Compressive Strength Forecasting of Rubberised Lightweight Foamed Concrete with Fresh Density of 1350kg/m^3 during the Hardening Process Utilising Elastic Wave Method

NGUI JUN KIT

UNIVERSITI TUNKU ABDUL RAHMAN

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NGUI JUN KIT

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering with Honours

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

SEPTEMBER 2023

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : 

Name : Ngui Jun Kit

ID No. : 1801843

Date : 18 SEPTEMBER 2023

APPROVAL FOR SUBMISSION

I certify that this project report entitled **“Compressive Strength Forecasting of Rubberised Lightweight Foamed Concrete with Fresh Density of 1350kg/m^3 during the Hardening Process Utilising Elastic Wave Method. ”** was prepared by **NGUI JUN KIT** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature : 

Supervisor : Ir Ts Dr. Lee Foo Wei

Date : 18 SEPTEMBER 2023

Signature : -

Co-Supervisor : -

Date : -

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ABSTRACT

The issue of tyre waste has grown as a significant environmental concern, caused mainly by annual population expansion. In modern times, lightweight foamed concrete is widely used across various sectors. Additionally, there is a growing trend of reusing tyre waste into crumb rubber, which replaces fine aggregate in the production of rubberised lightweight foamed concrete. It is essential to do the compressive strength test on the existing structure created using rubberised lightweight foamed concrete. Nevertheless, the current approach to assessing the compressive strength of preexisting structures continues to be invasive. The primary objective of this research is to assess the compressive strength of rubberised lightweight foam concrete using an innovative, non-destructive test method. The flexural strength and splitting tensile strength tests were conducted to analyse further the tensile strength of the rubberised lightweight foamed concrete. This study investigates a sample of rubberised lightweight foamed concrete using the destructive test method and non-destructive test method. The compressive strength of rubberised lightweight foamed concrete is determined through the application of loading until failure occurs, utilising a compression test machine within the framework of the destructive test method. The study utilises the non-destructive test method of ultrasonic pulse velocity of the elastic wave method. The alteration in P-wave properties has been investigated to establish a correlation with the compressive strength obtained from the destructive test. The parameter of P-wave amplitude exhibits a strong positive correlation with compressive strength, as indicated by a regression coefficient greater than 0.8. The correlation between the velocity of the P-wave parameter and compressive strength exhibits a regression degree below 0.8. This indicates that the wave amplitude is more suitable to forecast the compressive strength of rubberised lightweight foamed concrete than wave velocity since it exhibits a substantially higher degree of regression. In summary, it can be concluded that rubberised lightweight foam concrete has favourable characteristics that make it a viable option for construction purposes. The higher regression degree of the non-destructive test method enables an adequate prediction of the compressive strength of rubberised lightweight foam concrete.

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LIST OF SYMBOLS / ABBREVIATIONS

D	depth, m
T	thickness, m
C_p	P-wave speed in an object, m/s
f	frequency, Hz
f_T	thickness frequency, Hz
f_D	frequency of the fundamental mode, Hz
V	compressional wave velocity, m/s
E	dynamic modulus of elasticity, GPa
ρ	density, kg/m^3
ν	dynamic Poisson's ratio
V_s	velocity of S-wave, m/s
V_p	velocity of P-wave, m/s
V_R	velocity of R-wave, m/s
f_{ck}	compressive strength, kN/m^2
f_{st}	splitting tensile strength, MPa
P	maximum load applied, kN
A	cross-sectional area, m^2
w	width, m
t	time, s
R	flexural strength, MPa
L	span length, mm
B	average width, mm
l	length, mm
FC	foam concrete
DT	destructive test
NDT	non-destructive test
UPV	ultrasonic pulse velocity
W/C ratio	water-to-cement ratio

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

In the Fourth Industrial Revolution, infrastructure is being developed better than in previous times. During old generation, they tended to walk rather than take public transport or drive to their destination. It is because most of the locations visited were nearby, and there were fewer modern conveniences available than there are now. Due mainly to these factors, more individuals prefer to own vehicles to get around since they are more convenient, especially when travelling to distant locations or other locations inaccessible by public transportation. When many individuals have their cars due to necessity, the number of waste tyres will increase and might harm the environment. It is because more tyres must be produced to satisfy consumer demand; for instance, one automobile needs four tyres, and used tyres would go to waste.

Recycling tyres is one of the environmentally beneficial methods for reducing the dependence on waste tyres. Recycling waste tyres saves natural resources, saves energy, reduces air and water pollution, reduces solid waste, and reduces greenhouse gases (Bolden, Abu-Lebdeh and Fini, 2013). Nowadays, researchers' studies have investigated that waste tyres can be used in the construction industry as a material for mixing concrete. Traditional concrete mix uses water, coarse and fine aggregates, and cement. At the same time, rubberised concrete mix utilises water, coarse and fine aggregates, cement, and waste tyre particles. As the waste tyre can be used to mix concrete, it has also provided an advantage in the civil industry and some limitations for rubberised concrete.

This study uses the rubberised lightweight foamed concrete to analyse the compressive strength during the hardening process via the elastic wave method. Rubberised lightweight foamed concrete is a type of lightweight concrete that incorporates recycled rubber particles (waste tyre particles) as a partial replacement for the fine aggregate in the concrete mix. The recycled particles used in rubberised lightweight foamed concrete are typically derived from waste tyres, which are ground into small pieces and mixed with the concrete. However, the elastic wave method is a type of non-destructive compressive test method that can be utilised to determine the compressive strength of the concrete. This method involves measuring the velocity of an elastic wave (generally using an ultrasonic pulse velocity test) as it travels through the concrete. The advantage of utilising this method is that the concrete will not undergo any damage while being tested for compressive strength.

1.2 Importance of the Study

Researchers have studied and analysed rubberised concrete for about 30 years (Eltayeb, et al., 2021). It continues to be one of the most popular research topics that draws researchers worldwide. This study can help reduce the number of waste tyres and it is an environmentally friendly material compared to traditional concrete. There are two reasons inspired the related research in utilising rubber from waste tyres in the construction industry.

One of the reasons to study rubberised concrete is the environmental pollution from the many tyres withdrawn from use every year. Waste rubber is the most substantial waste and one of the biggest environmental problems worldwide. Generally, most waste tyres are disposed of by landfill, and the stockpiles threaten the environment. They are also dangerous because of fire risks and serve as the rat, mouse, and mosquito breeding grounds (Eltayeb, et al., 2021). Therefore, this situation can be overcome by grouping the used tyres and compressing them into size particles before using them in the concrete mix.

The second reason is the shortage of natural resources, namely sand. Due to the increasing demands of infrastructure development, natural sand is increasingly used as a fine aggregate in mortar and concrete manufacturing. Nevertheless, some countries like Australia lack natural sand due to the populous of the east coast, and they need to reuse the waste materials to reduce the need for natural sand in their country (Eltayeb, et al., 2021).

1.3 Problem Statement

In the past decades, the number of used tyres is increasing worldwide, which seriously impacts the environment. According to Czajczyńska, et al., the European Tyre & Rubber Manufactures' Association (ETRMA) approximated the worldwide number of passenger and commercial vehicles as 1.3 billion in 2016 and assumed that the global number of tyres will be over 1.6 billion by 2024. In Malaysia, 8.2 million or approximately 57391 tonnes of waste tyres are produced annually (Thiruvangodan, 2006).

Waste tyre disposal has been an issue in many areas worldwide, resulting in wrong views and numerous additional effects. For instance, improper disposal can clog storm water drains or water channels, altering flow patterns and thus raising the danger of flooding. Besides that, the piles of used tyres make good shelters for rats and serve as breeding grounds for mosquitoes that spread hazardous illnesses, such as yellow fever and dengue (Czajczyńska, et al., 2020). The environment, human health, and even life will be seriously endangered if this method of tyre disposal is used.

One of the most workable solutions to this challenge is recycling used tyres by breaking them down into rubber particles in concrete. The qualities of lightweight foamed concrete can be improved by adding rubber particles to create rubberised lightweight foamed concrete, which can improve the ductility and toughness of the concrete. In addition, utilising recycled rubber can cut costs, be more environmentally friendly, and utilise fewer natural resources by reducing the fine aggregate (sand) in concrete. In certain countries, natural sand scarcity makes it difficult for people to continue using sand to cast concrete. To overcome this situation, these countries can use recycled rubber to replace recycled rubber in the proper proportions. For example, they lack natural sand in Australia because they are populous on the east coast. Additionally, adding rubberised particles to concrete will provide new benefits that usual concrete lack, significantly making it a valuable building material for the civil industry since waste rubber may assist in safeguarding and improving environmental aspects (Eltayeb, et al., 2021).

1.4 Aim and Objectives

The aim is to analyse the mechanical strength of rubberised lightweight foamed concrete with a fresh density of 1350kg/m^3 by containing different rubber content with difference in the water to cement ratio. The objectives are listed below to achieve the aim of the study:

1. To determine the compressive strength, flexural strength, splitting tensile strength and workability of rubberised lightweight foamed concrete with a fresh density of 1350kg/m^3.
2. To compare the compressive strength of rubberised lightweight foamed concrete with different water to cement ratio and mix proportions by utilising DT and NDT methods.
3. To forecast the compressive strength of rubberised lightweight foamed concrete with different water to cement ratio and mix proportions by utilising NDT methods.

1.5 Scope and Limitation of the Study

The research uses the elastic wave method (NDT) to examine lightweight rubberised foamed concrete. This study can be carried out by replacing the fine aggregate (sand) proportion from 0% to 70% of rubberised particles with an increment of 10%, respectively. Besides that, the difference in w/c ratio will affect the result of this study. Thus, five types of w/c ratios will be used to analyse the result, which are 0.50, 0.55, 0.60, 0.65, and 0.70.

In this research, some limitations have been set before the experiment starts. First, the compressive strength test of the concrete will be using the mould of 100mm length x 100mm width x 100mm height. Because the difference in the size of the concrete cast will affect the compressive strength obtained in the experiment result, the larger the concrete specimen cast, the lower the strength can be sustained due to the decreased volume-to-surface area ratio. Next, the concrete's splitting tensile strength test will use cylindrical specimens with a diameter of 100mm and 200mm in height. For the flexural strength test, the prism shape of concrete will be used to carry out the test with the dimensions of 500mm length x 100mm width x 100mm height. The second limitation is that the raw materials used for each specimen are the same to prevent external factors from influencing the result obtained, such as cement brand, fine aggregate, rubber particle size, and foaming agent concentration. Other than that, compressive strength testing can only utilise the DT method and elastic wave method (UPV test) instead of other NDT methods. Besides, the P-wave velocity is hard to obtain with the correlation regression of a degree higher than 0.80. This might be due to human error or the surrounding condition of the practical work.

Only some tests will be carried out for this research during day 1, day 7, day 28, and day 56. For each experiment in this study, five specimen cubes will be cast. Because the first specimen cube will be utilised for the 1st day, the second for the 7th day, the third for the 28th day, and the fourth for the 56th day. The fifth specimen cube will be used repeatedly for testing the compressive strength for day 1, day 7, day 28, and day 56 using a NDT method (UPV test). Each specimen cube will be used to evaluate if it meets the ASTM standards and requirements. The failure data may also be collected and recorded to better understand the performance of the concrete used in the research.

1.6 Contribution of the Study

The compressive strength of rubberised lightweight foamed concrete was studied in this research by replacing fine aggregate with rubber particles during the mix. The compressive strength can be analysed by DT and NDT. The reasons to study rubberised lightweight foamed concrete are to reduce the number of waste tyres and reduce the shortage of natural resources like fine aggregate that help decrease environmental issues. When the rubber particles are replaced with fine aggregate, it may decrease the compressive strength, and the mechanical properties of the lightweight foamed concrete will be changed, such as increased flexibility, energy absorption, sound absorption and impact resistance. The factors that affect the compressive strength of rubberised lightweight foamed concrete are mainly caused by rubber particle content in the concrete. Besides rubber replacement content, the w/c ratio, curing process, and size or shape of rubber particles will also influence the quality of the concrete, like compressive strength. The DT and NDT test results will be recorded and used to study. The NDT used for this study is the ultrasonic pulse velocity method; in this method, the P-wave parameter will be taken as the result, which uses to evaluate the compressive strength of the rubberised lightweight foamed concrete because P-wave is the most suitable parameter to forecast the compressive strength of the rubberised lightweight foamed concrete compared to S-wave and R-wave parameters. Therefore, the NDT test is suitable for replacing the DT test in the construction field to analyse the structure's compressive strength without damaging the existing structures or precast structures.

1.7 Outline of the Report

This research consists of a total of five chapters. Chapter 1 comprehensively addresses the environmental concerns associated with wasted tyres, using rubberised lightweight foamed concrete, and the current methodologies for measuring compressive strength. The text examines the importance and research question of the study within the constraints of the present circumstances. In addition, Chapter 1 delineates the study's aims, objectives, constraints, and contributions and furnishes an overview of the report's organisation. In Chapter 2, the literature review part undertakes a comprehensive examination and evaluation of relevant scientific journals and articles authored by other researchers about the subject matter in discussion. This study encompasses a range of aspects, including an investigation of the features and characteristics of rubberised lightweight foamed concrete, with an exploration of DT and NDT method for testing. Chapter 3 introduces the technique, providing a comprehensive overview of the sequential laboratory processes. The previously mentioned elements contain many aspects of the research's topic, such as the preparation of materials, mixing strategies, casting procedures, curing processes, and comprehensive information on testing methods, which encompass both DT and NDT method. Chapter 4 is devoted to providing an overview and discussion of the findings. The present chapter entails examining and associating outcomes derived from NDT and destructive evaluations. This evaluation encompasses various parameters such as compressive strength, wave amplitude, wave velocity, flexural strength, and splitting tensile strength. Chapter 5 serves as a comprehensive summary of the study's findings, conclusions, and recommendations. The conclusion states that the study effectively accomplished its stated aims and objectives while providing recommendations for potential enhancements in future research initiatives.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Rubberised lightweight foamed concrete is a type of concrete that combines lightweight foamed concrete with recycled rubber particles. The rubber particles are obtained from used tyres and are added to the concrete mix to enhance their mechanical properties. The addition of rubber particles to the concrete mix provides several advantages, such as increased impact resistance, improved energy absorption, enhanced thermal and acoustic insulation, and reduced weight. The rubber particles also help to enhance the ductility and toughness of the concrete, making it more resistant to cracking. Rubberised lightweight foamed concrete is commonly used for road and bridge foundations, slope stabilisation, retaining walls, and as a lightweight fill material. It also manufactures precast concrete products such as blocks, panels, and pipes.

The elastic wave method will be utilised in this research, and it is one of the NDT methods. NDT is the method use to evaluate and test the concrete without damaging or destroying them (Workman & O. Moore, 2012). NDT, serves the purpose of identifying and assessing any flaws or anomalies that may impact the efficiency or security of a component or system, without causing any damage that would render it unusable. The ultimate goal is to enable the part or system to continue to operate safely and effectively. The NDT method is suitable for large-scale structures such as bridges.

Another test is the DT method, the most common method for assessing compressive strength. DT is a method of testing or evaluating materials, components, or assemblies that involves causing permanent damage or deformation to the test specimen to assess its performance or properties.

2.2 Introduction to Compressive Strength

The compressive strength of lightweight foamed concrete can be significantly impacted by several factors, including variations in aggregate size and aspect ratio, differences in friction affect between concrete surfaces and loading plates, and differences in crack propagation and localised failure zones. Typically, larger concrete sections will result in lower compressive strength, but there is a point beyond which the decrease in strength stabilises. Cube-shaped concrete generally yields higher compressive strength measurements than cylindrical-shaped concrete, largely due to differences in section shape.

The compressive strength of concrete can be influenced by factors such as size and shape, as these can impact the cohesion and voids between aggregate and paste particles. Lightweight artificial concrete tends to exhibit lower cohesion and higher voids at the paste-aggregate interface than natural average aggregate concrete. To compensate for reduced strength in cases where the aspect ratio of concrete is less than 2.0, the ASTM standard provides a correction factor ranging from 14MPa to 42MPa. The CEB-FIP provision specifies the cylinder strength ratio as 150mm x 300mm to 150mm cube strength (Sim, et al., 2013).

2.3 Introduction to Lightweight Concrete

Structural lightweight concrete is a type of concrete with an oven-dry density that falls within a specific range. According to industry standards, this range is defined as not less than 800 kg/m^3 and not more than 2000 kg/m^3 (Clarke, 1993). This type of concrete is typically used in construction projects where the weight of the structure needs to be minimised, such as in high-rise buildings, bridges, and other structures where the weight-to-strength ratio is a critical factor. The lower density of structural lightweight concrete is achieved by using lightweight aggregates such as expanded shale, clay, or slate, or lightweight synthetic materials such as polystyrene beads or foam. Structural lightweight concrete has a lower compressive strength than typical Ordinary Portland Cement (OPC) concrete because of its low density and use of lightweight aggregates like clay, shale, perlite, and others. These lightweight aggregates are weak, have lower than 2.6 specific gravity, and are more porous than traditional aggregates such as crushed gravel, resulting in a weaker concrete mix.

Lightweight concrete frequently needs a higher water-cement ratio because a higher water-cement can further decrease the compressive strength of lightweight concrete and achieve the preferred workability. Furthermore, the compressive strength of lightweight concrete can still be utilised for many applications. It has advantages like reduced dead load on the structure, better fire resistance, and improved thermal and acoustic insulation properties.

There are three types of lightweight concrete, and each type of lightweight concrete has its own advantages and disadvantages. The selection of the appropriate type will depend on the specific requirements of the construction project (Mohammed and Hamad, 2014). Figure 2.1 shows the composition of particles in the different types of lightweight concrete.

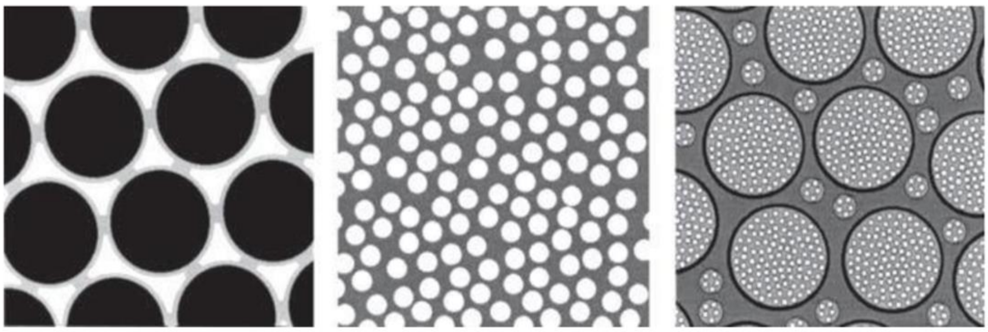

Figure 2.1: Type of lightweight concrete (Mohammed and Hamad, 2014)

2.3.1 Introduction to Aerated Concrete

Aerated concrete, also known as cellular concrete, is a type of lightweight concrete that can be produced in two main ways: foamed concrete and autoclaved aerated concrete. Foamed concrete is made by injecting pre-formed stable foam or adding air-entraining admixture into a cement paste or mortar base mix, while autoclaved aerated concrete is produced by adding a predetermined amount of aluminium powder and other additives into a slurry of ground-high silica sand, cement or lime, and water. Figure 2.2 shows the details about the type of aerated lightweight concrete. Figure 2.3 shows the microstructure of the aerated concrete.

