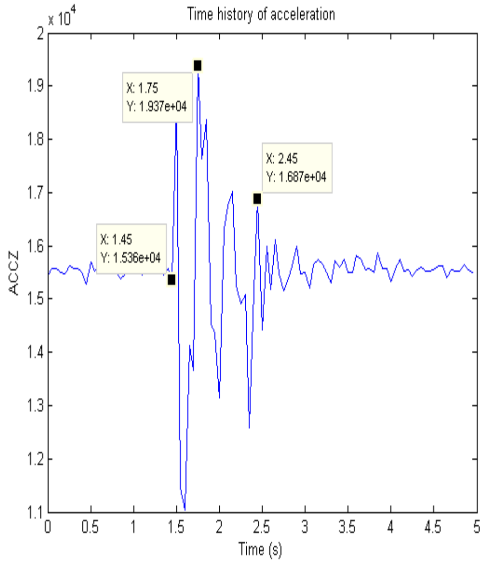


MPU6050 sensor (3 axis acceleration and 3axis rotation)

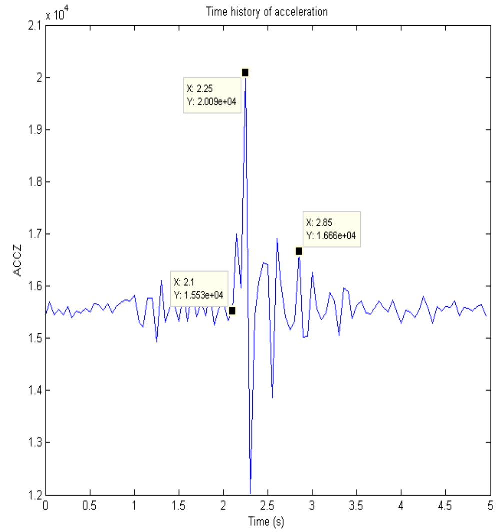
Arduino uno board

Two Set up of MPU6050 sensor (above and below the specimens)

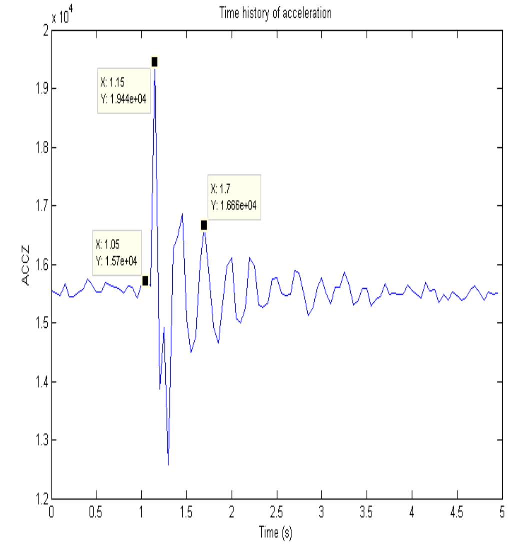
The logarithmic decrement signal of rubberized concrete with 10 N string load



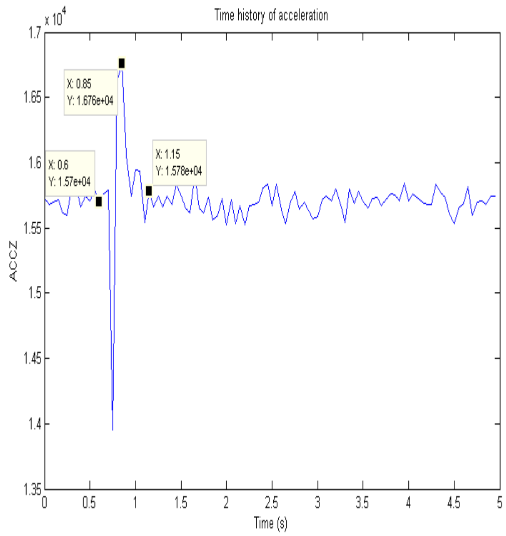
RCM-0 with 10 N string load



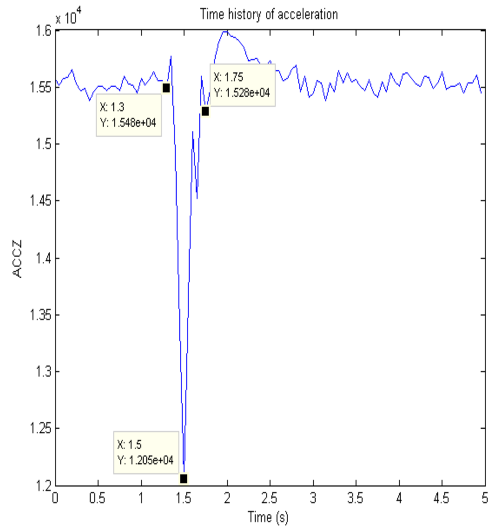
RCM-5 with 10 N string load



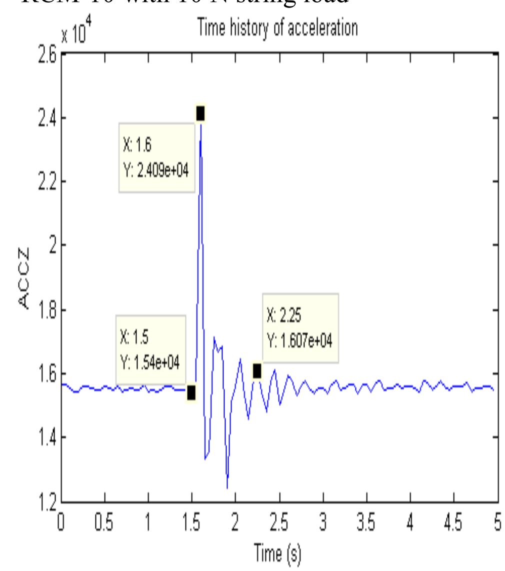
RCM-10 with 10 N string load



RCM-15 with 10 N string load

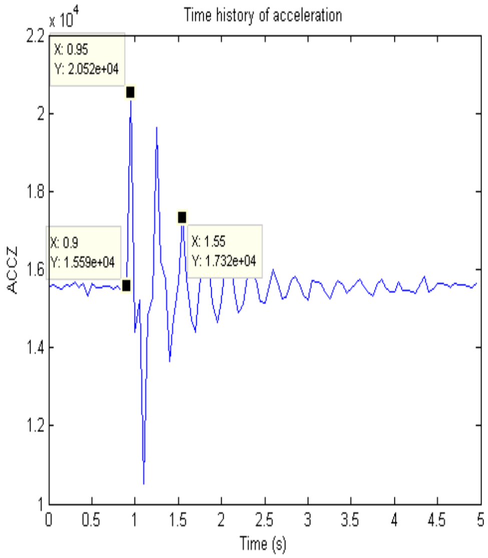


RCM-20 with 10 N string load

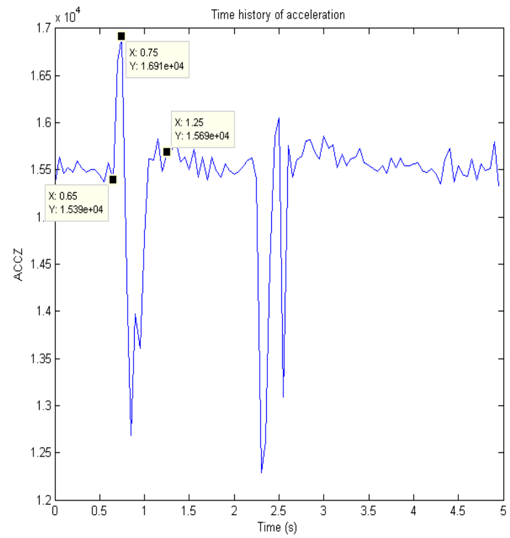


RCM-25 with 10 N string load

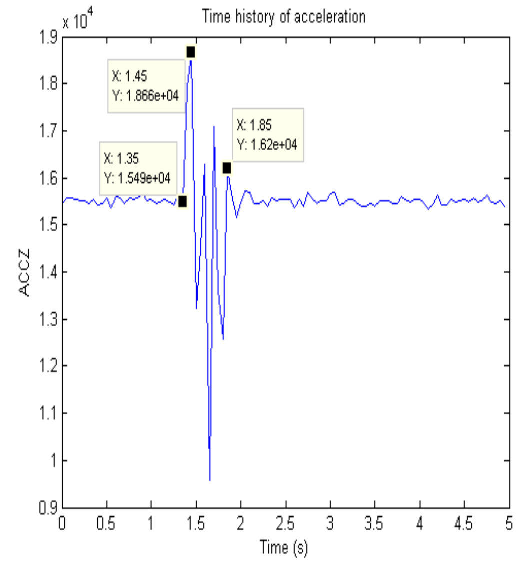
The logarithmic decrement signal of rubberized concrete with 15 N string load