Foamed concrete has been around since the early 1920s but was only recognised for construction works in the late 1970s. In contrast, autoclaved aerated concrete has been in use for around 100 years. In 1914, the Swedes made an important discovery regarding the production of building materials. They found that by combining lime, cement, water, sand and adding aluminium powder to the mixture, they could create a chemical reaction that produced hydrogen gas in the cement slurry. This resulted in the expansion of the mixture, creating a lightweight and durable material that could be used in construction. This discovery paved the way for the development of modern lightweight concrete, which is now widely used in the construction industry (Hamad, 2014).

Foamed concrete has several advantages, including high flowability, controlled low strength, low self-weight, and good thermal insulation properties. The density of foamed concrete ranges from 400kg/m^3 to 1600kg/m^3, depending on the appropriate limit of foam dosage. It can be used in various construction applications, including structural, insulation, partition, and filling grades (Hamad, 2014).

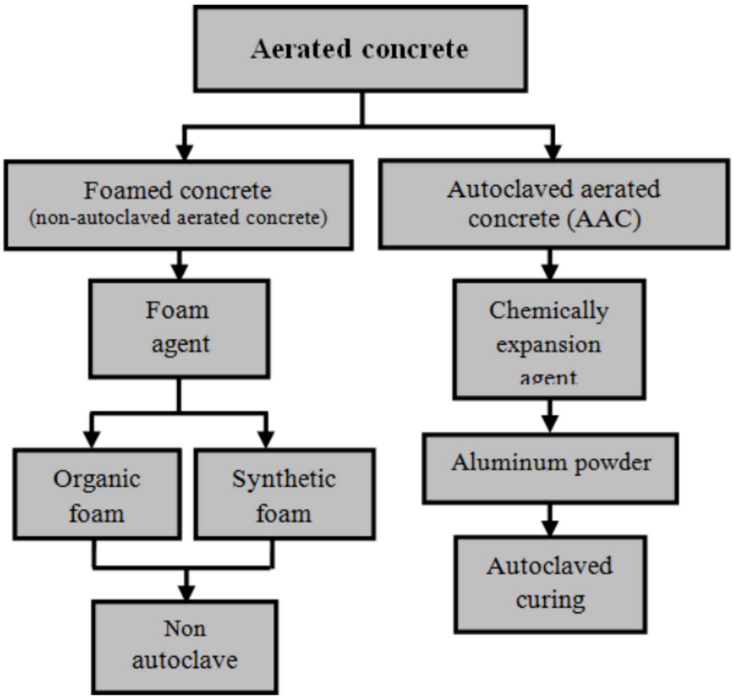

Figure 2.2: Type of Aerated Lightweight Concretes (Hamad, 2014)

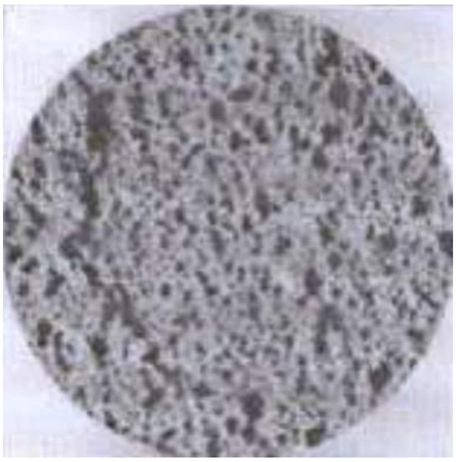

Figure 2.3: Aerated Concrete (Jagtap, et al., 2020).

2.3.1.1 Foam Agent

Foam agents are essential in producing foamed concrete, as they act as air-entraining agents that generate discrete bubbles in the cement paste. There are two main types of foam agents: synthetic and protein based. Synthetic foam agents, with a density of around 40g/litter, are chemical products that are stable at concrete densities of over 1000kg/m^3, providing good strength. They have a finer bubble size than protein foam but tend to result in lower strength foamed concrete, particularly at densities below 1000kg/m^3. In contrast, protein-based foaming agents, with a weight of around 80g/litter, come from animal proteins such as horns, bones, blood, and other animal carcasses. The quality of such foaming agents may vary between batches due to the use of different raw materials, and they tend to have a strong odor. They are suitable for densities ranging from 400kg/m3 to 1600kg/m^3 (Mohammed and Hamad, 2014).

2.3.1.2 Aluminium Powder

Aluminium powder is a key component in the production of autoclaved aerated concrete, as it acts as a foaming agent to obtain gas in a fresh mortar. This results in the formation of many gas bubbles when the concrete sets. There are three types of aluminium powder that can be used in concrete production: atomised, flake, and granules. Atomised particles are similar in size, while flake particles can be several hundred times longer and wider than their thickness. In the autoclaved aerated concrete industry, aluminium powder is typically made from scrap aluminium foil and has a microscopic flake-like shape. It is essential to ensure that the aluminium powder used has a grain size of less than 100µm and a friction of less than 50µm to avoid the formation of highly flammable dust clouds during vibration or pouring (Mohammed and Hamad, 2014).

2.3.2 Lightweight Aggregate Concrete

Lightweight aggregate concrete is a concrete made up of lightweight aggregates. These aggregates are made from materials that have a low particle density, typically less than 2000kg/m^3 or a dry loose bulk density of less than 1200kg/m^3 (Clarke, 1993). Lightweight aggregate is classified into two categories: natural materials and artificial materials (by-products). The resources of lightweight aggregate from natural materials are shales, clays, volcanic cinders, pumice, slates, and diatomite. At the same time, artificial materials are iron blast furnace slag, shale, and sintered fly ash. Figure 2.4 shows the natural and artificial lightweight aggregate.

Lightweight aggregate concrete has unique properties that make it suitable for various applications. The type of lightweight aggregate used can determine the properties of the concrete. Natural lightweight aggregates, such as pumice and volcanic ash, tend to produce concrete with lower compressive strength but better insulation properties. On the other hand, artificial lightweight aggregates, such as expanded clay and sintered fly ash, can produce concrete with higher compressive strength and better durability.

Apart from reducing the overall cost of the structure, the use of lightweight aggregate can also improve the insulation properties of the building, leading to reduced energy consumption for heating and cooling. Additionally, lightweight aggregate concrete has better fire resistance than normal weight concrete.

The application of lightweight aggregate is extensive, including in the production of lightweight concrete masonry, precast concrete products, structural lightweight and semi-lightweight cast-in-place concrete, concrete roofing tiles, and geotechnical applications such as lightweight fill materials for embankments and retaining walls (Mohammed and Hamad, 2014).

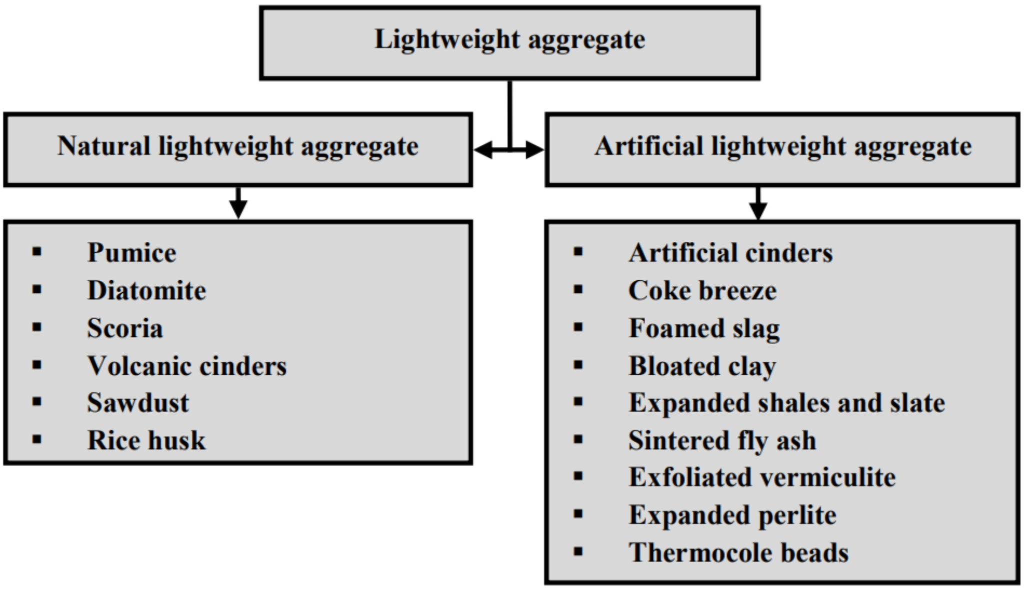

Figure 2.4: Natural and Artificial Lightweight Aggregate (Mohammed and Hamad, 2014).

2.3.3 No-fines Concrete

No-fine concrete is a type of concrete that is made by mixing cement, water, and coarse aggregate without adding any fine aggregate. Instead, each particle of coarse aggregate is covered with a layer of cement paste that is about 1.3mm thick or more. The density of no-fines concrete varies depending on the type and grade of aggregate used. Typically, low-density concrete can be produced using a single-size coarse aggregate with a maximum size ranging from 7mm to 75mm, although aggregate sizes from 10mm to 20mm are more commonly used. Figure 2.5 shows the microstructure of no-fines concrete.

One of the notable characteristics of no-fines concrete is the presence of large, uniformly distributed, and interconnected voids between the aggregate particles. This leads to a high void content, which can be more than 30% of the concrete. Despite its low density, no-fines concrete can still exhibit good compressive strength and durability, making it suitable for a variety of applications such as walls, pavements, and load-bearing structures. The use of no-fines concrete can also help to reduce construction costs and improve energy efficiency due to its low thermal conductivity (Mohammed and Hamad, 2014). Additionally, the absence of fine aggregates reduces the capillary movement of water, which helps to prevent water damage in wet conditions.

Overall, no-fines concrete has several advantages that make it a useful material in construction projects (Jagtap, et al., 2020).

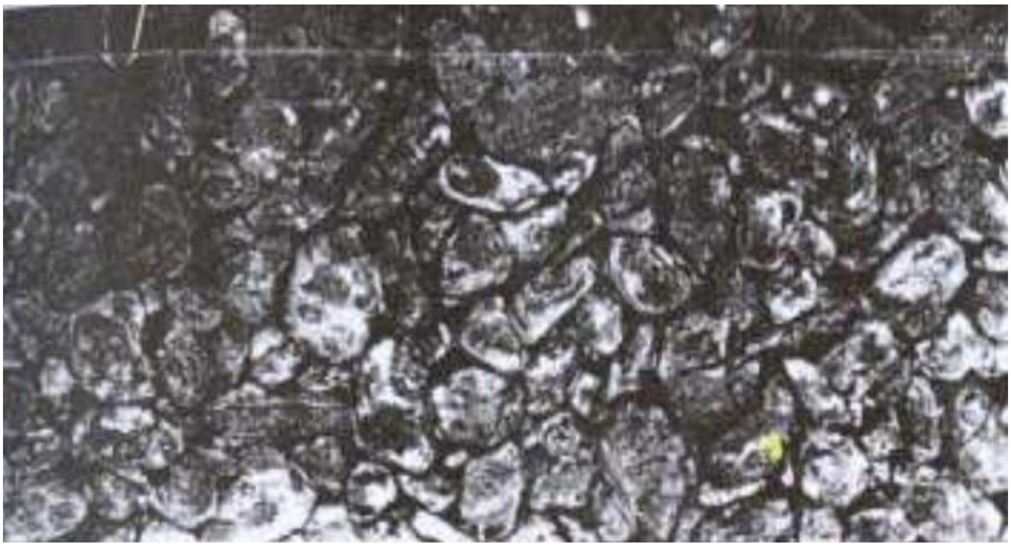

Figure 2.5: No-Fines Concrete (Jagtap, et al., 2020).

2.4 Pros and Cons of Lightweight Concrete

Lightweight concrete is a type of concrete that has a dry density of less than 2000kg/m^3 and is lighter than regular concrete, which has a self-weight of about 2400kg/m^3 to 2500kg/m^3. It has been used in construction for over 50 years in countries such as the United States, Italy, Hong Kong, and Sweden. While it has many advantages, there are also some limitations, which are listed in the table below (Agrawal, et al., 2021). Table 2.1 shows pros and cons of lightweight concrete.

Table 2.1: Pros and cons of lightweight concrete (Agrawal, et al., 2021).

Pros	**Cons**
Reduction in c1oncrete density.	Hard to place and finish due to the porosity and angularity of the aggregate.
Reduces the total dead load of an entire structure.	Very sensitive to water content.
Savings in all over cost of construction.	Mixing time is longer than conventional concrete.

Table 2.1 (Continued)

Construction growth rate increase due to high-speed work and lower haulage and handling costs.	Lightweight concretes are porous and show poor resistance.
Relatively low thermal conductivity.	
Greater fire and free thaw resistance than ordinary concrete.	
Good sound absorption.	

2.5 Difference Between Lightweight Concrete and Reinforced Concrete

Concrete has been a popular and valuable construction material for hundreds of years due to its flexibility in usage and surpassing steel and timber in popularity. To produce concrete, a proper ratio of cement, coarse aggregate, fine aggregate, and water is mixed. The aggregate in concrete plays a crucial role in terms of strength and bonding. Aggregate is typically described as having an apparent specific gravity of 2.4 or more and can be further classified by particle shape and surface texture. Standard concrete has an aggregate density of about 2400kg/m^3.

Reducing the density of concrete can result in economic benefits by lowering the cost of transportation, constructability, and handling costs. Lightweight aggregate and air-entraining agents are some of the ways to produce lighter concrete. Technological advancements have also presented humanity with various challenges to improve the quality and uses of concrete. The present of air entraining and lightweight aggregate in the concrete can reduce dead load, lower haulage and handling costs, and faster construction time. However, lightweight concrete is also limited because it is unsuitable for specific purposes compared to standard concrete (Jagtap, et al., 2020). Table 2.2 shows the comparison between lightweight concrete and reinforced concrete.

Table 2.2: Comparison between lightweight concrete and reinforce concrete (Jagtap, et al., 2020).

Lightweight concrete	**Reinforce concrete**
Compressive flexural strengths are low.	Compressive and flexural strengths are high.
Density of concrete is lower compared to reinforce concrete and it has a density less than 2000kg/m^3.	Density of concrete is higher compared to lightweight concrete, and it has about 2400kg/m^3.
Workability of lightweight concrete is good due to the light density and high air content.	Workability of reinforce concrete is difficult to work with because it has higher density and less air content.
Lightweight concrete has ability to absorb sound due to the porous structure and the present of air voids within the material.	Reinforce concrete is weak in absorbing sound due to its dense and non-porous nature.
It has lower thermal conductivity due to the present of air voids within the material.	It has a higher thermal conductivity due to the higher density and less air voids.
It can help to reduce dead load of the structure due to its content lower density.	It has higher density and can cause the dead load of the structure become higher.
Lightweight concrete can increase the progress of the construction work due to its lighter weight and improved workability.	Reinforce concrete has a slower progress of the construction due to its heavy weight and lower workability compared to lightweight concrete.
Lightweight concrete can improve energy efficiency due to the lower thermal conductivity of the concrete. It will result the structure need to install lesser heating and cooling machine-like air-conditioning and fan.	Reinforce concrete need higher cost compared to lightweight concrete due to its weight and density.

Table 2.2 (Continued)

Its concrete is economical compared to the reinforce concrete due to the materials used (less cement and aggregates used than reinforce concrete), transportation fee (lighter in weight and cause easier to transport) and formwork fee (due to the lighter in weight less stress on the formwork result less formwork to be installed).	Reinforce concrete having a higher thermal conductivity of the concrete and it will result the structure need to install more heating and cooling system.

2.6 Introduction of Rubberised Particles

Environmental pollution is a significant issue globally, and waste tire disposal is one of the contributing factors. Various disposal methods such as burning, landfilling, and recycling have been used, but they pose environmental, health, and economic risks. Recent research has focused on using waste tire rubber to produce concrete, which is an environmentally friendly solution. The properties of rubberised concrete are influenced by factors such as particle size, content, shape, cleanliness, and quality of the rubber particles. The addition of rubber to concrete can improve its impact resistance, thermal insulation properties, and noise reduction. Additionally, rubberised fibres can be added to enhance the concrete's toughness, durability, and prevent cracking (Liu, et al., 2016). Using waste tire rubber in concrete production can reduce the amount of waste tires and has the potential to create a more sustainable construction industry.

2.6.1 Classification and Composition of Rubber Particles in Rubberised Concrete

Different methods have been developed for processing waste tires to obtain crumb rubber particles of an optimal size for use in construction. Mechanical grinding and cryogenic grinding are two common methods used to produce crumb rubber (Li, et al., 2019). The size of crumb rubber particles may vary depending on the method used, but generally, particles ranging from 2mm to 4mm are used. Four categories of discarded tire rubber are commonly used in research, including ash, granular, fibre rubbers, and chips. Table 2.3 provides detailed information on the characteristics of these four categories. Table 2.4 and Table 2.5 show the general composition and chemical elements present in crumb rubber obtained from waste tires. Figure 2.6 show the various size of scrap tire particles in rubberised concrete.

Table 2.3: Classification of rubber particles used in previous studies (Li, et al., 2019).

Type	**Rubber size**	**Replaced Material**
Ash/powder	63mm - 0.63mm Length larger than 75mm can pass #200 sieve 20 mesh Passed No. #30 sieves (0.6mm) 70% from size (mesh 40) 100 - 600mm	Cement Fine aggregate
Chip	40% from 5mm size and 60% from 10mm size 50% from 4 to 10mm and 50% from 10 to 20mm	Coarse aggregate
Granular	1 - 6mm 1 - 8mm 30% from size (1-4mm) Granule size 2/4 and 4/6 < 4.75mm 40% of 1 - 3mm and 20% of 3 - 5mm size 35% from 1 to 3 mm and 25% from 2 to 4mm	Coarse aggregate Fine aggregate
Fibre	#1.2mm 2 - 5mm in width, up to 20mm in length 2 - 4mm wide and up to 22mm long	Fine aggregate

Table 2.4: General composition of rubber particles from waste tires (Li, et al., 2019).

Type of Tyres	Rubber polymers (%)	Carbon black (%)	Sulphur (%)	Ash content (%)	Acetone extract (%)	Water, mineral, textile material etc. (%)
A	38.30	31.30	3.23	5.43	7.30	14.44
B	44.60	30.70	0.50	4.20	16.90	3.10
C	40 - 55	30 - 38	≤5	3 - 7	10 - 20	-
D	40 - 55	20 - 25	-	-	-	-

Table 2.5: Chemical elements of waste rubber (Li, et al., 2019).

Type of Tyres	C (%)	O (%)	Zn (%)	S (%)	Si (%)	Mg (%)	Al (%)	Na (%)	H (%)	Ga (%)
A	87.50	9.24	1.77	1.07	0.20	0.14	0.08	-	-	-
B	87.51	9.23	1.76	1.08	0.20	0.14	0.08	-	-	-
C	91.50	3.30	3.50	1.20	-	-	-	0.20	0.20	0.10

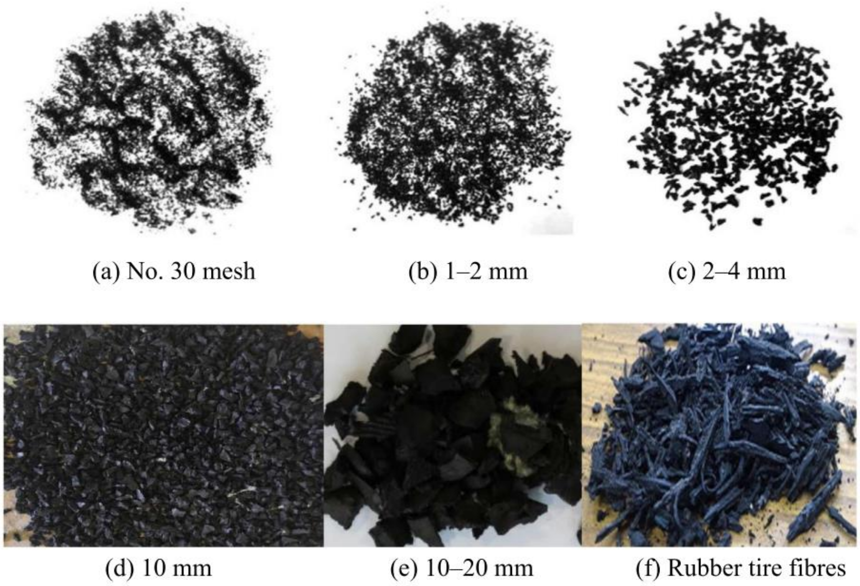

Figure 2.6: Various size of scrap tire particles in rubberised concrete (Li, et al., 2019).