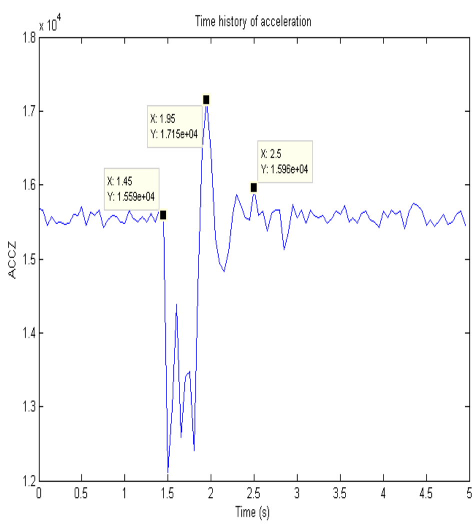
RCM-0 with 15 N string load



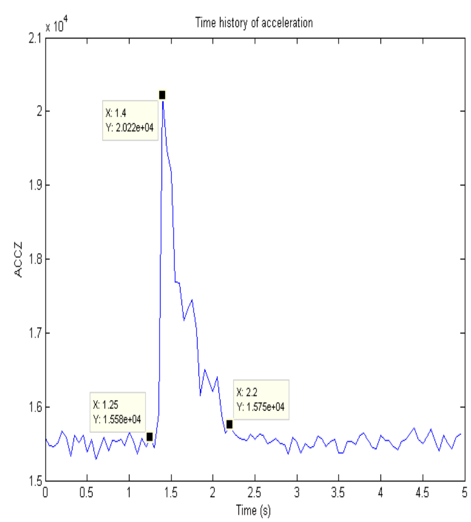
RCM-5 with 15 N string load



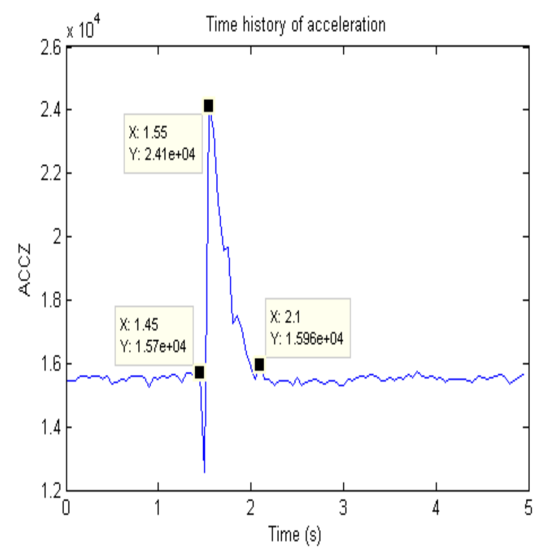
RCM-10 with 15 N string load



RCM-15 with 15 N string load

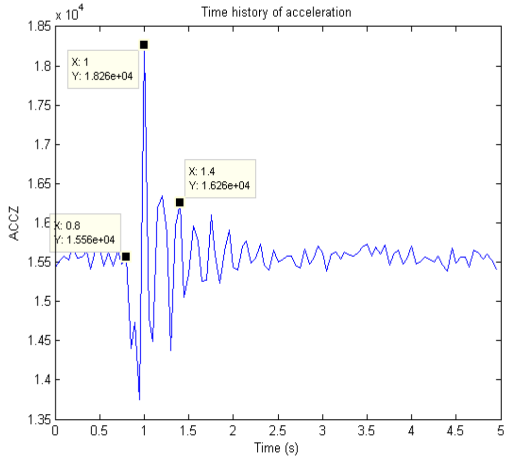


RCM-20 with 15 N string load

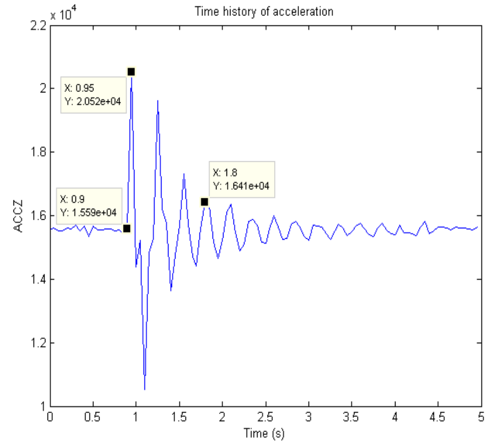


RCM-25 with 15 N string load

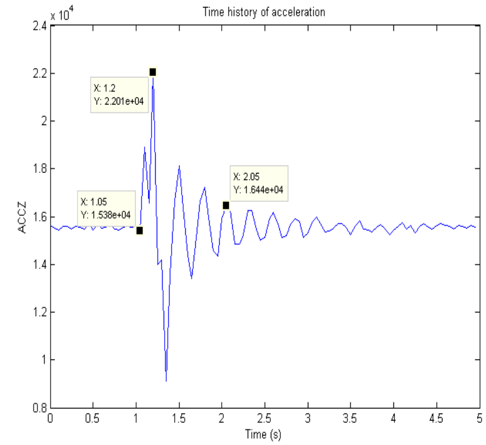
The logarithmic decrement signal of rubberized concrete with 20 N string load



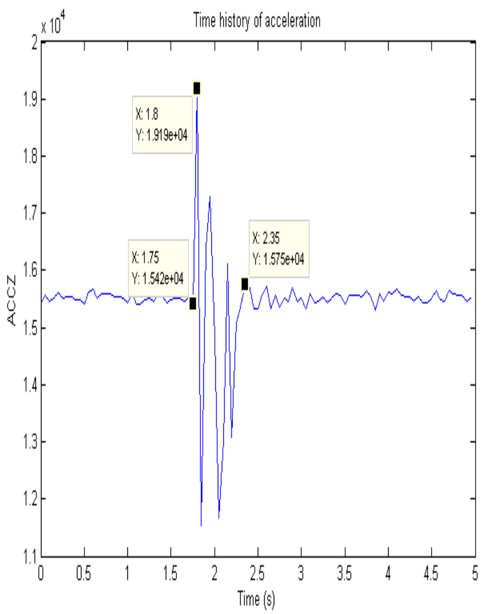
RCM-0 with 10 N string load



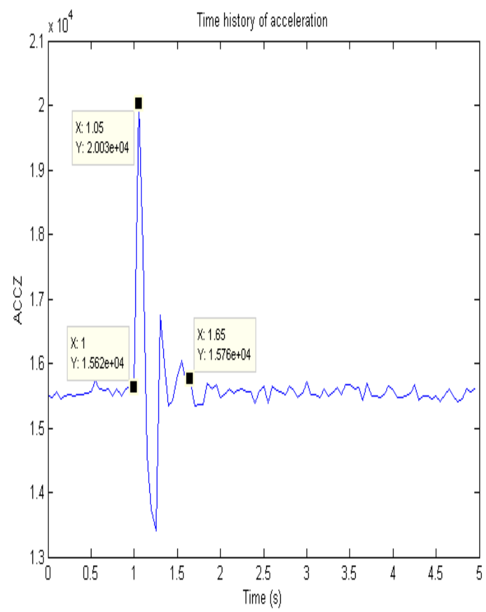
RCM-5 with 10 N string load



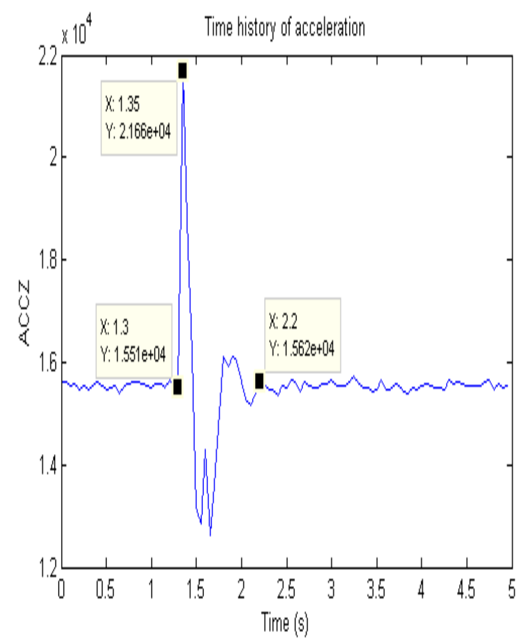
RCM-10 with 10 N string load



RCM-15 with 20 N string load

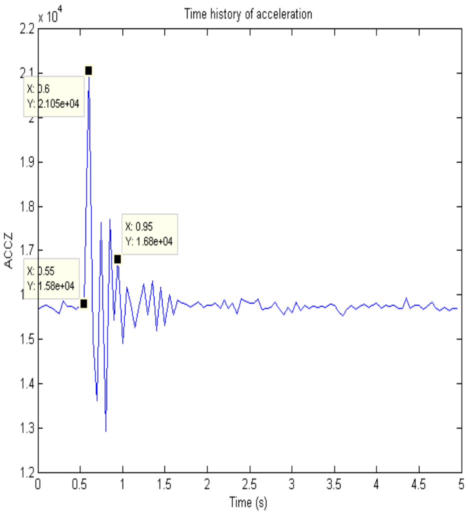


RCM-20 with 20 N string load

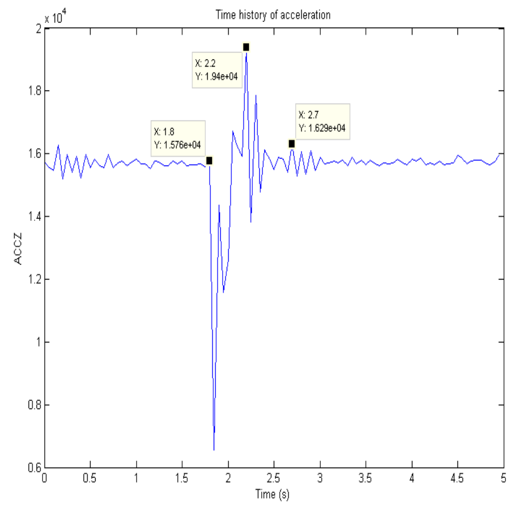


RCM-25 with 20 N string load

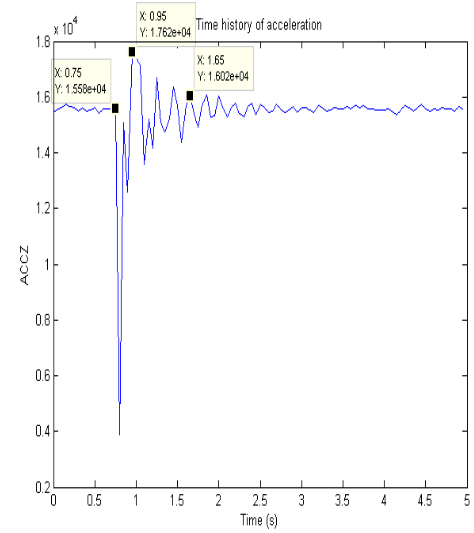
The logarithmic decrement signal of rubberized concrete with 35 N string load