2.6.2 Mechanical Properties

Research has shown that incorporating crumb rubber into concrete mixtures can lead to a reduction in its mechanical properties. This includes a decrease in compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity. Table 2.6 provides a more detailed explanation of these effects. However, some studies have also reported an increase in the toughness and ductility of the concrete. The specific effects of crumb rubber on the mechanical properties of concrete can depend on various factors, including the type of rubber used, the particle size and shape, the mixing method, and the curing conditions (Li, et al., 2019).

Table 2.6: Fresh and mechanical properties of crumb rubber concrete (Li, et al., 2019).

Properties	Rubber size/type	Replacement pattern	Rubber replacement ratio	Concrete type	Results
Workability (slump values)	0–6 mm (granular), 5–20 mm (chip)	Fine and coarse aggregate	30–60% by volume	Concrete	↓13–56%
	0–4 mm (granular), 4–20 mm (chip)	Fine and coarse aggregate	20–60% by volume	Concrete pavement	↓16.6–37.5%
	1–4 mm (granular)	Fine aggregate	10–40% by volume	Rubber long hollow blocks and bricks	↑119–476%
	0.075–4.75 mm (powder and granular)	Fine aggregate	5–25% by volume	Concrete	↑4.2–43.8%
Fresh density	8–14, 14–30, and 30 mesh (granular and powder)	Fine aggregate	5–30% by volume	HS concrete	Density: ↓2–6%
	60% of 0.8–4 mm (granular) and 40% powder	Fine aggregate	2.5–20% by weight	HS concrete	Bulk density: ↓0–9.6%
	0.2–4 mm (granular)	Fine aggregate	10–60% by volume	Mortar	Unit weight: ↓3.1–10.7%
	0–6 mm (granular), 5–20 mm (chip)	Fine and coarse aggregate	30–60% by volume	Concrete	Unit weight: ↓9.4–22.3%
Compressive strength (28-day)	0.075–4.75 mm (powder and granular)	Fine aggregate	5–30% by volume	Self-consolidating rubberized concrete	↓11.8–57.9%
	1.18–2.36 mm (granular)	Fine aggregate	10% by volume	Concrete tactile paving blocks	↑2.2%
	63 μm–0.63 mm (ash/powder)	Cement	2.5–10% by weight	Concrete	↓28%–38.2% (5% rubber), ↓37.1% (10% rubber)
	40% from 5 mm size and 60% from 10 mm size (chip)	Coarse aggregate	5–20% by weight	Concrete	↓14.3–53.6% (conventional CRC); ↓10.8–48.5% (SCRC)
Flexural strength (28-day)	1.18–2.36 mm (granular)	Fine aggregate	10–50% by volume	Concrete tactile paving blocks	↓18–32%
	0.075–4.75 mm (powder and granular)	Fine aggregate	5–25% by volume	Concrete	↑7–21% (5–15% CR), ↑9.3% (20% CR), ↓9.3% (25% CR)
	63 μm–0.63 mm (ash/powder)	Cement	2.5–10% by weight	Concrete	↓23.3% (2.5% GTR), ↓20% (5% GTR), ↓20% (10% GTR)
	1–6 mm (granular)	Coarse aggregate	10–15% by weight	Concrete	↓9–19%
Splitting tensile strength (28-day)	150 μm–4.75 mm (powder and granular)	Fine aggregate	5–15% by volume	SCRC	↓1.6–14.3%
	0.075–4.75 mm (powder and granular)	Fine aggregate	5–40% by volume	Self-consolidating rubberized concrete	↓16.5–31%
Modulus of elasticity (28-day)	0.075–4.75 mm (granular)	Fine aggregate	5–25% by volume	Concrete	↓2.44–31.74%
	1.18–2.36 mm (granular)	Fine aggregate	10–50% by volume	Concrete	↓4.8–51.5%

2.6.2.1 Compressive Strength

The study of rubberised concrete found that when the replacement of rubber to fine aggregate increases, the compressive strength decreases. This condition is due to the poor chemical reaction between the rubber particles and the cementitious matrix. The weak interfacial transition zone can reduce the load transfer to the concrete, resulting in the compressive strength drop. The rubber quality, like size, shape, and composition, will affect the compressive strength. When there having inconsistent rubber quality can impact the overall performance of the concrete. Furthermore, high rubber content in the concrete can disrupt the cement matrix structure because a large amount of rubber content will create more voids or weak spots within the matrix structure, causing the strength to drop too.

However, in some research, they found that a certain percentage of rubber replacement to fine aggregate can increase the compressive strength of the rubber concrete. Sure, rubber content in rubber concrete can cause chemical treatment, improving its adhesion to the cement matrix. The chemical treatment can enhance the bonding strength between the rubber particles and cement to increase the compressive strength. In addition, the amount added to the concrete mix is another factor to increase the compressive strength. The optimal rubber content can enhance the strength of the rubber concrete, but at the same time, when the rubber content is exceeded or lesser than the optimal rubber content, the rubber concrete strength will drop too (Li, et al., 2019).

2.6.2.2 Flexural Strength

Different rubber replacements, rubber sizes, and types of rubber can influence flexural strength. The rubber replacing the fine aggregate can cause a drop in flexural strength. Nevertheless, the flexural strength will also decrease when the rubber replaces with fine aggregate and cement. However, it has higher flexural strength than rubberised concrete, which is only replaced with a fine aggregate.

Less rubber content replacement can increase flexural strength because rubber can increase its ductility. Rubberised concrete having less rubber content tend to exhibit higher deformation capacity before cracking, allowing it to undergo significant deflections without sudden failure (Li, et al., 2019).

2.6.2.3 Splitting Tensile Strength

The rubber content, mix proportions, and curing conditions can influence the splitting tensile strength. The splitting tensile strength test refers to the ability of the concrete specimen to sustain the tensile forces that are applied to it to cause its split or crack. This test is based on the standard of ASTM C496/C496M. The rubber content in the mix proportion can enhance flexibility, impact resistance, and thermal insulation. However, it may affect the tensile strength of the concrete, as the rubber particles will interrupt the formation of bonding of continuous bonds within the concrete (Li, et al., 2019).

2.6.2.4 Modulus of Elasticity

Modulus of elasticity, also known as Young’s modulus, is a measure of a concrete material’s stiffness or ability to deform elasticity when applied the stress onto the concrete. According to Li et al. research, the rubber particle replacement increases with fine aggregate, and the modulus of elasticity will be decreased. The modulus of elasticity will decrease due to the rubber particles interrupting the formation of continuous bonds within the concrete matrix.

The rubber particles act as a flexible element in the rubber concrete, preventing the stress from transmitting to the concrete. Therefore, the rubberised concrete has a low modulus of elasticity compared to OPC, and it is more flexible and can stretch greater under stress.

2.7 Advantage and Disadvantage of Adding Rubberised Particles into Concrete

Table 2.7 shows the pros and cons of adding rubberised particles to the concrete. As the rubber particles are added to the concrete, rubber particles act as a replacement for coarse aggregate and fine aggregate, which can cause the concrete's characteristics to differ.

Table 2.7: Pros and cons of adding rubberised particles to the concrete.

Advantages	Disadvantages
Rubberised concrete is resistant to damage from vibration, impact, and other stresses.	Rubberised concrete is expensive than the traditional concrete due to the extra process of discarded the waste tire into crumb rubber.
Adding rubberised particles into the concrete can results concrete become flexible, reducing the risk of cracking and increase the ability to sustain seismic load.	Rubberised concrete is difficult to mix and may need specialised equipment to be used, which can cause the time of construction become longer and extra cost to be needed.
Rubberised concrete can provide a better sound absorption than traditional concrete.	Adding of rubberised particles into the concrete may decrease the compressive strength of the concrete and making it not suitable for certain application such as sustain the heavier load.
Environmental benefits because recycle of waste tires will be used as the rubberised concrete which can lead to reduce of waste.	Limited availability because not every place available for rubberised particles.

2.8 Influence of Rubber Addition to Traditional Concrete

One of the most outstanding and flexible building materials is Portland cement. Nevertheless, due to its flexible building material, some researchers modify its properties by adding rubber particles into the Portland I concrete during the mixing process. The rubber particles and Portland I concrete can be combined by developing techniques combining concrete and polymer technology (Albano, et al., 2005).

According to Dessouki et al. conducted research on developing composites using Portland cement and natural rubber latex to create polymeric moulds. The study focused on factors affecting the preparation process, such as the concentration of each component, additives formation, mixing time, and the effect of sodium metasilicate, a retarding agent. The addition of the retarding agent to the rubber increased the time needed for moulding without affecting the concrete. However, increasing the water content reduced the strength of the material, and a higher rubber portion was found to reduce compressive strength while promoting tensile strength. Despite this, the researchers concluded that cement-natural rubber moulds have great potential in the construction industry, particularly for injecting soil and filling cracks and gaps.

The experiment involved creating a conventional concrete compound using water, concrete, and fine and coarse aggregates. Natural sand was used as the fine aggregate, and crush stones of the same average size were used as the coarse aggregate. Table 2.8 depicts the mix proportion for traditional concrete without and with 5% and 10% weight of rubber. Portland Type I cement and scrap rubber from waste tyre treads were used, with the w/c ratio kept constant. The study replaced a portion of the fine aggregate with scrap rubber, using weights of 5% and 10% with particle sizes of 0.29mm and 0.59mm. Traditional mix methods were used to obtain rubber composites with a slump test value between 6cm and 10cm, and a compressive strength of 280kg/cm^2 at 28 days. (Albano, et al., 2005).

Table 2.8: Mix proportion for traditional concrete without and with 5% and 10% weight of rubber (Albano, et al., 2005).

Materials	**Traditional Concrete (TC)**	**CSRM with 5 wt% of Scrap Rubber**	**CSRM with 10 wt% of Scrap Rubber**
Cement (kg)	18.8	18.8	18.8
Water (kg)	9.2	9.2	9.2
Sand (kg)	53.6	47.7	41.8
Stone (kg)	35.7	35.7	35.7
Scrap rubber (kg)	-	5.9	11.8

According to Albano et al. reported that the addition of rubber to concrete mixtures leads to a reduction in the compressive strength of the concrete. The slump test, which measures the workability of the concrete, was also affected by the addition of rubber. The slump test value decreased from 8cm for the traditional concrete mixture to 1cm for the mixture with 5% weight rubber content and continued to decrease by 0.5cm for every 1% increase in weight rubber content up to 10%. The researchers concluded that as the weight of the rubber content in the concrete increases, the compressive strength of the concrete decreases.

2.9 Influence of Rubber Particles in Foam Concrete

Foam concrete (FC) is a type of lightweight cellular concrete that contains discrete or entrained foam to create random air voids. It has a low density, typically ranging from 400kg/m^3 to 1850kg/m^3.There are many advantages compared to traditional concrete, such as low density, minimal aggregate consumption and high fluidity. High strength-to-weight ratio, outstanding thermal insulation, strong fire resistance, and excellent sound insulation are just a few of the additional benefits of foam concrete. Furthermore, compared to conventional concrete, FC has a lower strength and elastic modulus. FC has fundamental and auxiliary components, just like all other types of concrete (Eltayeb, et al., 2020).

Foam concrete is typically made using a mixture of cement, fine aggregate (such as sand), water, and foaming agents. However, supplementary materials such as silica fume, fly ash, fibres, and superplasticizers may also be added. The choice of filler materials can also vary, including fly ash, standard sand (coarse, fine, or mixed sizes), natural sand mixed with stone, and very fine sand. The proportion and mixing technique of these materials can significantly affect the quality of the resulting foam concrete. Various parameter like type of cements, w/c ratio, sand quality, sand/cement ratio and foaming agent used can also impact the characteristic of the foam concrete. Additionally, foam concrete can enhance its fresh and hardening qualities by adding concrete additive like fly ash, fibres, silica fume, and other water-reducing compound during the mixing process (Eltayeb, et al., 2020).

Numerous researchers have studied the effects of adding rubber particles to foam concrete. The results show that the partial replacement of rubber particles for aggregates in FC can improve its toughness, ductility, impact resistance, energy dissipation, and damping ratio. However, it can also decrease its compressive strength, tensile strength, and modulus of elasticity when compared to regular concrete. The reduction in strength is attributed to the lower stiffness of rubber particles compared to traditional aggregates. Nonetheless, this drawback can be mitigated by the increased ductility and toughness of the concrete, which may be beneficial in applications where crack resistance and energy absorption are critical, such as in earthquake-prone regions. Additionally, the thermal insulation properties of foam concrete can be further enhanced by adding rubber particles, making it an eco-friendly and sustainable alternative to traditional concrete (Gupta, et al., 2014).

Various studies have investigated the effects of incorporating rubber particles into foam concrete (FC) and have found that while it can improve toughness, ductility, impact resistance, energy dissipation, and damping ratio, it can also lead to a decrease in compressive strength, tensile strength, and modulus of elasticity when compared to regular concrete. According to Kashani et al. found that specimens with 10% rubber had a 10% reduction in compressive strength, but the rubberised specimens showed 100% porosity, deficient water absorption, and excellent sound and thermal insulation. Similarly, Eltayeb et al. observed a decrease in FC density as the proportion of rubber particles in the mix increased. They also found that the compressive strength and elasticity modulus decreased, while the rate of splitting tensile strength increased and decreased beyond a total rubber content of 17%. Despite these drawbacks, high-percentage rubber FC can provide additional advantages such as low water absorption and superior acoustic and thermal insulation. Studies have also investigated different rubber pre-treatment techniques, such as covering the rubber particles with silica fume, to increase compressive strength. Figures 2.7 and 2.8 show the effect of rubber replacement on FC compressive strength.

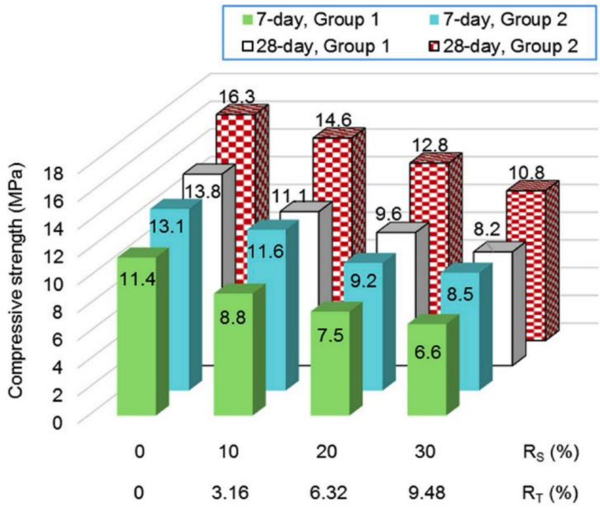

Figure 2.7: Effect of Rubber Replacement on FC Compressive Strength (Eltayeb, et al., 2020).

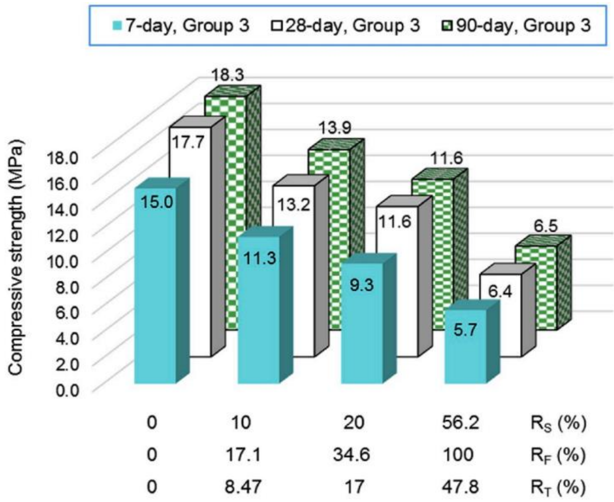

Figure 2.8: Effect of Rubber Replacement on FC Compressive Strength (Eltayeb, et al., 2020).

2.10 Introduction to Rubberised Lightweight Foamed Concrete

Rubberised lightweight foamed concrete is a mixture of cement, water, foam agent, fine aggregate, and rubber particles. The amount and size of rubber particles added to the mix can alter the properties of the resulting concrete. Kashani et al. found that increasing the size or amount of rubber particles used to replace the fine aggregate led to a decrease in compressive strength and workability. Larger rubber particles required more cement paste to fill spaces around them, which could make the mix harder to work with and produce weaker areas inside the matrix of the concrete, potentially lowering its strength. On the other hand, smaller rubber particles could be easier to mix and might result in a more uniform distribution, enhancing the mix's workability and strength.

Although the addition of rubber particles can reduce the overall strength of the concrete since they do not provide as much mechanical support as fine aggregate, they can enhance energy absorption and impact resistance if they are well-distributed within the mix. Kashani et al. also provided samples of lightweight foamed concrete with 10wt%, 20wt%, and 30wt% rubber added, which showed black spots as concrete pores, light grey spots as hydrated cement, and dark grey spots as tyre particles. Figure 2.9, Figure 2.10, Figure 2.11 and Figure 2.12 show the microstructure of the lightweight foamed concrete with differences in rubber content, which are control mix, 10wt%, 20wt%, and 30wt% of rubber added into the lightweight foamed concrete.

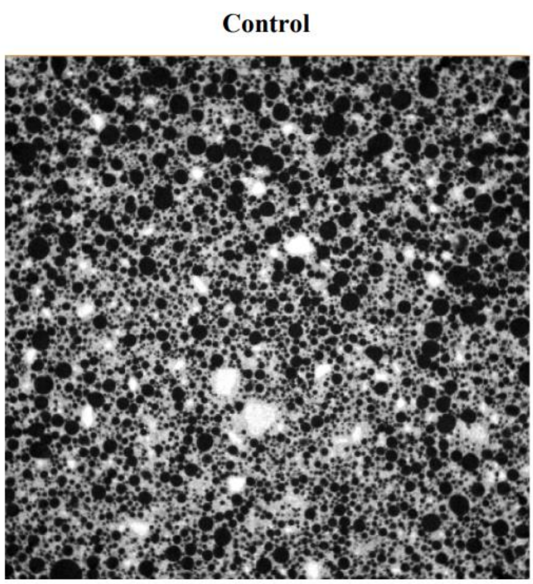

Figure 2.9: Normal Lightweight Foamed Concrete (Kashani, et al., 2017).

10% RTC

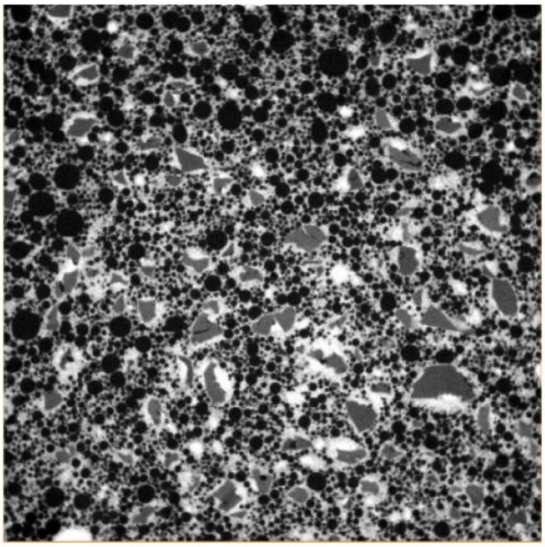

Figure 2.10: Lightweight Foamed Concrete Content 10% Rubber Particles (Kashani, et al., 2017).