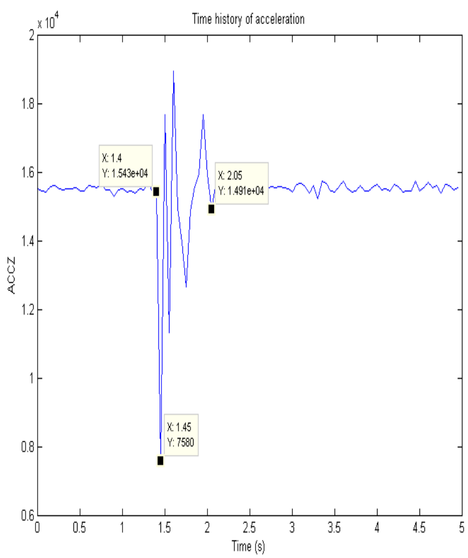
RCM-0 with 35 N string load



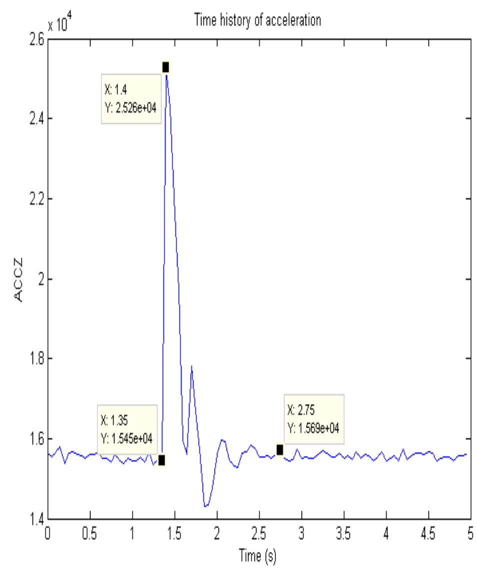
RCM-5 with 35 N string load



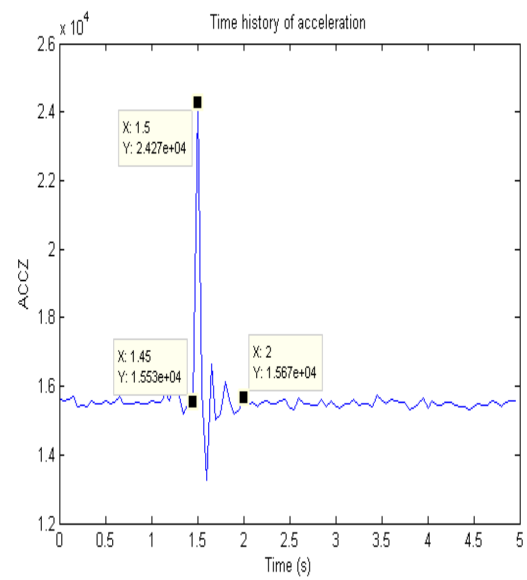
RCM-10 with 35 N string load



RCM-15 with 35 N string load

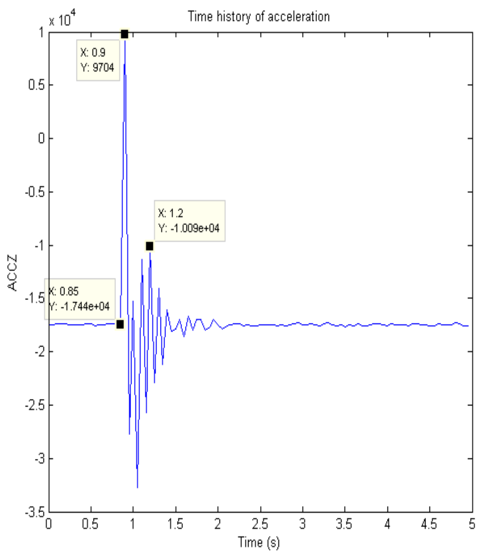


RCM-20 with 35 N string load

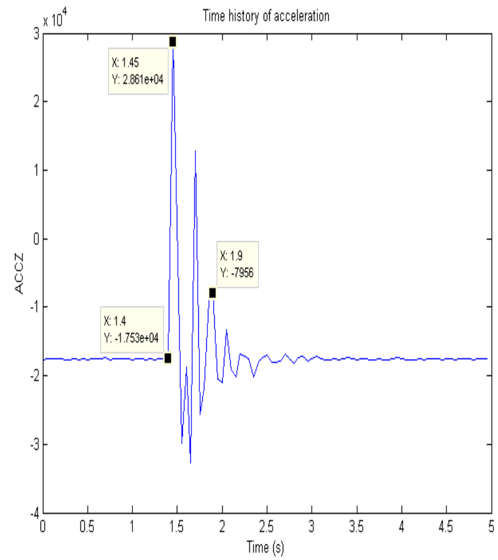


RCM-25 with 35 N string load

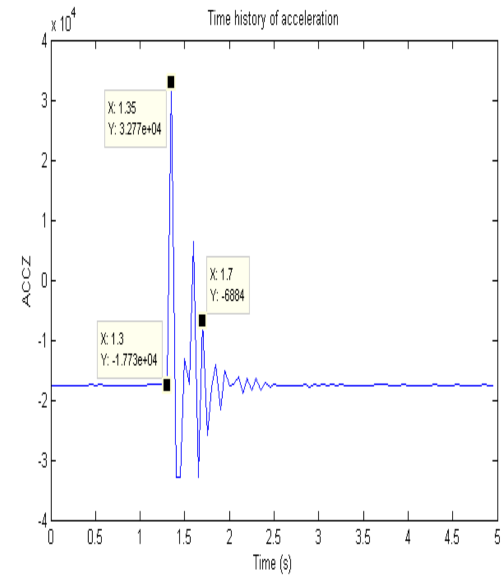
The logarithmic decrement signal of rubberized concrete with 10 N impact load