20% RTC

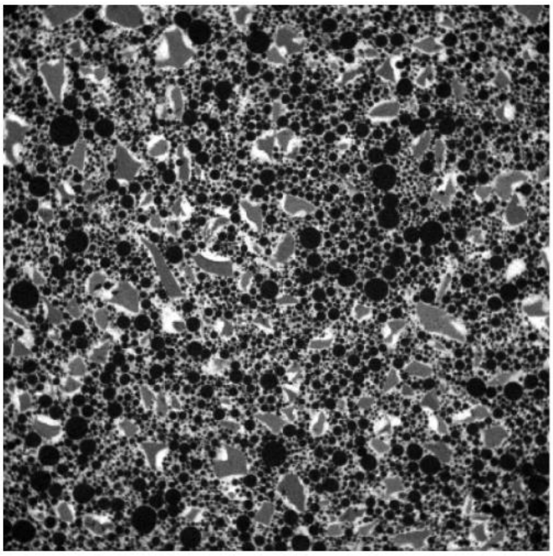

Figure 2.11: Lightweight Foamed Concrete Content 20% Rubber Particles (Kashani, et al., 2017).

30% RTC

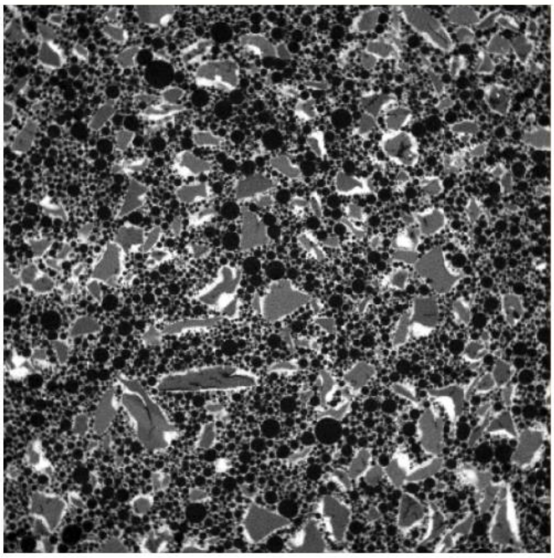

Figure 2.12: Lightweight Foamed Concrete Content 30% Rubber Particles (Kashani, et al., 2017).

2.11 Factors Affect the Compressive Strength of Rubberised Lightweight Foamed Concrete

The compressive strength of the concrete will be influenced by several factors, which measure its ability to withstand compression forces. These factors are considered because the good mix proportion of the concrete can produce great compressive strength performance.

2.11.1 Cement

Cement is the main material in concrete, as the amount and chemical content in the cement can determine its strength. The compression strength will be better and tougher when the amount of cement increases. At the same time, it is the same as the chemical content in the cement too. Because different brands of OPC cement got different chemical content, which can lead to the quality products of the specimens (Kumar, et al., 2009). The variations can affect the performance and properties of the cement, including compression strength. The difference in the chemical deposition of cement can influence the rate of hydration and formation of hydration products, which ultimately contribute to the compressive strength of the concrete.

2.11.2 Rubber Content

The difference in the rubber content can influence the compressive strength of the concrete due to the relationship between them is inversely proportional. As the rubber content replacements increase, the compressive strength will decrease, which is happening due to some factors.

One of the factors is rubber particles having a different surface texture compared to fine aggregate. This factor will lead to the interfacial bonding between the cement matrix and the rubber content. As the boding is different, the concrete's cohesion and compressive strength can be affected, causing the compressive strength to decrease (Raffoul, et al., 2016).

Next, the rubber particles are light in weight and more porous than the fine aggregate. When the replacement between the rubber and fine aggregate, it can affect the void and porosity within the concrete (Raffoul, et al., 2016). As the replacement of the rubber increases, the additional void and porosity within the concrete will be increased. It will tend to reduce the compressive strength of the concrete and result in lower compressive strength.

2.11.3 Water to Cement Ratio (W/C Ratio)

The w/c ratio refers to the water weight to the cement weight used in the mixture. The relationship between w/c ratio is inversely proportional to the compressive strength. Because when the w/c ratio is higher, the water will dilute the cement paste and weaken the concrete, resulting in lower compressive strength. Besides that, the chemical reaction between water and cement will produce hydration products such as C-S-H gel, which will contribute to the compressive strength and durability of the concrete. If the w/c ratio is low and causes insufficient water in the mix can obstruct the hydration process, which leads to incomplete hydration and strength development (Kondraivendhan, et al., 2016). Excessive water will affect the porosity and density of the concrete. Thus, excessive voids and porosity can weaken the concrete matrix and lower the compressive strength.

2.11.4 Concrete Curing

Concrete curing refers to maintaining moisture and temperature conditions in freshly placed concrete to promote hydration and development of its desired properties. Water curing can help to promote the hydration process of cement. Adequate moisture allows cement particles to react chemically by forming hydration products that contribute to the compressive strength of the concrete. During the curing process, the presence of moisture ensures complete hydration so that it can achieve optimal strength development over time. Water curing can help to prevent shrinkage from happening in concrete. Shrinkage happens as water evaporates from the concrete, causing its volume reduction and potential development crack. Water curing can minimise the formation of cracks and preserve the compressive strength of the concrete. The proper curing method is very crucial in the steps of storing the concrete. Because proper curing can promote the development of a dense and durable concrete matrix, the water curing process can help to enhance its resistance and lead the concrete to be more compact and less porous due to the formation of hydration products (Safiuddin, et al., 2007).

2.12 Application of Rubberised Lightweight Foamed Concrete

Rubberised lightweight foamed concrete provides outstanding characteristics for some construction applications, such as road and bridge foundations, slope stabilisation, retaining walls, and as a lightweight fill material.

2.12.1 Road and Bridge Foundation

Rubberised lightweight foamed concrete might be an ideal material for road and bridge foundations due to its unique mix of characteristics. One of the characteristics of rubberised lightweight foamed concrete is significantly lighter than traditional concrete, making it an ideal material for bridge foundations. Rubberised lightweight foamed concrete can help reduce the bridge's overall weight, improving its structural integrity and reducing the risk of collapse. Next, the impact resistance of the concrete can be increased by including rubber particles in the mix. It might be especially crucial for the foundations of roads and bridges, which may be subjected to significant loads and impacts over time. Moreover, rubberised lightweight foamed concrete has been found to have excellent energy absorption properties, which can help reduce the risk of damage and collapse in an earthquake or other natural disaster. Other than that, the road and bridge's thermal and acoustic insulation capabilities can also be enhanced using rubberised lightweight foamed concrete in the foundations. It may help lower noise pollution and enhance the building's energy effectiveness (Kist and Kigali, 2008). Therefore, its lightweight, improved impact resistance, energy absorption properties, and thermal and acoustic insulation make it an attractive alternative to traditional concrete.

2.12.2 Slope Stabilisation

Rubberised lightweight foamed concrete might be helpful in stabilising slopes because it is significantly lighter than traditional concrete, making it an ideal material for slope stabilisation. Its lightweight nature reduces the slope's overall load and helps prevent further slope movement. Next, the high porosity of rubberised lightweight foamed concrete makes it simple for water to drain. It is crucial for stabilising slopes since too much water can cause erosion and instability. Besides that, in the case of an earthquake or other natural disaster, rubberised lightweight foamed concrete has been proven to offer excellent energy absorption qualities that can assist in lessening the danger of damage and collapse. Furthermore, rubberised lightweight foamed concrete is more flexible than traditional concrete, which can help it better conform to the slope's contours. Rubberised lightweight foamed concrete may increase its efficiency in stabilising slopes with complicated geometries or irregular shapes (Kist and Kigali, 2008).

2.12.3 Retaining Wall

Due to its lightweight qualities, rubberised lightweight foamed concrete is an excellent choice for retaining walls. It can help to avoid wall failure caused by excessive pressure by reducing the load on the soil behind the Wall. Rubberised lightweight foamed concrete has been found to have good energy-absorbing properties, which can assist in reducing the risk of damage and collapse in the event of an earthquake or other natural disaster (Qiu, et al., 2021). Next, the porous nature of rubberised lightweight foamed concrete makes it simple for water to drain. It is crucial for retaining walls since excess water can cause erosion and instability. Finally, the rubberised lightweight foamed concrete is more flexible than conventional concrete. It may be more capable of adapting to the curvature of the retaining wall. As a result, it may be more effective in stabilising walls with complicated geometries or irregular shapes.

2.12.4 Summary

Due to its unique qualities, rubberised lightweight foamed concrete is particularly beneficial. However, even though most people of the older generation may not accept this material, it proves that rubberised lightweight foamed concrete has brought several advantages over regular concrete, especially considering its lightweight and better energy absorption. Furthermore, utilising rubberised lightweight foamed concrete is environmentally friendly since it may minimise waste tyres (recycling method) and the shortage of natural resources (sand) needed in the building industry because of the high demand for manufacturing.

2.13 Introduction to DT and NDT

The DT and NDT are used to obtain results on the concrete's compressive strength. A DT is a testing method used to analyse the physical properties of a material or component by subjecting it to stress or loading until it reaches its maximum limit of strength and its crack. DT is done by damaging or breaking the material to obtain performance, durability, and reliability data.

Construction, aerospace, automotive, and industrial industries adopt DT to evaluate materials or products to find faults or weaknesses. While for NDT is a method utilised to analyse the physical properties of a material or component without causing any damage to it. NDT involves varying techniques to evaluate the material or component and detect defects or irregularities. NDT generally ensures the safety, reliability, and quality of various components, such as pipes, bridges, welds, aircraft parts and nuclear reactors. NDT is frequently utilised as a preventative tool by enabling the early identification of possible issues before they develop into catastrophic failures (Oke, et al., 2017).

2.13.1 Destructive Test (DT)

DT can carry out many tests, such as compressive tests, splitting tensile tests, flexural strength tests and ductility. These tests can be done by subjecting loads or forces into the specimens until they fail to obtain the result (Malek & Kaouther, 2014). DT are typically used for quality control, research or evaluate the material's suitability in the construction field.

2.13.2 Non-Destructive Test (NDT)

The NDT is one of the most convenient methods to evaluate the compressive strength of a large structure. NDT can be utilised everywhere without delivering it to the lab for compressive strength tests. NDT can evaluate the present structures of walls, columns and beams. Because the NDT test can analyse the strength and performance of the concrete structure without bringing any damage to the structure as DT does. For example, cracking of the concrete can be detected via the NDT test (Ramesh, et al., 2020).

2.13.2.1 Ultrasonic Pulse Velocity (UPV Test)

This method predicts the compressive strength and dynamic modulus of elasticity of the concrete in situ. UPV also can be applied to evaluate the quality of the concrete and detect any defects, durability and internal cracking. UPV test is based on the standard of ASTM C 597. UPV test is set up by using a transmitting and receiving transducer attached to the concrete specimen on the opposite side of the concrete surface. Then, the transmitting transducer will transmit the high-frequency sound wave through the concrete specimen to the receiving transducer (Helal, et al., 2015). The travelling time between both transducers can be used to determine the concrete's quality by using its length to divide the travelling time to get the pulse velocity (Ramesh, et al., 2020). Table 2.9 shows the measure of how to decide the quality of the concrete.

Table 2.9: Quality of Concrete (Ramesh, et al., 2020).

Velocity of Pulse (km/sec)	**Quality of Concrete**
> 4.5	Very Good
< 4.5	Good
< 3.5	Medium
< 3.0	Weak

Furthermore, the compression wave velocity can be determined by using dynamic Poisson's ratio and modulus of elasticity by using the equation 2.1 (Kencanawati, et al., 2018).

$$V = \sqrt{\frac{KE}{\rho}} \tag{2.1}$$

where,

$V =$ compressional wave velocity, m/s

$K = \frac{(1-\mu)}{[(1+\mu)(1-2\mu)]}$; $\mu =$ dynamic Poisson's ratio.

$E =$ dynamic modulus of elasticity, GPa

$\rho =$ density, kg/m^3

2.13.2.2 Impact-Echo Method

The impact-echo method is a NDT method that uses a mechanical impact to introduce a stress pulse into a structure, which travels through the structure as P- and S-waves and along the surface as an R-wave. This method follows the guideline of ASTM C 1383-04 (Helal, et al., 2015). The reflections of these waves are detected by a sensor on the structure's surface to estimate the location and size of internal defects and evaluate the structure's compressive strength. P-waves are of primary importance in plate-like structures as they provide accurate information about the structure's condition. The frequency of P-wave arrivals can be determined using the FFT technique, which allows the analysis of a signal in terms of its frequency components to identify any anomalies or defects within the structure. The thickness frequency and the frequency of cross-sectional vibration modes can also be calculated using specific formulas, and the details of the calculation will be listed in Equation 2.2, Equation 2.3 and Equation 2.4 (Hsiao, et at., 2008).

$$D = \frac{C_p}{2f} \tag{2.2}$$

where,

f = frequency, s^{-1}

D = depth of internal defect, m

C_p = speed of P-waves, m/s

The thickness frequency can be determined by using this formula:

$$f_t = 0.96\left(\frac{C_p}{2T}\right) = \frac{0.96C_p}{2T} = \frac{C_{p,plate}}{2T} \tag{2.3}$$

where,

f_t = frequency of thickness, s^{-1}

T = thickness of the plate

$C_{p,plate}$ = speed of P-waves in the concrete plate

For a solid square bar, the frequency of the fundamental mode f_D is related to the P-wave speed in an infinite medium, C_p, and the cross-sectional dimension, D, as follows:

$$f_D = \frac{0.87C_p}{2D} \tag{2.4}$$

Another three higher modes have the frequencies given by $1.4f_D$, $1.9\ f_D$, and $2.4f_D$ (Hsiao, et at., 2008).

2.13.2.3 Rebound Hammer Test

The rebound hammer test is a popular NDT method because it can predict the service life and the structure's compressive strength. It is famous because it costs low and simple to operate the test. The rebound hammer test is based on the standard of ASTM C 805. This test evaluates the surface hardness of the concrete to determine the strength of the concrete. For example, the number of rebounds is low, indicating that the concrete surface is soft and weak (Helal, et al., 2015). Unsurprisingly, there is no theoretical connection between concrete strength and surface hardness. Table 2.10 shows the grade of the concrete surface.

Table 2.10: Grade of the concrete surface (Ramesh, et al., 2020).

Number of Rebound Hammer	**Grade of the Concrete Surface**
Above 40	Very Good
< 40	Good
< 30	Fair
< 20	Poor Concrete
0	Delaminated

2.14 Elastic Wave Method

Concrete is a complex composite material because it comprises 75% of the concrete volume from aggregate, 15% of the concrete volume is cement, and another 10% is water (Lawson, et al., 2011). The strength of concrete is a critical factor to consider when designing the mix proportion or grade of concrete for various applications. It is important to design the concrete appropriately, as it can lead to unnecessary expenses during construction. The compressive strength of concrete is typically evaluated through DT or NDT methods using concrete specimens on the 7th and 28th day. In this study, ultrasonic pulse velocity is chosen as a reliable and accurate elastic wave NDT method for evaluating the compressive strength of concrete cube specimens. This method uses ultrasonic waves to locate and evaluate defects that can affect the compressive strength of concrete, such as cracks, voids, and debonding (Aggelis, et al., 2012).

Traditionally, P-wave pulse velocity is the most popular to be applied to the concrete structure analysis due to its ease of generating and handling to obtain the result. However, the P-wave velocity is weaker than S-wave and R-wave because its energy is much lesser than S-wave and R-wave (Lee & Oh, 2016).

2.14.1 P-waves (Pressure Waves)

P-waves are applied to analyse the concrete structure's compressive strength, elastic modulus, and defect. This analysis can be done by using the reflected wave or velocity of the elastic wave to evaluate the quality of the concrete. Equation 2.5 can be used to calculate the P-wave velocity generated by the UPV system (Park, et al., 2019).

$$V_p = \sqrt{\frac{E(1-v)}{\rho\,(1+v)(1-2v)}} \tag{2.5}$$

where,

V_p = velocity of P-wave, m/s

v = dynamic Poisson’s ratio.

E = dynamic modulus of elasticity, GPa

ρ = density, kg/m^3

There are two types of pressure waves, which are direct and indirect transmission. Direct transmission refers to pulse-echo and through transmission. Typically, the transmission will be applied by using the wave to pass through the concrete specimen from one surface of the transmission sensor to the opposite surface of the receiver sensor. For the pulse-echo method, the transmitter transducer sends and receives the pulsed waves. Indirect transmission refers to the transmitters being located on the same surface, and it will be applied to the situation when cracking occurs on the surface of the concrete structure (Lee & Oh, 2016).

2.14.2 S-waves (Shear waves)

S-waves are also known as transfer waves due to the propagation being perpendicular to the direction of the wavefront. S-wave has about 60% wave velocity compared to P-wave. However, MIRA equipment will be used to measure S-waves by obtaining the shear wave tomography. The MIRA system is not the same as pulse-echo methods due to this system does not need any coupling agent to carry out the UPV test. Nevertheless, the MIRA system is still based on the standard ultrasonic pulse-echo principle to operate. Equation 2.6 will be used to calculate the velocity of S-waves that pass through the concrete specimen (Lee & Oh, 2016).

$$V_s = \sqrt{\frac{E}{2(1+v)\rho}} \tag{2.6}$$

where,

$V_s =$ velocity of S-wave, m/s

$v =$ dynamic Poisson’s ratio.

$E =$ dynamic modulus of elasticity, GPa

$\rho =$ density, kg/m^3

2.14.3 R-waves (Rayleigh waves)

R-wave velocity can be obtained by calculating the time difference between the first and second peaks of two receivers. However, using this method easily occurs systematic error. The dispersion curve of Lamb waves will be generated with MASW to prevent the systematic error from occurring. The data collection of MASW is based on the N-wave signals. Equation 2.7 will be used to calculate the R-wave velocity that travels along the free surface of the concrete (Lee & Oh, 2016).

$$V_R = \frac{0.87+1.12v}{1+v}\sqrt{\frac{E}{\rho}\frac{1}{2(1+v)}} \tag{2.7}$$

where,

V_R = velocity of R-wave, m/s

v = dynamic Poisson's ratio.

E = dynamic modulus of elasticity, GPa

ρ = density, kg/m^3

2.15 Summary

To summarise, the literature review provides an understanding and overview of rubberised lightweight foamed concrete, highlighting its differences from traditional concrete, the testing methods used to evaluate its compressive strength, and the various NDT methods available for quality control. Additionally, the review discusses potential applications of rubberised lightweight foamed concrete in construction projects. Furthermore, introduction of DT and NDT tests are listed to explain it deeply about the tests for the use in the construction field. Besides that, the literature review also presents the elastic wave method (UPV test) because this method is the NDT that will be used for this study for evaluate the compressive strength test.

Rubberised lightweight foamed concrete is an environmentally friendly material in the construction industry. Rubberised lightweight foamed concrete can help reduce the waste tyres in the earth and reduce the use of the natural resource (sand) during the casting of the concrete for the development of commercial and infrastructure nowadays. Moreover, rubberised lightweight foamed concrete also bring advantage to daily life. This concrete is light in weight, noise reduction, thermal insulation, and others.