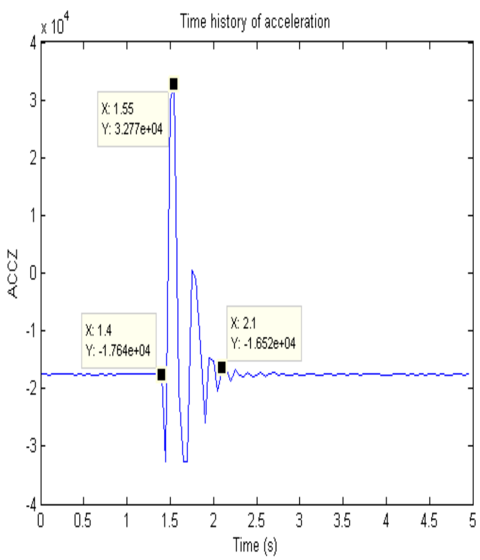
RCM-0 with 10 N impact load



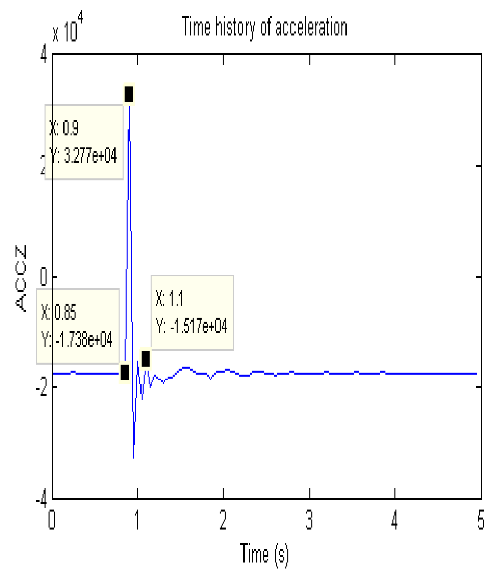
RCM-5 with 10 N impact load



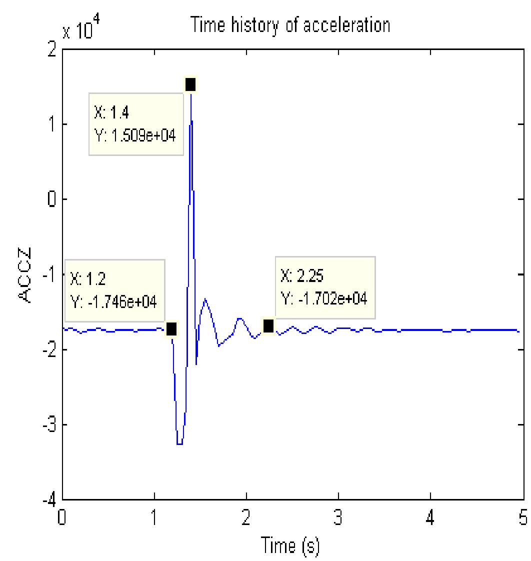
RCM-10 with 10 N impact load



RCM-15 with 10 N impact load

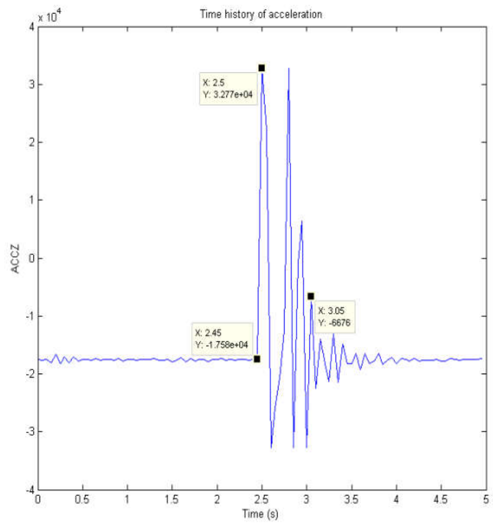


RCM-20 with 10 N impact load

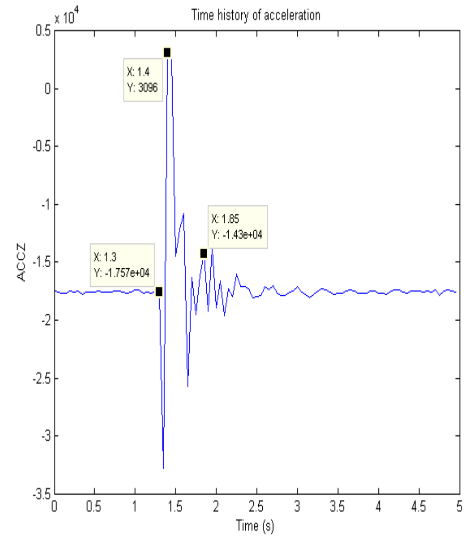


RCM-25 with 10 N impact load

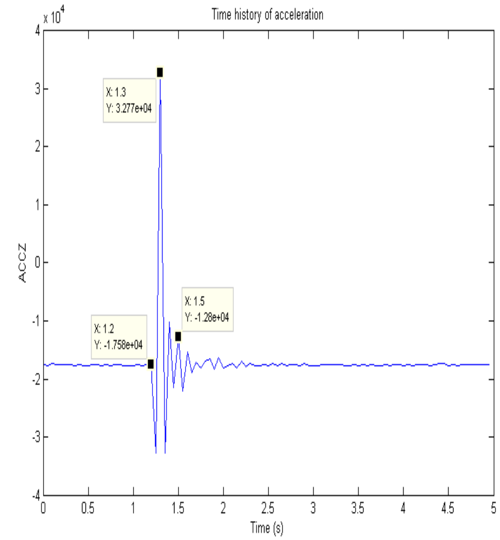
The logarithmic decrement signal of rubberized concrete with 20 N impact load