In this study, rubberised lightweight foamed concrete will be used to evaluate the concrete's compressive strength by using a different portion of rubber content to replace the fine aggregate and the different w/c ratio of water during concrete mixing. Because rubberised lightweight foamed concrete can be designed for the application used for the structural and slowly replace traditional concrete to reduce the environmental impact.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The methodology for this research aims to forecast the compressive strength of the rubberised lightweight foamed concrete with a fresh density of 1350kg/m3. To achieve this goal, many cube specimens were cast. Cylinder and Prism specimens were added to this research to evaluate the splitting tensile and flexural strength tests. Figure 3.1 shows the overall workflow to carry out this study.

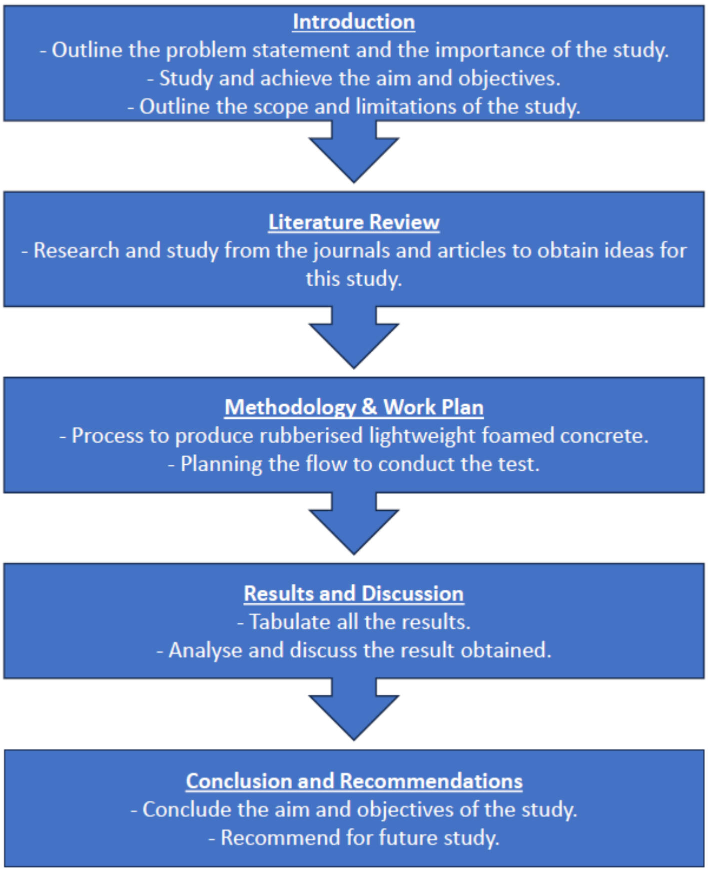

Figure 3.1: Overall Workflow

The methodology process of producing rubberised lightweight foamed concrete has undergone some stages: preparation of materials, mixing technique, casting process, demoulding process, curing process, and evaluation via some tests. Cube specimens was undergoing a compressive strength test using DT and NDT tests, cylinder specimens underwent a splitting tensile test, and prism specimens underwent a flexural strength test. The procedure to produce rubberised lightweight foamed concrete is shown in Figure 3.2.

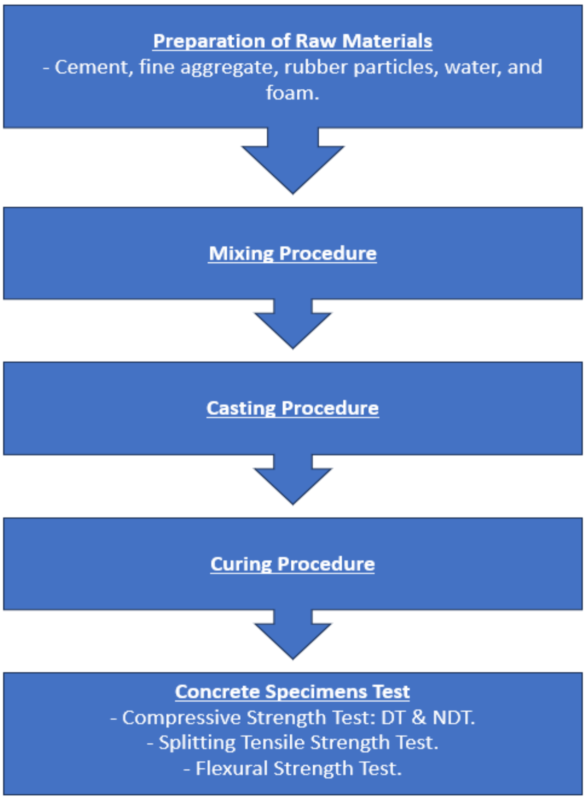

Figure 3.2: Methodology Flow Chart

3.2 Preparation of Raw Materials

In this study, there is a total of five materials that have to prepare before proceeding to the mix of the concrete process. The five materials are cement, fine aggregate, rubber particles, water and a foaming agent.

3.2.1 Cement

Ordinary Portland Cement (OPC) type 1 was used in this research, as shown in Figure 3.3. This YTL 'Orang Kuat' cement is the brand of OPC used in this study with the Malaysia Standard of MS EN 197-1, CEM1. The OPC should be sieved with a 600-micron meters sieve before using it for casting. The amount used for the casting was calculated so that the correct amount of cement was prepared and then stored in an airtight container to prevent the cement from having a hydration process with humid air.

Figure 3.3: Ordinary Portland Cement (YTL)

3.2.2 Fine Aggregate

The fine aggregate used to mix the rubberised lightweight foamed concrete is sand, as shown in Figure 3.4. The sand used must be according to the standard of ASTM C33 (ASTM, 2011). The amount of sand needed was calculated. Sand can be prepared by oven drying at about 100°C for 24 hours to ensure the sand is dry without containing water inside the sand. After the sand was oven-dried, 600-micron meters of sieve were used, and the sand was sent to the container to store it.

Figure 3.4: Fine Aggregate

3.2.3 Rubber Particles

Rubber particles are a type of crumb rubber that is manufactured from recycled waste tyres, as shown in Figure 3.5. This study chose rubber powder as a rubber particle with a size of 0.42mm. The rubber particles were prepared by following the proportion that needed to be replaced with the fine aggregate with the ratio of 0% to 70% increment of 10% for each set of specimens.

Figure 3.5: Rubber Particles

3.2.4 Water

According to ASTM C1602, the water used should be clean, which means do not contain any impurities in the water with a suitable pH value (Mohammed, et al., 2017). In this study, the water resources used were collected from tap water. The proportions and volume needed for the water were calculated based on the w/c ratio from 0.50 to 0.70 with an increment of 0.05, respectively.

3.2.5 Foaming Agent

SikaAER®-50/50 was used as a foaming agent in this study as shown in Figure 3.6. This foaming agent was chosen because it can produce a stable foam according to the standard of ASTM C796 (ASTM, 2012). Every batch of foam needed for the mixing process is calculated to ensure that the quality of the foam is in good condition. If the foam generator produces the foam for a more extended period, the foam can be affected and cause the foam quality to be reduced. It may result in the rubberised lightweight foamed concrete having an unstable density that may cause it to be out of the density tolerance range. The foam should be added slowly to avoid the concrete density dropping too fast.

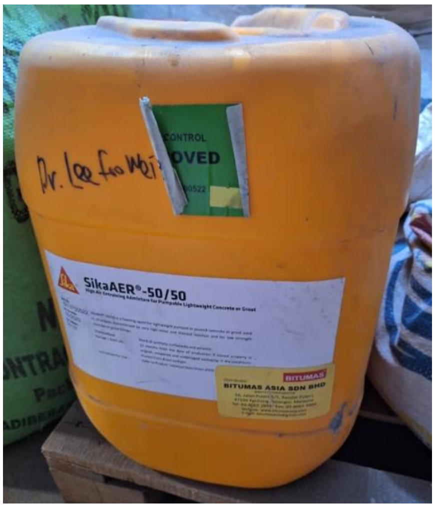

Figure 3.6: Sika Foaming Agent

3.3 Procedure to General Foam Agent

In order to obtain foam, the foam generator in the UTAR Civil Engineering Lab can be utilised. However, before generating foam, permission must be obtained from the lab assistant and the help of a tutor is needed. The methodology for generating foam involves several steps. Figure 3.7 shows the foam generator used in this study. Figure 3.8 shows that stable foam is produced.

Firstly, the concentration of the foaming agent needed must be prepared and calculated. Then, the foaming generator must be cleaned thoroughly using compressed air and water to ensure that the foam produced is stable and consistent.

Next, the foaming agent is poured into the foam generator and allowed to dilute with water at a ratio of 1:20 (1 representing the amount of foaming agent and 20 representing the water). All the valves are then closed and compressed air is filled into the foam generator.

Stable foam agent is obtained when the foam generator achieves 0.5MPa. However, the first batch of foam must be discarded due to its instability. The foam agent can then be collected from the wire mesh. Finally, the foam generator must be cleaned after the casting work. Following these steps carefully ensures that high-quality foam agent is obtained, and the foam generator is kept in good condition for future use.

Figure 3.7: Foam Generator

Figure 3.8: Stable Foam

3.4 Mould

In this study, three types of mould were prepared: cube, cylindrical, and prism shaped. Because the different shapes of specimens can be tested for different properties, such cubes are tested for compressive strength, cylindrical are tested for splitting tensile strength, and prisms can be tested for flexural strength according to ASTM and BS codes standards. The size of the mould was mentioned:

1. Cube: 100mm (length) x 100mm (width) x 100mm (height)
2. Cylinder: 100mm (diameter) x 200mm (height)
3. Prism: 500mm (length) x 100mm (width) x 100mm (height)

There are some precautions to be taken before the casting process. First, all screws and nuts should be tightened tightly to prevent the water from the concrete from being linked. Next, the moulds should be adequately cleaned using a scraper and pressure cleaner to prevent previously cast concrete from sticking in the mould. The third precaution was applying oil inside the mould with a brush to ease the de-moulding work as shown in Figure 3.9.

Figure 3.9: Apply Oil Before Casting

3.5 Mix Proportions

The concrete specimens prepared in this study were two hundred and eighteen specimens. One hundred and sixty cubes were undergoing the compressive strength test for DT, and forty were undergoing the NDT test. The remaining specimens were nine prism specimens that underwent a flexural strength test, and another nine-cylinder specimens underwent a splitting tensile strength test. The specimens were divided into five w/c ratios, which are 0.50, 0.55, 0.60, 0.65, and 0.70. The cube specimens need to prepare five cubes for each proportion. In each of the w/c ratios, the fine aggregate replaces rubber particles with eight different replacement rubber content, which is from 0% to 70%, with the increment of each set is 10%. The 0% of rubber content was known as the control mix. While for the prism and cylinder specimens were less because of the addition of specimens, which were three for control of w/c 0.60, three for 40% rubber content of w/c 0.60 and three for 70% rubber content of w/c 0.60, respectively.

The concrete specimens had the same targeted density of 1350kg/m^3. Therefore, the mix proportion for all concrete specimens was calculated and mentioned in the Tables 3.1 to 3.5, Table 3.6 and Table 3.7—the amount needed in the mix proportion table for each specimen.

3.5.1 Mix Proportion for Cube Specimens

Tables 3.1 to 3.5 show the mix proportion needed for the cube specimens for each water-to-cement ratio with differences in rubber replacement to fine aggregate. The water-to-cement ratio is from 0.50 to 0.70, and the rubber replacement content is 0% to 70%.

Table 3.1: Amount of Mix Proportion for w/c 0.50.

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	533.47	533.47	266.74	0.00	16.32	1350
10	546.54	491.89	273.27	22.69	15.61	1350
20	560.27	448.21	280.13	46.51	14.88	1350
30	574.70	402.29	287.35	71.57	14.10	1350
40	589.89	353.93	294.95	97.94	13.28	1350
50	605.91	302.96	302.96	125.76	12.42	1350
60	622.83	249.13	311.41	155.12	11.51	1350
70	640.71	192.21	320.36	186.17	10.55	1350

Table 3.2: Amount of Mix Proportion for w/c 0.55.

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	523.26	523.26	287.79	0.00	15.69	1350
10	535.83	482.24	294.70	22.24	14.98	1350
20	549.01	439.21	301.96	45.58	14.25	1350
30	562.86	394.00	309.57	70.09	13.47	1350
40	577.43	346.46	317.59	95.87	12.65	1350
50	592.77	296.38	326.02	123.03	11.79	1350
60	608.95	243.58	334.92	151.66	10.89	1350
70	626.03	187.81	344.32	181.90	9.93	1350

Table 3.3: Amount of Mix Proportion for w/c 0.60.

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	513.43	513.43	308.06	0.00	15.08	1350
10	525.52	472.97	315.31	21.81	14.38	1350
20	538.20	430.56	322.92	44.68	13.64	1350
30	551.50	386.05	330.90	68.68	12.87	1350
40	565.48	339.29	339.29	93.89	12.05	1350
50	580.19	290.09	348.11	120.42	11.19	1350
60	595.68	238.27	357.41	148.36	10.29	1350
70	612.02	183.60	367.21	177.83	9.34	1350

Table 3.4: Amount of Mix Proportion for w/c 0.65.

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	503.96	503.96	327.58	0.00	14.50	1350
10	515.61	464.05	335.15	21.40	13.80	1350
20	527.81	422.24	343.07	43.82	13.06	1350
30	540.59	378.42	351.39	67.32	12.28	1350
40	554.02	332.41	360.11	91.99	11.47	1350
50	568.12	284.06	369.28	117.91	10.62	1350
60	582.97	233.19	378.93	145.19	9.72	1350
70	598.61	179.58	389.10	173.94	8.77	1350

Table 3.5: Amount of Mix Proportion for w/c 0.70.

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	494.84	494.84	346.39	0.00	13.94	1350
10	506.06	455.45	354.24	21.01	13.24	1350
20	517.81	414.24	362.46	42.99	12.50	1350
30	530.11	371.08	371.08	66.01	11.73	1350
40	543.01	325.81	380.11	90.16	10.92	1350
50	556.56	278.28	389.59	115.51	10.07	1350
60	570.79	228.32	399.56	142.16	9.17	1350
70	585.78	175.73	410.05	170.21	8.23	1350

3.5.2 Mix Proportion for Prism and Cylinder Specimens

Tables 3.6 and 3.7 show the mix proportion needed for the w/c 0.60 for prism and cylinder specimens.

Table 3.6: Amount of Mix Proportion for w/c 0.60 (Prism)

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	2567.15	2567.15	1540.30	0.00	75.40	1350
40	2827.40	1696.45	1696.45	469.45	60.25	1350
70	3060.10	918.00	1836.05	889.15	46.70	1350

Table 3.7: Amount of Mix Proportion for w/c 0.60 (Cylinder)

Concrete Mixtures	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)	Foam (kg/m^3)	Targeted Fresh Density (kg/m^3)
0	806.09	806.09	483.65	0.00	23.68	1350
40	887.80	532.69	532.69	147.41	18.92	1350
70	960.87	288.25	576.52	279.19	14.66	1350

3.6 Mixing and Casting Process

To cast rubberised lightweight foamed concrete, the materials and equipment needed must be prepared before starting the process. The following steps outline the procedure to cast the rubberised lightweight foamed concrete.

Firstly, the amount of OPC cement, fine sand, rubber particles, and water required for the mixing process is weighed. Then, the cement, fine sand, and rubber particles are poured into the concrete mixing bowl and mixed in the dry state to ease the mixing process as shown in Figure 3.10. After dry mix process is well mix, then added water to the mixing bowl for the wet mix process until the materials inside the mixing bowl is well mix as shown in Figure 3.11.

Next, the stable foam is weighted and added to the concrete mix to ensure that the amount of stable foam required is the same as calculated as shown in Figure 3.12. The stable foam is mixed thoroughly with fresh cement to produce fresh rubberised lightweight foamed concrete with a targeted density of 1350kg/m^3, but there is a $\pm$50kg/m^3 tolerance. The foam is added gradually, and the density of the fresh concrete is weighted by using a 1-litre cylindrical container from time to time to ensure that the rubberised lightweight foamed concrete reaches the target density according to ASTM C 796. Figure 3.14 shows the fresh density measurement.

The cube, cylinder, and prism moulds are tightened, and the surface of the mould is oiled. The fresh concrete mix is transferred to the mould without vibrating the mix as shown in Figure 3.15. The cube, cylinder and prism specimens are left there overnight (about 24 hours) to let the fresh concrete harden before demoulding it.

After demoulding, these specimens are placed into a water tank filled with water for the curing process as shown in Figure 3.16. By following these steps carefully, high-quality rubberised lightweight foamed concrete can be produced.

Figure 3.10: Dry Mix

Figure 3.11: Wet Mix

Figure 3.12: Adding Foam Agent

Figure 3.13: Weighing Foam Agent

Figure 3.14: Fresh Density Measurement

Figure 3.15: Casting Process

Figure 3.16: Curing Process for the Specimens

3.7 Workability of the Concrete Specimens.

The workability of the rubberised lightweight foamed concrete can be determined by using two conventional methods: the flow table test and the inverted slump cone test. Workability is an essential property to analyse and evaluate in concrete because it indicates how easily the concrete can be mixed, placed, compacted and finished during the casting process.

3.7.1 Flow Table Test

Flow table test was used to assess the workability of the rubberised lightweight foamed concrete by measuring the diameter of the concrete mixture spread on the flat circular table when the concrete mixture was touching one of the corners of the flat circular table or with 25 times the number of drops. The test aimed to assess the consistency of the freshly mixed mortar under the standards outlined in ASTM C 1437 (ASTM, 2015). This test is helpful to analyse the flow and spread of the rubberised lightweight foamed concrete mixture by observing whether the mixture has mixed well. Figure 3.17 shows the flow table test.

Figure 3.17: Flow Table Test

3.7.2 Inverted Slump Test

An inverted slump test is another method to assess the workability of the concrete. However, the difference between this study's inverted slump and flow table tests was that the inverted slump test was carried out after adding the foaming agent. This test evaluated the workability of lightweight foamed concrete according to ASTM C 1611 (ASTM, 2005). However, a flow table test is done before adding a foaming agent to the rubberised lightweight foamed concrete mixture.

This test assesses the workability of the lightweight foamed concrete mixture by observing the slumps or sinks when a standard cone is removed. The inverted slump test can help determine whether the mix has the desired consistency and flowability for the rubberised lightweight foamed concrete mixture. It provided valuable information about the concrete's ability to be handled and placed based on the collected data. Figure 3.18 shows the inverted slump test.

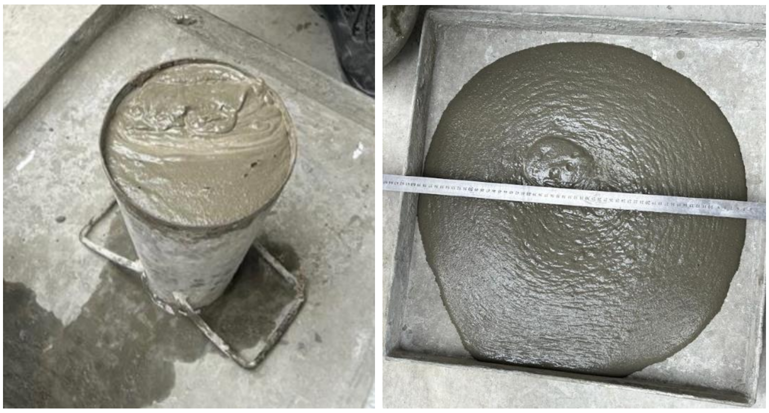

Figure 3.18: Inverted Slump Test

3.8 Curing Process

The curing process is the process that maintains adequate moisture, temperature (16 °C to 27 °C), and time to allow the concrete specimens to achieve their desired strength and durability. Proper curing is essential because it can ensure the concrete specimens develop their full potential in strength and resistance to cause the concrete specimens to crack.