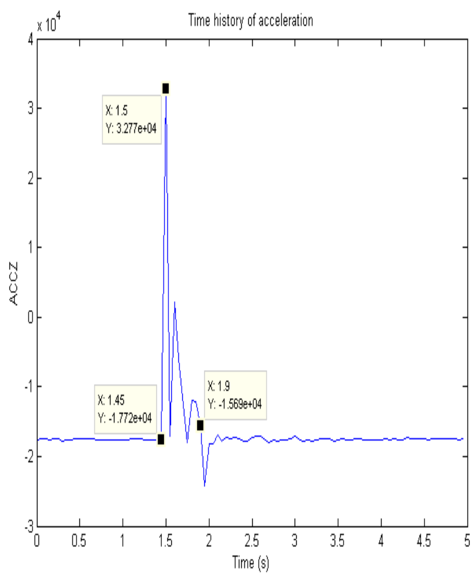
RCM-0 with 20 N impact load



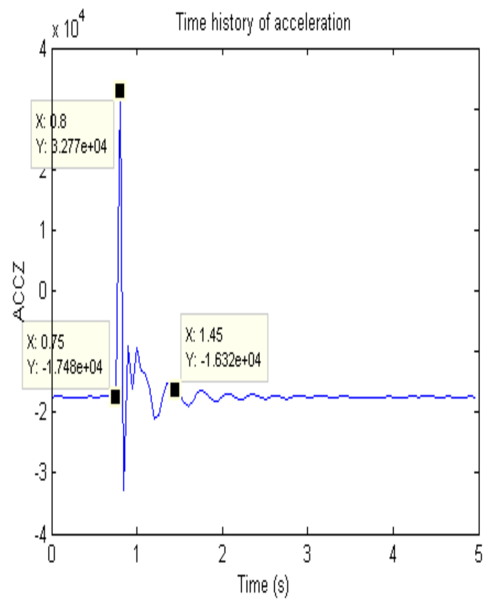
RCM-5 with 20 N impact load



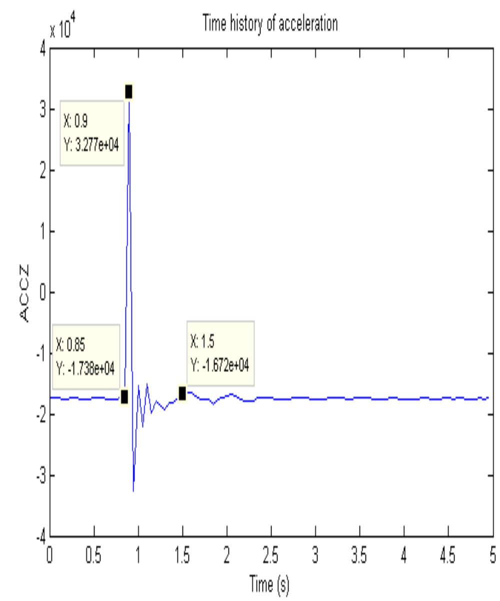
RCM-10 with 20 N impact load



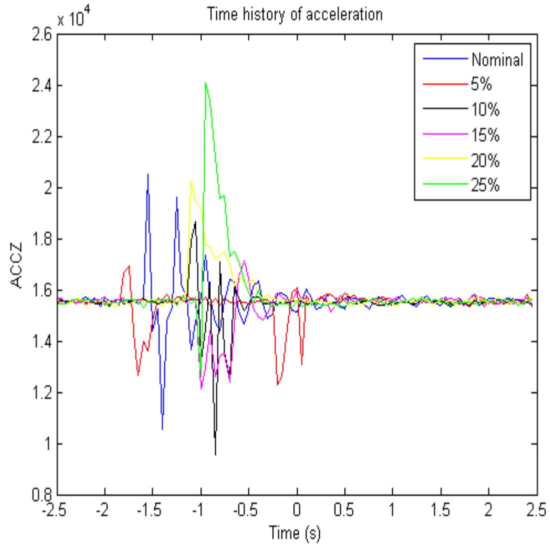
RCM-15 with 20 N impact load



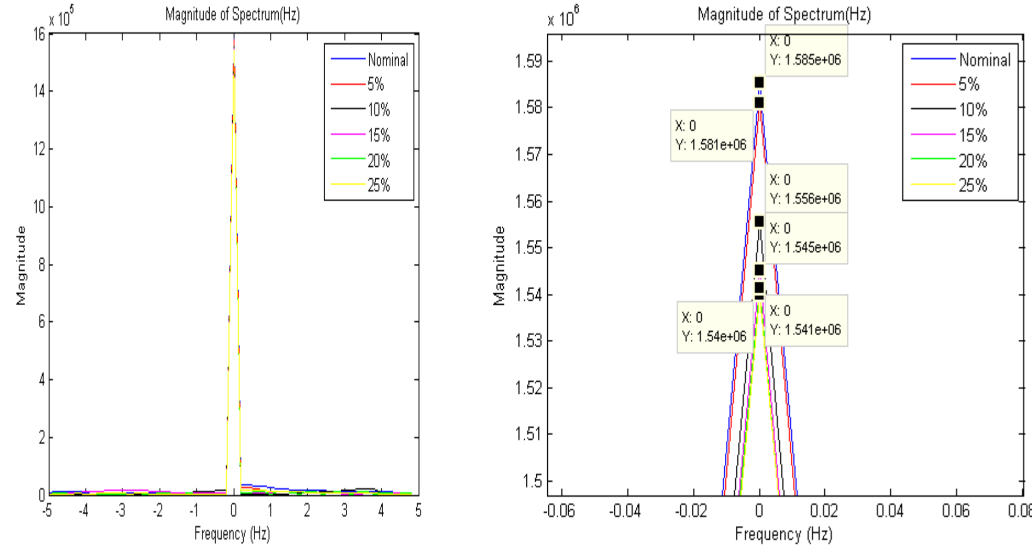
RCM-20 with 20 N impact load



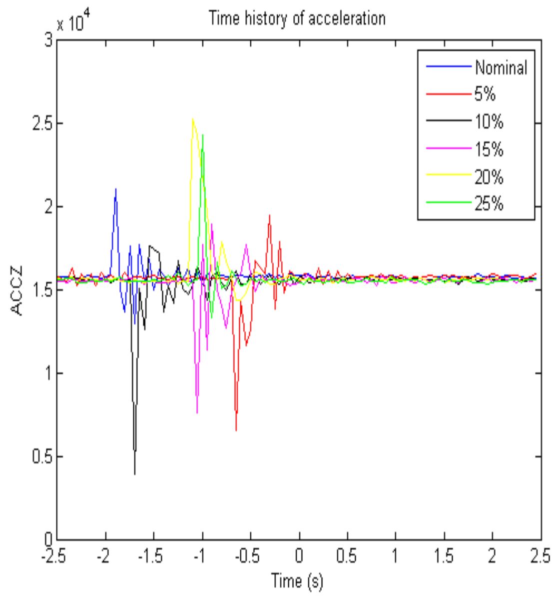
RCM-25 with 20 N impact load



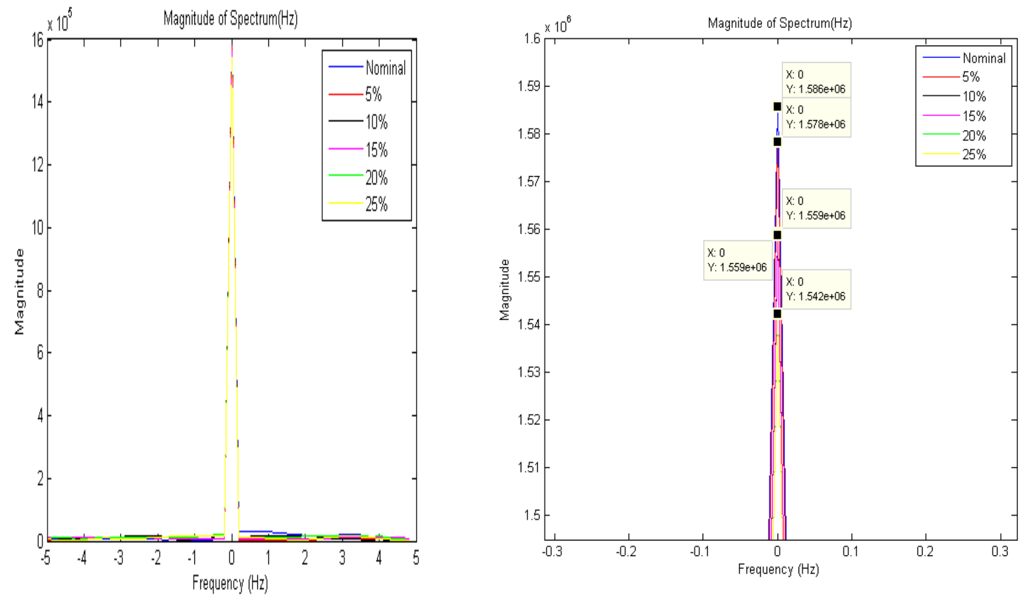
Time history of acceleration response with 15N string load