In this study, the concrete specimens were placed into the water tanks for curing after demoulding the concrete. However, the concrete specimens cannot be demoulded and placed into the water tank earlier than 24 hours because it can affect the early strength development of the concrete specimens. On the 7^{th} day, 28^{th} day and 56^{th} day, the concrete specimens were stored in the water tank for curing. Since the concrete specimens were stored in the water tank, the specimens were taken out one day before the day of strength testing to air dry the concrete sample.

3.9 Concrete Specimens Test

This research carried three types of strength tests: compressive strength test, splitting tensile strength test, and flexural strength test. Most tests can be done using the DT method to evaluate and analyse the compressive strength, splitting tensile strength, and flexural strength. However, this study used an ultrasonic pulse velocity test to analyse the compressive strength test using elastic wave software for ultrasonic pulse velocity and some instruments to obtain the results.

3.9.1 Compressive Strength Test

The compressive strength test is an essential part of this study, and it is carried out using two different methods, DT and NDT. The compressive strength test is carried out four times, once on the 1st day, the 7^{th} day, the 28th day, and then on the 56th day after casting the cube specimens. The results obtained from the test were recorded, and the average value ware calculated for each test method. These results were used to generate the results and discuss the research.

3.9.1.1 Destructive Test (DT)

The DT test involving a compression test machine was based on the BS EN 12390-3:2001(E) standard (Standard, B., 2009). To conduct this test, the first step is to measure the cross-sectional area of the concrete cube specimens because the cross-sectional area of the cube specimens can affect the result of compressive strength. Next, it is essential to use the flat surface of the cube specimens to locate in the compressive test machine to ensure the load applied is distributed evenly.

The testing procedure is conducting the test by placing the cube specimens into the machine and applying a compressive load to the cube specimen until it fails, as shown in Figure 3.19. The maximum load applied to the cube specimens was recorded during this process. The maximum load recorded was used to calculate the compressive strength using Equation 3.1 below.

$$f_{ck} = \frac{P}{A} \tag{3.1}$$

where,

$f_{ck} = compressive\ strength, kN/m^2$

$P = maximum\ load\ applied, kN$

$A = cross - sectional\ area, m^2$

Figure 3.19: Compression test machine.

3.9.1.2 Non-Destructive Test (NDT) – UPV Test

The elastic wave method of a NDT uses the ultrasonic pulse velocity method to determine the compressive strength of the cube specimen without damaging it. This method can be done by using two different types of piezoelectric transducers, transmitter and receiver, to attach to the opposite ends of the cube specimens. With the assistance of NDT software (LabView Signal Express), an amplitude versus time graph is generated.

First, a coupling agent wax was used to attach the piezoelectric transducers to the cube specimens on the opposite side. Next, open the LabView Signal Express software and make sure the setting and the connection of the data logger are set properly. The steel ball tool was used to hit the cube specimen, then the elastic wave is express in term of an amplitude versus time graph was generated by the LabView Signal Express software (Lim, et al., 2020). Figure 3.20 shows the elastic wave method apparatus.

Figure 3.21 shows the steel ball tool that hit the specimens to provide wave parameters. Figure 3.22 shows the coupling agent wax.

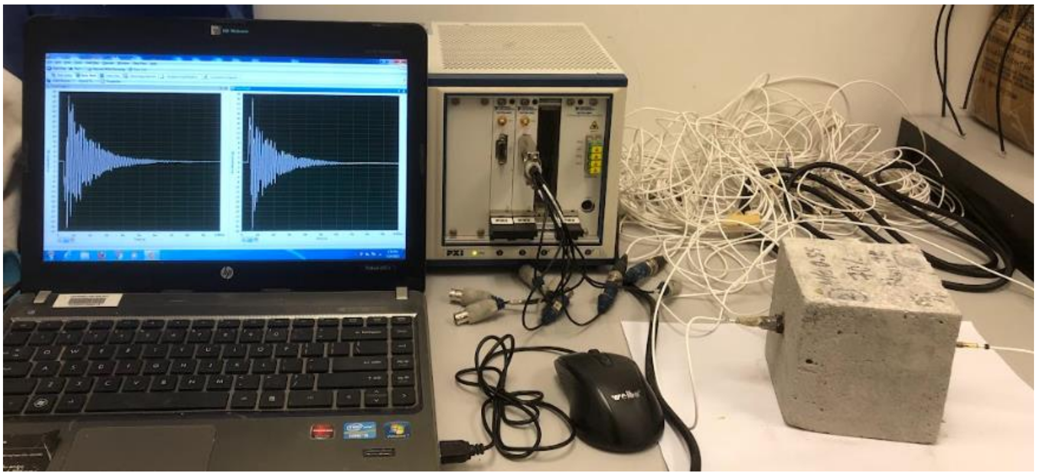

Figure 3.20: Elastic Wave Method (UPV)

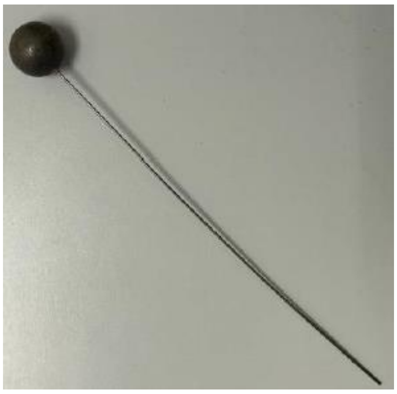

Figure 3.21: Steel Ball Tool

Figure 3.22: Coupling Agent Wax

In this study, P-wave was used to analyse and evaluate the parameters obtained from the graph. This graph can provide sufficient parameters to calculate each specimen's wave amplitude and velocity. When the piezoelectric transducers were attached to the cube specimens, the steel ball tool produced the P-wave during the hit. Since every hit might have a different force applied, ten data sets were recorded to get the average value. P-wave was determined by observing the first changes in the graph's amplitude obtained. The P-wave velocity could be determined by using Equation 3.2. By analysing the wave amplitude and velocity obtained, the compressive strength of the cubes can be determined.

$$V_p = \frac{w}{(t_{out} - t_{in})} \tag{3.2}$$

where,

$V_p = velocity\ of\ P - waves, m/s$

$w = width\ of\ concrete\ cube, m\ (100mm\ width\ of\ cube = 0.1m)$

$t_{out} = time\ passes\ through\ at\ the\ output\ tranducer, s$

$t_{in} = time\ passes\ through\ at\ the\ input\ tranducer, s$

3.9.2 Flexural Strength Test

A flexural strength test was used to measure and analyse the tensile strength of the rubberised lightweight foamed concrete. The prism concrete specimens were used to analyse the tensile strength with dimensions of 500mm length, 100mm width and 100mm height. The flexural strength test was done under third point loading according to the ASTM C78 (Madandoust, et al., 2017). Figure 3.23 shows the flexural strength test under third point loading.

First, label the prism concrete specimens and adjust the steel rod following the label. It is to ensure the load was applied to the adequate position to obtain a precise and accurate reading of flexural strength. Then, setting up the flexural strength test machine, the maximum force applied was obtained, and the result was collected to calculate the strength using Equation 3.3.

$$R = \frac{PL}{BD^2} \tag{3.3}$$

where,

$R = modulus\ of\ rupture\ or\ flexural\ strength, MPa$

$P = maximum\ applied\ load\ from\ the\ machine, N$

$L = span\ length, mm$

$B = average\ width\ of\ the\ specimens, mm$

$D = average\ depth\ of\ the\ specimens, mm$

Figure 3.23: Flexural Strength Test (Third Point Loading)

3.9.3 Splitting Tensile Strength Test

Splitting tensile strength is indirect tensile strength or Brazilian tensile strength. It is used to measure and analyse the tensile strength of the cylinder concrete specimens, which is perpendicular to the direction of an applied force. The dimension of cylinder concrete specimens used in this study was 100mm diameter and 200mm height. The splitting tensile strength test can be done by following the standard of ASTM C496 (Madandoust, et al., 2017). Figure 3.24 shows the splitting tensile test in the laboratory.

First, the cylinder concrete specimen was put into a cylinder cage and placed in the splitting tensile strength test machine. The machine used for this test is similar to the compressive strength test. Next, the applied load was applied to the cage until the specimen failed. The maximum load was recorded to obtain the splitting tensile strength using Equation 3.4.

$$f_{st} = \frac{2P}{\pi l d} \tag{3.4}$$

where,

$f_{st} = splitting\ tensile\ strength, MPa$

$P = maximum\ force\ applied\ to\ the\ specimen, N$

$l = length\ of\ the\ cylinder\ specimen, mm$

$d = diameter\ of\ the\ cylinder\ specimen, mm$

Figure 3.24: Splitting Tensile Test

3.10 Summary

The methodology in this study pertains to the procedures employed for conducting the research, investigations, and laboratory work. It comprehensively explains the entire laboratory process, including designing and calculating concrete mix proportions required for casting concrete specimens. Before the casting process, raw materials were accurately prepared, and standardised mould sizes were employed per the provided guidelines and standards according to the ASTM and BS codes. Additionally, the production of a stable foam agent was carried out following the specified procedure. This research involved utilising two workability tests: flow table and inverted slump tests. Furthermore, four tests were conducted, consisting of both DT and

NDT assessments of compressive strength, flexural strength, and splitting tensile strength tests. The elastic wave of the NDT test was using ultrasonic pulse velocity in this study.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results obtained from the laboratory work of rubberised lightweight foamed concrete are discussed in this chapter. The workability of the rubberised lightweight foamed concrete mixture is obtained by using two methods to analyse it: flow table test and inverted slump test. The main discussion of this chapter is the compressive strength of the rubberised lightweight foamed concrete using the elastic wave method, type of NDT (UPV test) and DT test. The additional results of the flexural strength and splitting tensile strength are obtained to analyse better the effect of the rubber particles adding to the lightweight foamed concrete by replacing the fine aggregate. Moreover, this chapter examines and discusses the relationship between the test results obtained with the variation of w/c ratio and rubber replacement content with the fine aggregate and the correlation between the development from the DT and NDT tests.

4.2 Workability of Rubberised Lightweight Foamed Concrete

The workability of the rubberised lightweight foamed concrete could be evaluated and analysed by observing the slump diameter and the number of drops for the flow table test. Theoretically, the w/c ratio increases, the water content in the specimen mixture is higher, and the slump diameter will be higher than the lower w/c ratio concrete specimen's mixture. However, excessive water or less water will influence the strength of the rubberised lightweight foamed concrete.

4.2.1 Flow Table Test

Table 4.1 shows the variations in the w/c ratio and the proportion of rubber replacement with the fine aggregate. This data corresponds to the outcomes related to the number of drops and the diameters of the concrete mixture spread on the circular table. Figure 4.1 shows the number of drops versus the rubber content graph for better observation.

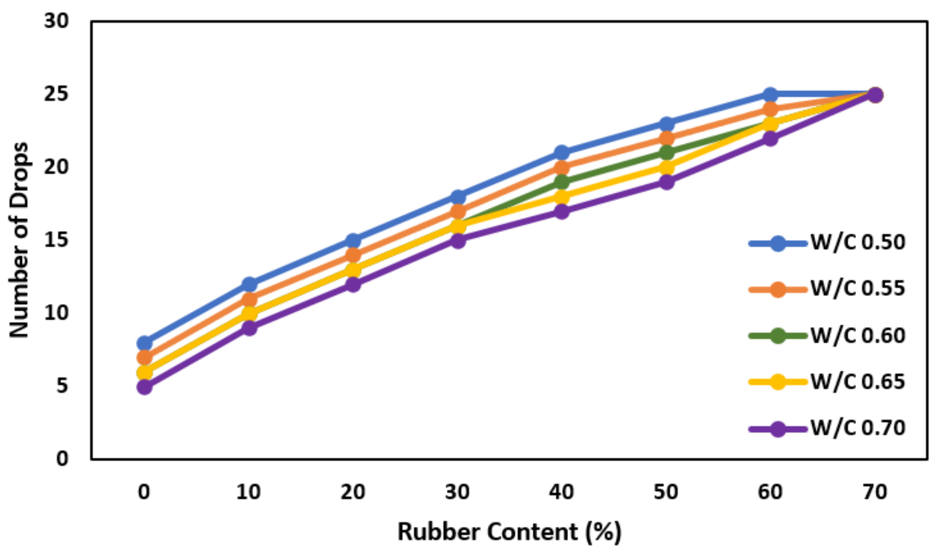

Figure 4.1: Number of Drops Versus Rubber Content

Figure 4.1 shows the pattern of the increase trend. It shows the relationship between the number of drops, rubber content, and the w/c ratio. The number of drops increases as the rubber content in the rubberised lightweight foamed mixture increases. However, the number of drops will decrease as the w/c ratio increases. For example, the number of drops of the control mixture of w/c 0.50 to w/c 0.70 declined, the same as the others of w/c ratio with the various rubber content. However, according to the ASTM guidelines, the number of drops of the w/c ratio from 0.50 to 0.70 with the rubber content will stop in the 25 number of drops due to the maximum drops being 25, then will use the diameter of spread diameter to analyse the workability.

Table 4.1: Flow Table Test Results

W/C Ratio	Rubber Content (%)	Flow Table Test	
		Number of Drops	Diameters (cm)
0.50	0	8	23.00
	10	12	23.50
	20	15	23.50
	30	18	23.75
	40	21	23.75
	50	23	23.75
	60	25	22.00
	70	25	21.00
0.55	0	7	23.00
	10	11	23.00
	20	14	23.00
	30	17	23.00
	40	20	23.50
	50	22	23.50
	60	24	23.75
	70	25	22.00
0.60	0	6	23.50
	10	10	23.00
	20	13	23.50
	30	16	23.75
	40	19	23.75
	50	21	23.00
	60	23	23.00
	70	25	22.75
0.65	0	6	23.75
	10	10	23.50
	20	13	23.75
	30	16	24.00
	40	18	24.00
	50	20	23.30
	60	23	23.50
	70	25	23.00
0.70	0	5	23.75
	10	9	23.50
	20	12	23.00
	30	15	23.00
	40	17	22.00
	50	19	23.50
	60	22	23.50
	70	25	23.75

From Table 4.1, a conclusion can be made that when the w/c ratio increases, the workability of the concrete mixture increases, making it easier to place, compact, and finish. The rubber content increases, the workability of the substantial mixture drops, and the mixture's diameters decrease because the rubber powder absorbs more water than the fine aggregate (Roychand, et al., 2020). Therefore, the rubber content in the rubberised lightweight foamed concrete needed a higher w/c ratio than traditional concrete. This is because rubber powder is not as absorbent as conventional aggregates, so a higher w/c percentage may be required to ensure enough water for proper mixing and hydration. This test was used to evaluate the workability of cement mortar by observing the mortar flow when rotating the flow table equipment.

4.2.2 Inverted Slump Test

Table 4.2 shows that the inverted slump test results vary in difference of w/c ratio and rubber content replacement. This result was used to analyse the workability of the concrete mixture after adding the foaming agent. Figure 4.2 shows the relationship between the inverted slump test, rubber content, and w/c ratio.

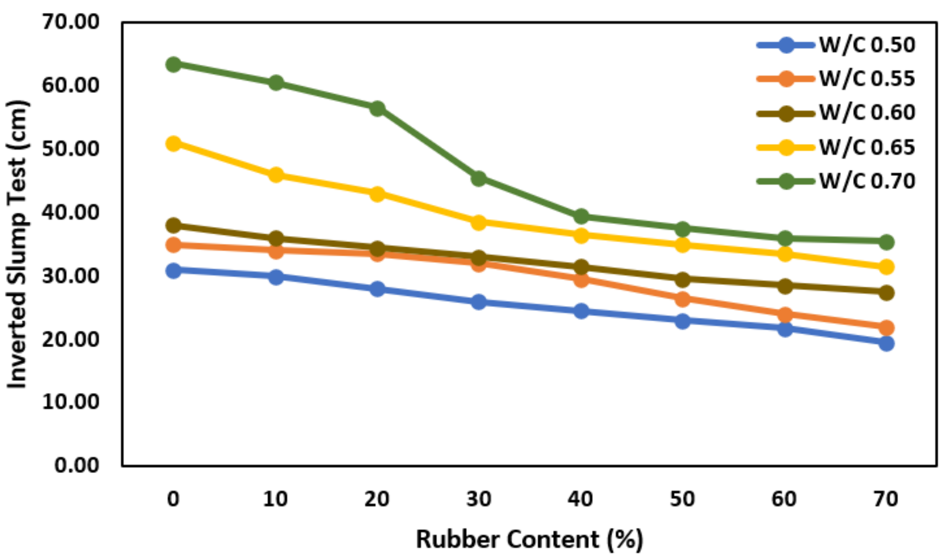

Figure 4.2: Inverted Slump Test Versus Rubber Content

Table 4.2: Inverted Slump Test Results

W/C Ratio	Rubber Content (%)	Inverted Slump Test (cm)
0.50	0	31.00
	10	30.00
	20	28.00
	30	26.00
	40	24.50
	50	23.00
	60	21.80
	70	19.50
0.55	0	35.00
	10	34.00
	20	33.50
	30	32.00
	40	29.50
	50	26.50
	60	24.00
	70	22.00
0.60	0	38.00
	10	36.00
	20	34.50
	30	33.00
	40	31.50
	50	29.50
	60	28.50
	70	27.50
0.65	0	51.00
	10	46.00
	20	43.00
	30	38.50
	40	36.50
	50	35.00
	60	33.50
	70	31.50
0.70	0	63.50
	10	60.50
	20	56.50
	30	45.50
	40	39.50
	50	37.50
	60	36.00
	70	35.50

Figure 4.2 shows that the inverted slump test decreases as the rubber content increases. For example, the inverted slump test was decreased from 10% to 70% of rubber content in the w/c 0.50. The w/c ratio will influence the inverted slump test. As the inverted slump test decreases, the w/c ratio is lesser. For instance, the control mixture of w/c 0.70 has a higher inverted slump test than w/c 0.50.

Table 4.2 shows that the w/c ratio increases, and the slump diameter increases, which means that the workability of the concrete mixture is easier to place, compact, and finish. However, the rubber replacement content increase will decrease the workability of the concrete mixture. This is because rubber powder can absorb more water than fine aggregate (Roychand, et al., 2020). This test was carried out to evaluate the workability of the rubberised lightweight foamed concrete and concrete mixture condition, which can contribute to the overall w/c ratio, which required adjustments in the mix design to achieve the desired properties. Thus, after the test, it showed that the reading pattern was almost similar to the flow table test pattern. As the rubber content increased, the workability and consistency of the rubberised lightweight foamed concrete decreased.

4.3 Destructive Test Method (DT) – Compressive Strength Test

The DT method is the conventional method used to evaluate and analyse the compressive strength using a compression test machine. The size of the cube specimens of rubberised lightweight foamed concrete is 100mm x 100mm x 100mm with a volume of 0.001m^3. Tables 4.3 to 4.7 show the cube specimens' fresh density, air dry density and compressive strength with various types of w/c ratios and rubber replacement.

Table 4.3: Compressive Strength Test Result of Rubberised Lightweight Foamed Concrete with W/C 0.50.

W/C Ratio	Day	Rubber Content (%)	Fresh Density (kg/m³)	Air Dry Density (kg/m³)	Compressive Strength (MPa)
0.50	1	0	1340	1350.0	1.82
		10	1355	1362.0	1.91
		20	1330	1355.9	2.22
		30	1322	1345.0	2.64
		40	1318	1325.6	3.28
		50	1362	1375.2	3.09
		60	1326	1334.4	2.60
		70	1363	1372.2	2.23
	7	0	1340	1363.0	4.25
		10	1355	1367.2	4.36
		20	1330	1366.0	4.58
		30	1322	1353.8	5.46
		40	1318	1332.4	6.05
		50	1362	1381.6	5.84
		60	1326	1345.6	5.45
		70	1363	1379.8	4.87
	28	0	1340	1391.0	4.98
		10	1355	1369.8	5.22
		20	1330	1372.0	5.67
		30	1322	1367.2	6.39
		40	1318	1341.3	7.02
		50	1362	1389.8	6.81
		60	1326	1358.4	6.34
-		70	1363	1385.1	6.07
	56	0	1340	1394.3	5.17
		10	1355	1375.2	5.34
		20	1330	1345.5	5.87
		30	1322	1341.9	6.58
		40	1318	1334.6	7.24
		50	1362	1385.3	6.99
		60	1326	1350.0	6.49
		70	1363	1388.1	6.15

Table 4.4: Compressive Strength Test Result of Rubberised Lightweight Foamed Concrete with W/C 0.55.

W/C Ratio	Day	Rubber Content (%)	Fresh Density (kg/m³)	Air Dry Density (kg/m³)	Compressive Strength (MPa)
0.55	1	0	1320	1329.8	1.99
		10	1319	1322.4	2.08
		20	1328	1335.8	2.45
		30	1308	1311.2	2.89
		40	1345	1352.4	3.38
		50	1349	1351.4	3.31
		60	1312	1324.2	2.97
		70	1325	1326.8	2.65
	7	0	1320	1341.2	4.32
		10	1319	1338.4	4.48
		20	1328	1340.0	4.99
		30	1308	1322.6	5.61
		40	1345	1359.2	6.31
		50	1349	1356.2	5.99
		60	1312	1336.1	5.80
		70	1325	1338.4	5.52
	28	0	1320	1356.0	5.34
		10	1319	1349.2	5.59
		20	1328	1354.0	6.09
		30	1308	1336.1	6.71
		40	1345	1362.5	7.46
		50	1349	1381.2	6.98
		60	1312	1346.2	6.79
		70	1325	1346.1	6.47
	56	0	1320	1366.0	5.61
		10	1319	1355.0	5.72
		20	1328	1352.5	6.39
		30	1308	1350.2	6.88
		40	1345	1361.8	7.56
		50	1349	1360.2	7.18
		60	1312	1356.6	6.99
		70	1325	1348.9	6.68

Table 4.5: Compressive Strength Test Result of Rubberised Lightweight Foamed Concrete with W/C 0.60.

W/C Ratio	Day	Rubber Content (%)	Fresh Density (kg/m³)	Air Dry Density (kg/m³)	Compressive Strength (MPa)
0.60	1	0	1365	1372.5	2.21
		10	1312	1316.6	2.32
		20	1364	1372.2	2.71
		30	1308	1318.6	3.16
		40	1375	1381.4	3.68
		50	1343	1345.6	3.40
		60	1325	1329.8	3.23
		70	1322	1333.2	3.07
	7	0	1365	1388.6	4.18
		10	1312	1325.8	4.59
		20	1364	1383.8	5.31
		30	1308	1324.4	6.20
		40	1375	1389.2	7.03
		50	1343	1355.0	6.77
		60	1325	1341.6	6.43
		70	1322	1340.2	6.02
	28	0	1365	1390.4	5.61
		10	1312	1336.6	5.74
		20	1364	1391.4	6.45
		30	1308	1332.1	7.23
		40	1375	1395.7	8.29
		50	1343	1364.6	8.06
		60	1325	1354.2	7.85
		70	1322	1352.6	7.44
	56	0	1365	1392.8	5.98
		10	1312	1343.5	6.29
		20	1364	1398.8	6.75
		30	1308	1341.2	7.48
		40	1375	1396.2	8.49
		50	1343	1369.2	8.26
		60	1325	1361.8	8.05
		70	1322	1358.7	7.74

Table 4.6: Compressive Strength Test Result of Rubberised Lightweight Foamed Concrete with W/C 0.65.

W/C Ratio	Day	Rubber Content (%)	Fresh Density (kg/m³)	Air Dry Density (kg/m³)	Compressive Strength (MPa)
0.65	1	0	1325	1329.5	1.68
		10	1365	1369.2	1.88
		20	1328	1331.2	2.06
		30	1336	1336.6	2.57
		40	1302	1311.6	3.10
		50	1309	1315.6	2.96
		60	1350	1352.8	2.63
		70	1352	1357.8	2.37
	7	0	1325	1335.2	3.87
		10	1365	1375.2	4.06
		20	1328	1336.6	4.25
		30	1336	1351.2	4.97
		40	1302	1321.8	5.81
		50	1309	1331.2	5.72
		60	1350	1358.1	5.36
		70	1352	1362.8	4.78
	28	0	1325	1350.0	4.98
		10	1365	1391.7	5.12
		20	1328	1344.8	5.45
		30	1336	1381.6	6.08
		40	1302	1347.6	6.82
		50	1309	1350.2	6.61
		60	1350	1362.1	6.42
		70	1352	1369.1	6.19
	56	0	1325	1362.0	5.15
		10	1365	1395.0	5.29
		20	1328	1355.2	5.61
		30	1336	1383.2	6.23
		40	1302	1352.2	7.03
		50	1309	1357.6	6.91
		60	1350	1366.8	6.53
		70	1352	1375.6	6.31

Table 4.7: Compressive Strength Test Result of Rubberised Lightweight Foamed Concrete with W/C 0.70.

W/C Ratio	Day	Rubber Content (%)	Fresh Density (kg/m³)	Air Dry Density (kg/m³)	Compressive Strength (MPa)
0.70	1	0	1341	1349.0	1.53
		10	1360	1366.2	1.69
		20	1310	1316.6	1.86
		30	1307	1311.6	2.35
		40	1346	1350.2	2.79
		50	1342	1349.2	2.64
		60	1321	1331.8	2.34
		70	1350	1359.2	2.09
	7	0	1341	1353.6	3.60
		10	1360	1371.0	3.76
		20	1310	1321.6	4.10
		30	1307	1319.5	4.72
		40	1346	1355.9	5.58
		50	1342	1354.2	5.29
		60	1321	1341.2	4.71
		70	1350	1366.8	4.32
	28	0	1341	1366.2	4.78
		10	1360	1386.2	5.01
		20	1310	1345.3	5.39
		30	1307	1325.3	5.99
		40	1346	1360.2	6.67
		50	1342	1361.3	6.31
		60	1321	1350.2	5.92
		70	1350	1372.1	5.59
	56	0	1341	1371.9	4.95
		10	1360	1389.2	5.18
		20	1310	1352.9	5.52
		30	1307	1348.6	6.10
		40	1346	1366.8	6.87
		50	1342	1365.2	6.64
		60	1321	1355.2	6.22
		70	1350	1377.1	5.98

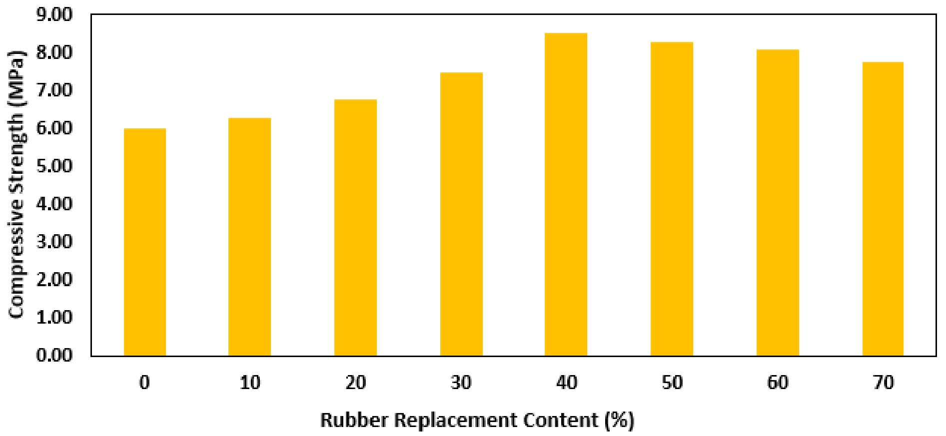

Figure 4.3: Compressive Strength of W/C 0.60 for Day 56th

Tables 4.3 to 4.7 present the comprehensive findings of the DT conducted on the compression test machine for the rubberised lightweight foamed concrete. These tests involved varying percentages of rubber replacement with fine aggregate, ranging from 0% to 70%. Figure 4.3 shows a significant relationship between the rubber replacement content and the compressive strength of the rubberised lightweight foamed concrete. The bar chart presented in Figure 4.3 shows that control specimens have the lowest compressive strength compared to those with rubber content. For example, the highest compressive strength obtained in tew/c ratio of 56th day result is 40% rubber replacement with a value of 8.49MPa, followed by 50% (8.26MPa), 60% (8.05MPa), 70% (7.74MPa), 30% (7.48MPa), 20% (6.75MPa), 10% (6.29MPa) of rubber content in the lightweight foamed concrete and the lowest is the control mixture with a value of 5.98MPa. The increment of the compressive strength between the control and 40% rubber content specimens is 41.97%, and the increment of the compressive strength between the control and 70% rubber content is 29.43%.

The phenomenon mentioned above can be attributed to two underlying variables: the characteristic of elasticity and the size of the particles required. The higher percentage of rubber replacement means more rubber in the mix, and these rubber particles possess properties that improve concrete strength due to their elasticity property. The elasticity property can let the rubberised lightweight foamed concrete deflect more than the lightweight foamed concrete. It can be used to lengthen the crack that happens when the rubberised lightweight foamed concrete fails. The particle size may influence the compressive strength since the rubber particles are 0.42mm, while the fine aggregate particles measure less than 0.60mm. Therefore, the rubber particles exhibit a finer particle size distribution. The smaller particles can occupy the empty spaces between larger aggregate particles, resulting in an enhanced compact density when well mixed—the increased compact density of the concrete results in a corresponding increase in compressive strength. Rubber particles can generate dense concrete by filling voids and capillary pores (Roychand, et al., 2020).

Nevertheless, it is observed that the compressive strength of the rubberised lightweight foamed concrete exhibits a drop as the rubber replacement percentage exceeds 50%. The decreased compressive strength of rubberised lightweight foamed concrete can be due to the increased percentage of rubber particles. A higher percentage of rubber replacement results in a lower percentage of fine aggregate. This result leads to a weak interfacial connection between the rubber particles and the cement matrix in the concrete specimens. (Valente & Sibai, 2019). Thus, the compressive strength will drop due to the weak bonding between the rubber and cement particles.

Additionally, it shows a significant relationship between the curing period and the compressive strength, indicating that as the duration of curing grows, the compressive strength also tends to increase. According to the data in Table 4.5, the compressive strength of rubberised lightweight foamed concrete increased from 3.68MPa to 8.49MPa when the rubber content was replaced by 40% fine aggregate. As the curing period increases, the rubberised lightweight foamed concrete undergoes a hardening process and experiences an increase in strength. The hardening process of rubberised lightweight foamed concrete involves a chemical reaction known as hydration, which happens between water and cement. This reaction leads to the formation of calcium silicate hydrate (C-H-S). The C-H-S material will effectively fill the space between the rubberised lightweight foamed concrete particles and establish a strong connection. Consequently, the extended duration of curing leads to an enhancement in compressive strength due to the prolonged hydration process, which facilitates a more robust bonding between the particles.

In the comparison of compressive strength between rubberised lightweight foamed concrete and w/c ratio, as presented in Tables 4.3 to 4.7 above, it is observed that the compressive strength of rubberised lightweight foamed concrete exhibits an increase when the w/c ratio is raised from 0.50 to 0.60. However, compressive strength decreases when the w/c ratio is further increased from 0.60 to 0.70. These variations in compressive strength are observed under identical curing periods and rubber content. As evidenced by the data presented in Tables 4.5 and 4.6, when subjected to a curing duration of 56 days and control specimens, the compressive strength of the material exhibits a value of 5.98 MPa for a w/c 0.6, whereas a w/c 0.65 yields a compressive strength value of 5.15 MPa. The decrease in strength can be attributed to the development of a cement paste with low-strength properties. As the w/c ratio is elevated, there is a corresponding increase in the proportion of water relative to cement. This increase in water content leads to a weaker cement paste, which diminishes the bonding capacity when it interacts with the aggregate. Consequently, the compressive strength of rubberised lightweight foamed concrete is reduced. Moreover, the porosity of rubberised lightweight foamed concrete increases by an elevation in the w/c ratio. This is due to the excess of water, which generates an extra void, decreasing the strength of the rubberised lightweight foamed concrete (Panda, et al., 2020). Hence, as the w/c ratio increases, the failure of rubberised lightweight foamed concrete underloading will occur more rapidly.

The compressive strength of the curing specimens displays an increasing trend during the curing period from the 28th day to the 56th day, in contrast to the period from the 7th day to the 28th day. As an illustration in Table 4.7, the compressive strength of a w/c 0.70 on the seventh day is measured to be 5.58MPa when 40% of the rubber is replaced. Subsequently, the compressive strength experienced an increase of approximately 19.53% from day 7 to day 28, reaching 6.67MPa. Furthermore, the compressive strength continues to rise from 28th day to 56th day, reaching 6.87MPa, with an incremental growth of 3%. This condition occurred due to the hydration process slowing down after 28th day due to the depletion of the water available and unreacted cementitious materials. Consequently, significant improvements in strength were observed after day 28th of the curing process.

The results obtained from the traditional DT indicate that the compressive strength of rubberised lightweight foamed concrete is influenced by factors such as the w/c ratio, rubber content, and duration of curing. The compressive strength of rubberised lightweight foamed concrete is directly proportional to its curing period, whereby a longer curing period results in higher compressive strength. In theory, a lower w/c ratio is expected to result in higher compressive strength. However, the results of this study indicate that a w/c ratio of 0.60 yielded the maximum compressive strength compared to other ratios. Tables 4.3 to 4.7 show the data indicating that 40% of rubber replacement gives excellent outcomes, namely achieving a compressive strength of 8.49MPa at a w/c 0.60 on the 56th day.

4.4 Non-Destructive Test (NDT) – Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test, an elastic wave method, was employed as the primary method in this study. The wave parameters were obtained and assessed during the propagation of elastic waves through rubberised lightweight foamed concrete. The study employed P-wave analysis as an approach for evaluating the velocity. The study analyses two wave parameters, namely wave amplitude and wave velocity. A correlation exists between the compressive strength result of a traditional DT and two wave parameters.

4.4.1 Wave Amplitude

The programme employed for the analysis of elastic wave parameters was LabView Signal Express 2011. The rubberised lightweight foamed concrete was subjected to ten hits from a pendulum, producing ten data sets. These data points will be averaged and shown on a wave's graph afterwards. When an elastic wave is formed and propagates through rubberised lightweight foamed concrete, the energy level will decrease due to energy dissipation within the medium. The dissipation of energy occurs due to the absorption of wave energy by the medium and when the wave energy contacts heterogeneities such as voids and aggregates. Consequently, there is a drop in energy levels as the distance travelled increases. The graph presented in Figure 4.4 shows the relationship between amplitude and time. The present analysis uses the energy level as an indicator to indicate the magnitude of the P-wave. The amplitude in the graph refers to the initial point of change, frequently referred to as the sudden increase of the wave. Figure 4.5 shows the location in space of the P-wave amplitude inside the graph, representing the relationship between amplitude and time. Tables 4.8, 4.9, 4.10, 4.11, and 4.12 present data on the wave amplitude of rubberised lightweight foamed concrete. The tables specifically focus on fixed w/c ratios, varying rubber content, and varied curing times. Figure 4.6 shows the wave amplitude of the 56th day results. Figure 4.7 shows the wave amplitude versus w/c ratio of the 40% rubber content on the 56th day result.

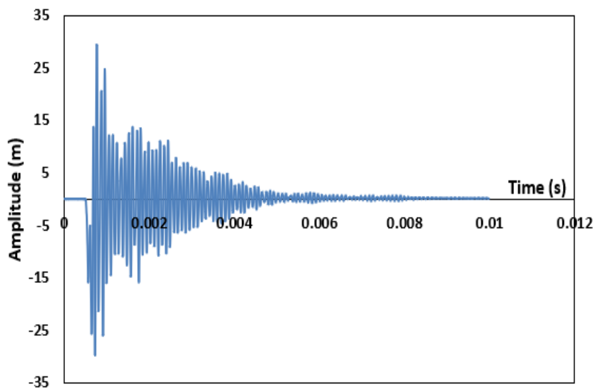

Figure 4.4: Amplitude Versus Time Graph

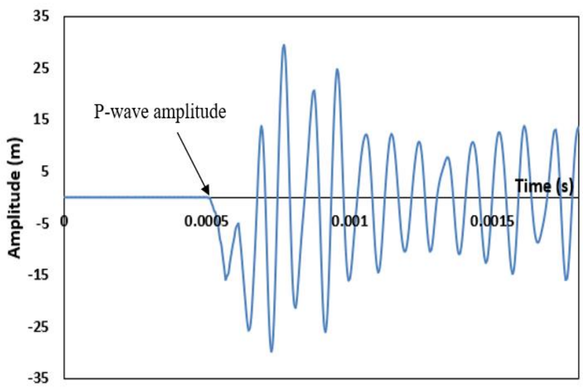

Figure 4.5: Location of P-Wave Amplitude's

Table 4.8: Wave Amplitude of Rubberised Lightweight Foamed Concrete of W/C 0.50.

W/C Ratio	Day	Rubber Content (%)	Wave Amplitude (m)
0.50	1	0	0.089872
		10	0.119216
		20	0.133209
		30	0.179792
		40	0.231819
		50	0.207938
		60	0.167593
		70	0.132289
	7	0	0.284562
		10	0.306191
		20	0.382901
		30	0.489912
		40	0.658911
		50	0.588746
		60	0.477693
		70	0.332389
	28	0	0.496824
		10	0.529611
		20	0.579102
		30	0.678251
		40	0.834175
		50	0.789546
		60	0.667961
		70	0.544238
	56	0	0.526482
		10	0.546101
		20	0.629201
		30	0.719512
		40	0.897542
		50	0.829645
		60	0.698971
		70	0.584832

Table 4.9: Wave Amplitude of Rubberised Lightweight Foamed Concrete of W/C 0.55.

W/C Ratio	Day	Rubber Content (%)	Wave Amplitude (m)
0.55	1	0	0.097342
		10	0.129621
		20	0.166302
		30	0.208972
		40	0.265118
		50	0.229978
		60	0.198735
		70	0.163322
	7	0	0.295784
		10	0.331169
		20	0.420091
		30	0.519987
		40	0.688891
		50	0.627846
		60	0.564561
		70	0.523892
	28	0	0.506428
		10	0.539881
		20	0.600254
		30	0.699913
		40	0.867541
		50	0.815649
		60	0.719867
		70	0.627838
	56	0	0.548942
		10	0.574121
		20	0.631021
		30	0.749521
		40	0.925724
		50	0.856954
		60	0.760102
		70	0.648422

Table 4.10: Wave Amplitude of Rubberised Lightweight Foamed Concrete of W/C 0.60.