Single-sided magnitude spectrum for 15N string load



Time history of acceleration response with 35N string load



Single-sided magnitude spectrum for 35N string load

Appendix C

How to programming Arduino soft to communicate with Excel using PLX DAQ and Arduino code used in this thesis

Different categories of PLX DAQ formatted commands:

I. Basic setup and communication: Commands here are used to format the sheet to log to and to send data to the sheet

CLEAR SHEET: Syntax: `Serial.println(“CLEARSHEET”);`

CLEAR DATA: Syntax: `Serial.println(“CLEARDATA”);`

LABEL: Syntax: `Serial.println(“LABEL,1st Column,2nd Column,Third one!”);`

DATA: Syntax `Serial.println("DATA,DATE,TIME”);`

```
   Serial.println( (String) "DATA,DATE,TIME," + millis() );
Serial.print("DATA,DATE,TIME,”);
Serial.print(myVariableA);
Serial.print(",”);
Serial.print(millis());
Serial.print(",”);
Serial.println(myVariableB);
```

II. Specific communication and manipulation:

CELL,SET

Syntax to set a value on the Active Sheet:

`Serial.println("CELL,SET,C9,MyValue”);`

Syntax to set a value on a named sheet somewhere in the work book:

`Serial.println("CELL,SET, ONSHEET,AnySheet,C,9,MyValue”);`

CELL,GET

```
void loop() {
  int myDelayValue;
Serial.println("CELL,GET,Jn-1);
  myDelayValue = Serial.readStringUntil(n).toInt();
Serial.println( (String) "Read value is: " + myDelayValue);
  delay(myDelayValue);
}
```

ROW Syntax: `Serial.println("ROW,SET,2”);`

```
Serial.println("ROW,GET"); myRow = Serial.readStringUntil(10).toInt();
```

CUSTOM BOX Syntax for example:

```
Serial.println("CUSTOMBOX1,LABEL,Measure humidity as well?");
Serial.println("CUSTOMBOX1,GET");
myBoolValue = Serial.readStringUntil(10).toInt();
```

CLEAR RANGE Syntax: `Serial.println("CLEARRANGE,B,10,D,20");`

RE SET TIMER Syntax: `Serial.println("RESETTIMER");`

III. Excel workbook commands:

PAUSE LOGGING Syntax: `Serial.println("PAUSELOGGING");`

SAVE WORK BOOK Syntax: `Serial.println("SAVEWORKBOOK");`

FORCE EXCEL QUIT Syntax: `Serial.println("FORCEEXCELQUIT");`

IV. Miscellaneous commands:

BEEP Syntax: `Serial.println("BEEP");`

MSG Syntax: `Serial.println("MSG,Put your text here");`

DONE Syntax: `Serial.println("DONE");`

GET RANDOM Syntax:

```
    Serial.println("GETRANDOM,-31313,32323");
    int rndseed = Serial.readStringUntil(10).toInt();
    randomSeed(rndseed);
Serial.println( (String) "1st number: " + random(0, 50));
Serial.println( (String) "2nd number: " + random(0, 50));
Serial.println( (String) "3rd number: " + random(0, 50));
```

Codes used to read acceleration used to this paper

```
// Using MPU-6050 Msc Thesis damping properties of partial replacement of rubber in concrete
// By Arduino User Maru sete
#include<Wire.h>
const int MPU_addr=0x68;  // I2C address of the MPU-6050
int16_t AcX,AcY,AcZ,GyX,GyY,GyZ;
void setup(){
  Wire.begin();  Wire.beginTransmission(MPU_addr);
```

```
  Wire.write(0x6B);  // PWR_MGMT_1 register

  Wire.write(0);     // set to zero (wakes up the MPU-6050)

  Wire.endTransmission(true);

  Serial.begin(9600);

   //Serial.println("CLEARDATA"); // clears sheet starting at row 2

   Serial.println("CLEARSHEET"); // clears sheet starting at row 1

  // define 5 columns named "Data","Date", "Time", "AcX", "AcY","AcZ","Gyx","GyY","GyZ","

   Serial.println("LABEL,DATE,TIME,AcX,AcY,AcZ,GyX,GyY,GyZ");
}
void loop(){

  Wire.beginTransmission(MPU_addr);

  Wire.write(0x3B);  // starting with register 0x3B (ACCEL_XOUT_H)

  Wire.endTransmission(false);

  Wire.requestFrom(MPU_addr,14,true);  // request a total of 14 registers

  AcX=Wire.read()<<8|Wire.read();  // 0x3B (ACCEL_XOUT_H) & 0x3C (ACCEL_XOUT_L)

  AcY=Wire.read()<<8|Wire.read();  // 0x3D (ACCEL_YOUT_H) & 0x3E (ACCEL_YOUT_L)

  AcZ=Wire.read()<<8|Wire.read();  // 0x3F (ACCEL_ZOUT_H) & 0x40 (ACCEL_ZOUT_L)

   GyX=Wire.read()<<8|Wire.read();  // 0x43 (GYRO_XOUT_H) & 0x44 (GYRO_XOUT_L)

  GyY=Wire.read()<<8|Wire.read();  // 0x45 (GYRO_YOUT_H) & 0x46 (GYRO_YOUT_L)

  GyZ=Wire.read()<<8|Wire.read();  // 0x47 (GYRO_ZOUT_H) & 0x48 (GYRO_ZOUT_L)

  Serial.println( (String) "DATA,DATE,TIME," + AcX + "," +AcY+ "," +AcZ+ "," +GyX+ "," +GyY+ "," +GyZ );

  delay(20);
}
```