W/C Ratio	Day	Rubber Content (%)	Wave Amplitude (m)
0.60	1	0	0.123742
		10	0.150612
		20	0.199602
		30	0.245722
		40	0.291185
		50	0.257891
		60	0.228753
		70	0.193223
	7	0	0.338754
		10	0.369615
		20	0.451097
		30	0.581152
		40	0.719815
		50	0.646847
		60	0.536541
		70	0.398921
	28	0	0.534682
		10	0.561287
		20	0.625344
		30	0.748193
		40	0.895741
		50	0.849645
		60	0.751569
		70	0.641258
	56	0	0.589271
		10	0.611125
		20	0.672101
		30	0.795291
		40	0.961578
		50	0.885694
		60	0.802102
		70	0.684866

Table 4.11: Wave Amplitude of Rubberised Lightweight Foamed Concrete of W/C 0.65.

W/C Ratio	Day	Rubber Content (%)	Wave Amplitude (m)
0.65	1	0	0.077456
		10	0.087615
		20	0.103207
		30	0.150392
		40	0.219148
		50	0.189783
		60	0.155973
		70	0.118922
	7	0	0.278642
		10	0.301901
		20	0.349741
		30	0.452917
		40	0.638119
		50	0.566475
		60	0.459763
		70	0.312980
	28	0	0.418664
		10	0.476108
		20	0.541292
		30	0.649542
		40	0.807514
		50	0.759645
		60	0.659671
		70	0.518342
	56	0	0.488642
		10	0.512616
		20	0.599012
		30	0.705921
		40	0.865217
		50	0.796495
		60	0.718917
		70	0.598423

Table 4.12: Wave Amplitude of Rubberised Lightweight Foamed Concrete of W/C 0.70.

W/C Ratio	Day	Rubber Content (%)	Wave Amplitude (m)
0.70	1	0	0.066475
		10	0.076715
		20	0.093702
		30	0.139721
		40	0.198941
		50	0.168973
		60	0.137359
		70	0.092893
	7	0	0.229642
		10	0.259172
		20	0.337941
		30	0.449724
		40	0.611278
		50	0.547654
		60	0.436791
		70	0.289712
	28	0	0.396864
		10	0.458161
		20	0.522192
		30	0.625492
		40	0.785645
		50	0.736659
		60	0.637691
		70	0.493428
	56	0	0.466824
		10	0.496162
		20	0.570921
		30	0.685291
		40	0.847512
		50	0.777594
		60	0.679871
		70	0.533482

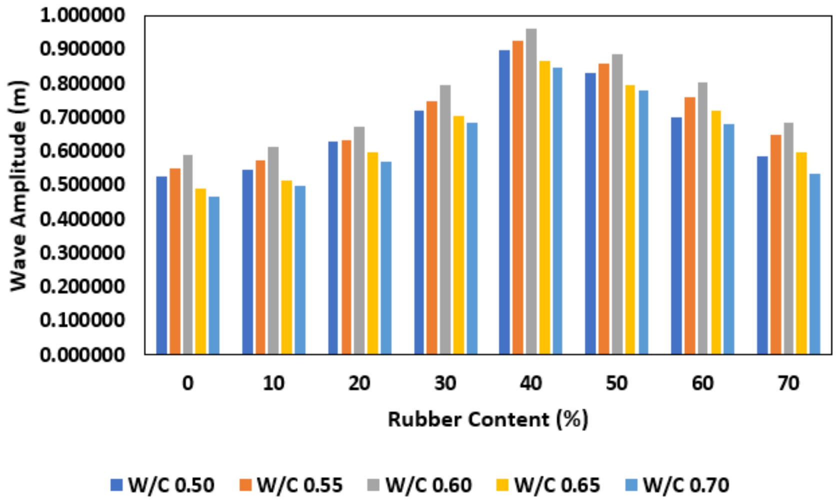

Figure 4.6: Wave Amplitude of the 56th Day Result

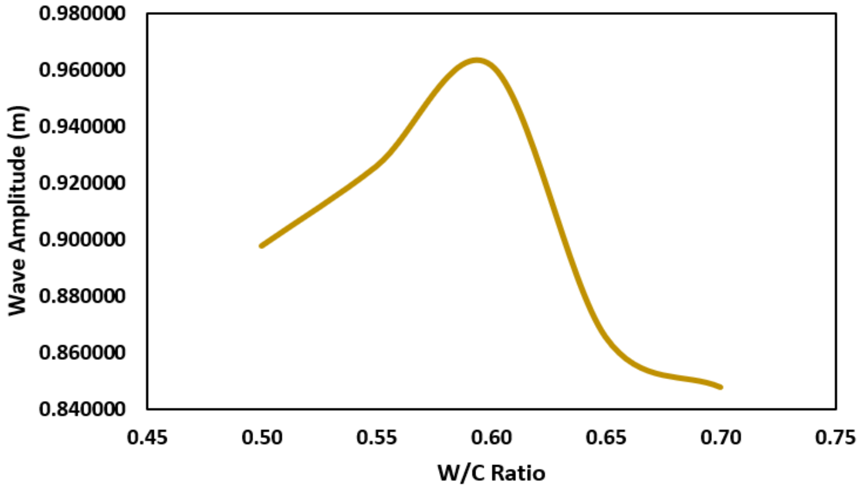

Figure 4.7: Wave Amplitude Versus W/C Ratio of the 40% Rubber Content on 56th Day Result

Table 4.10 shows an incremental rise in wave amplitude from control specimens to the specimens containing 40% rubber content. Furthermore, the wave amplitude demonstrates an upward trend beyond the 40% rubber content threshold. When the rubber content increases from 0% to 70%, there is an observed trend in the wave amplitude. Specifically, the wave amplitude increases from 0.123745m to 0.291185m as the rubber content reaches 40%. However, the wave amplitude declines beyond this point, reaching 0.193223m at 70% rubber content. These changes in wave amplitude occur throughout a curing period of 1 day—consequently, the decrease in energy level results in a decrease in wave amplitude. The rise of wave amplitude inclination observed when the rubber content is increased from 0% to 40% can be attributed to the smaller size of rubber particles compared to the fine aggregate. This smaller size allows the rubber particles to fill the voids and capillary pores effectively. Therefore, as the voids in the concrete specimens are reduced, the wave's amplitude will increase. The decrease in wave amplitude from 40% to 70% increase in rubber content can be attributed to the characteristics of rubber particles. Rubber particles exhibit a lower level of rigidity in comparison to alternative raw materials, such as cement and fine aggregate. Consequently, it will function as the dispersal mechanism for the P-wave. As the P-wave propagates in the medium, it dissolves energy due to the scattering phenomenon (Lim, et al., 2020).

According to Table 4.11, the curing period and wave amplitude have a direct proportional connection. The amplitude increases from 0.118922m to 0.598432m when the curing time is extended from 1 day to 56 days, with 70% of the rubber material replaced. The observed enhancement of wave amplitude can be attributed to the inherent stiffness of the rubberised lightweight foamed concrete material. As the curing period is extended, the rubberised lightweight foamed concrete will experience hydration, hardening and increasing its overall strength. The stiffness of rubberised lightweight foamed concrete exhibits a rise, resulting in less deformation as the P-wave propagates through the medium. Consequently, this phenomenon leads to a decrease in energy dissipation, thereby enhancing the wave's amplitude.

Tables 4.8, 4.9, 4.10, 4.11, and 4.12 present data on the wave amplitude of rubberised lightweight foamed concrete at varying w/c ratios. The rise in w/c ratio decreases wave amplitude, namely from w/c 0.60 to w/c 0.70. This phenomenon can be attributed to the porosity of the rubberised lightweight foamed concrete while keeping the rubber content and curing period the same. As seen in Tables 4.10 and 4.11, when the rubber content reaches 70% and the curing period extends to 56 days, the wave amplitude is measured to be 0.684866m at a w/c 0.60. Conversely, when the w/c ratio is increased to 0.65, the wave amplitude reduces to 0.598423m. The decrease in wave amplitude can be attributed to the increase in the w/c ratio, which results in higher water content within the rubberised lightweight foamed concrete. This increased water content increases porosity and void formation inside the concrete (Chan, et al., 2018). The vacuum serves as a medium for scattering and absorbing energy when a P-wave propagates. Consequently, the amplitude of the wave diminishes due to higher energy dissipation. Figure 4.7 shows the P-wave amplitude of 40% rubber content data for the w/c ratio from 0.50 to 0.70 for a better understanding of their relationship.

Figure 4.6 shows that the P-wave amplitude of control lightweight foamed concrete has the lowest value compared to other rubberised lightweight foamed concrete in the w/c ratio of 0.50 to 0.70. The highest P-wave amplitude is 40% of rubber content in the w/c ratio of 0.50 to 0.70. As mentioned above, the rubber particle size has an advantage in filling the void structures obtained in the concrete. This results in the concrete being denser, and when the void structures are less, the P-wave amplitude will be higher. For example, control lightweight foamed concrete has 0.589271m of P-wave amplitude, and the 40% rubber content lightweight foamed concrete has 0.961578m of P-wave amplitude in the w/c 0.60 of 56thday result. The increment of P-wave amplitude between the control and 40% rubber content is 63.18%. This means that rubberised lightweight concrete has more advantages than the lightweight foamed concrete in this study.

The wave amplitude of rubberised lightweight foamed concrete is influenced by the duration of the curing period, the w/c ratio, and the percentage of rubber content. An instance of rubberised lightweight foamed concrete with the most extended curing period, the least amount of rubber content, and the lowest w/c ratio demonstrate the highest wave amplitude. However, this study's highest wave amplitude was attained on 56th day with a value of 0.961578m of w/c 0.60 with 40% rubber content. In contrast, the w/c ratio and rubber content are recommended to be 0.60 and 40%, respectively.

4.4.2 Wave Velocity

The study considers wave velocity as the speed at which the elastic wave propagates through the medium. The P-wave was selected as the primary wave for analysing wave velocity due to its higher speed than other waves, such as the S-wave and R-wave. This choice was made in order to produce more precise and reliable results. Moreover, P-waves are longitudinal waves that exhibit superior crack detection capabilities compared to surface waves such as S-waves and R-waves. The P-wave velocity was determined by dividing the width of the rubberised lightweight foamed concrete, which was 0.1m (100mm), by the travelling time associated with its size. The calculation of travel time involved reducing the time obtained from the receiving sensor (output) from the time gained from the transmitting sensor (input). The following tables, namely Tables 4.13, 4.14, 4.15, 4.16, and 4.17, present the rubberised lightweight foamed concrete wave velocity data. These tables specifically focus on the wave velocity measurements obtained at fixed w/c ratios while considering variations in rubber content and curing time. Figure 4.8 shows the wave velocity versus rubber content of the 56^{th} day results. Figure 4.9 shows the wave velocity versus w/c ratio of the 40% rubber content on 56^{th} day result.

Table 4.13: Wave Velocity of Rubberised Lightweight Foamed Concrete of W/C 0.50.

W/C Ratio	Day	Rubber Content (%)	Wave Velocity (m/s)
0.50	1	0	2000.000
		10	2000.000
		20	2000.000
		30	2000.000
		40	2500.000
		50	2222.222
		60	2000.000
		70	1818.181
	7	0	2222.222
		10	2222.222
		20	2222.222
		30	2222.222
		40	2857.143
		50	2500.000
		60	2222.222
		70	2000.000
	28	0	2500.000
		10	2500.000
		20	2500.000
		30	2500.000
		40	3000.000
		50	2857.143
		60	2500.000
		70	2222.222
	56	0	2857.143
		10	2857.143
		20	2857.143
		30	2857.143
		40	3333.333
		50	3000.000
		60	2857.143
		70	2500.000

Table 4.14: Wave Velocity of Rubberised Lightweight Foamed Concrete of W/C 0.55.

W/C Ratio	Day	Rubber Content (%)	Wave Velocity (m/s)
0.55	1	0	2000.000
		10	2000.000
		20	2000.000
		30	2222.222
		40	2500.000
		50	2222.222
		60	2222.222
		70	2000.000
	7	0	2222.222
		10	2222.222
		20	2222.222
		30	2500.000
		40	2857.143
		50	2500.000
		60	2500.000
		70	2222.222
	28	0	2500.000
		10	2500.000
		20	2500.000
		30	2857.143
		40	3000.000
		50	2857.143
		60	2857.143
		70	2500.000
	56	0	2857.143
		10	2857.143
		20	2857.143
		30	3000.000
		40	3333.333
		50	3000.000
		60	3000.000
		70	2857.143

Table 4.15: Wave Velocity of Rubberised Lightweight Foamed Concrete of W/C 0.60.

W/C Ratio	Day	Rubber Content (%)	Wave Velocity (m/s)
0.60	1	0	2000.000
		10	2000.000
		20	2222.222
		30	2222.222
		40	2857.143
		50	2500.000
		60	2222.222
		70	2000.000
	7	0	2222.222
		10	2222.222
		20	2500.000
		30	2500.000
		40	3000.000
		50	2857.143
		60	2500.000
		70	2222.222
	28	0	2500.000
		10	2500.000
		20	2857.143
		30	2857.143
		40	3333.333
		50	3000.000
		60	2857.143
		70	2500.000
	56	0	2857.143
		10	2857.143
		20	3000.000
		30	3000.000
		40	3500.000
		50	3333.333
		60	3000.000
		70	2857.143

Table 4.16: Wave Velocity of Rubberised Lightweight Foamed Concrete of W/C 0.65.

W/C Ratio	Day	Rubber Content (%)	Wave Velocity (m/s)
0.65	1	0	2000.000
		10	2000.000
		20	2000.000
		30	2222.222
		40	2500.000
		50	2222.222
		60	2000.000
		70	1818.181
	7	0	2222.222
		10	2222.222
		20	2222.222
		30	2500.000
		40	2857.143
		50	2500.000
		60	2222.222
		70	2000.000
	28	0	2500.000
		10	2500.000
		20	2500.000
		30	2857.143
		40	3000.000
		50	2857.143
		60	2500.000
		70	2222.222
	56	0	2857.143
		10	2857.143
		20	2857.143
		30	3000.000
		40	3333.333
		50	3000.000
		60	2857.143
		70	2500.000

Table 4.17: Wave Velocity of Rubberised Lightweight Foamed Concrete of W/C 0.70.

W/C Ratio	Day	Rubber Content (%)	Wave Velocity (m/s)
0.70	1	0	1818.181
		10	1818.181
		20	2000.000
		30	2222.222
		40	2500.000
		50	2222.222
		60	2000.000
		70	1818.181
	7	0	2000.000
		10	2000.000
		20	2222.222
		30	2500.000
		40	2857.143
		50	2500.000
		60	2222.222
		70	2000.000
	28	0	2222.222
		10	2222.222
		20	2500.000
		30	2857.143
		40	3000.000
		50	2857.143
		60	2500.000
		70	2222.222
	56	0	2500.000
		10	2500.000
		20	2857.143
		30	3000.000
		40	3333.333
		50	3000.000
		60	2857.143
		70	2500.000

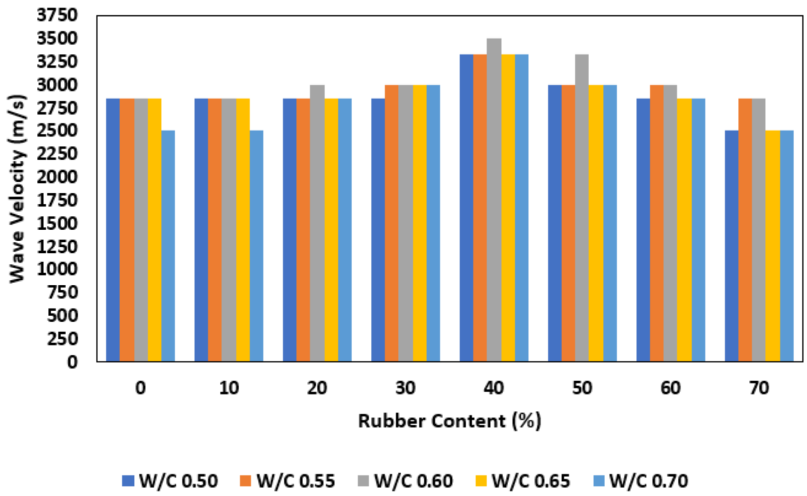

Figure 4.8: Wave Velocity Versus Rubber Content of the 56th Day Result

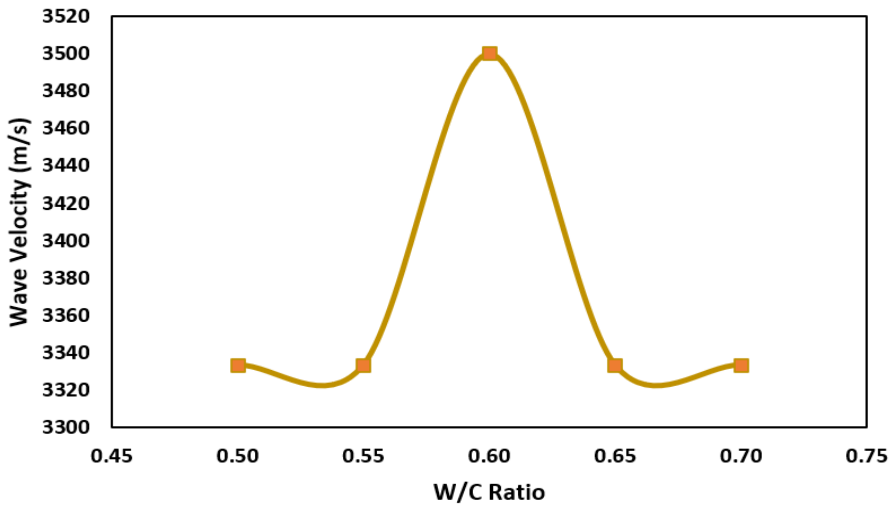

Figure 4.9: Wave Velocity Versus W/C Ratio of the 40% Rubber Content on 56th Day Result

Based on the data shown in Figure 4.8, it can be observed that an increase in rubber content leads to an increase in wave velocity. However, it is important to note that an excessively high rubber content can result in a drop in wave velocity, when considering the same curing day and w/c ratios. For instance, for a w/c 0.60 and a curing time of 56 days for concrete specimens, the wave velocity at 0% rubber content is 2857.143 m/s, increases to 3500.000 m/s at 40% rubber content, and then decreases to 2857.143 m/s at 70% rubber content. The observed increase in wave velocity, ranging from 0% to 40% rubber content, can be attributed to the disparity in particle size between the rubber and the fine aggregate. This is mostly owing to the fact that the rubber particles possess a finer granularity compared to the fine aggregate. The addition of a filling material can contribute to the reduction of voids and capillary pores in concrete, resulting in increased density and less availability of gaps or pathways for elastic waves to propagate. Consequently, this leads to an increase in wave velocity. The drop in wave velocity from 40% to 70% rubber content can be attributed to the inherent characteristics of rubber particles. When the rubber content exceeds a certain limit, it will block the transmission of waves through the rubberized lightweight foamed concrete. Scattering occurs when the P-wave undergoes propagation across a medium, resulting in an increase in the time required for traversal of that medium. The wave velocity is inversely proportional to the duration of time travel, such that an increase in time travel results in a decrease in wave velocity.

Table 4.16 demonstrates an increase in wave velocity from 2000.000m/s to 2857.143m/s when the curing period is extended from 1 day to 56 days. This observation is made at 0% rubber replacement and a w/c ratio 0.65. The curing process of rubberized lightweight foamed concrete over an extended duration results in the denser density of the material due to filling gaps by the C-S-H gel. The rate of energy transfer is higher when the P-wave propagates across the medium. Hence, it can be observed that the velocity of the wave has a positive correlation with the duration of the curing period.

Figure 4.9 shows that the wave velocity obtained via ultrasonic pulse velocity was compared to the w/c ratio. It was observed that w/c ratios of 0.50, 0.55, 0.65, and 0.70 exhibited the same wave velocity value of 3333.333m/s on the 56th day. However, with a w/c ratio of 0.60 with a 40% rubber content, the wave velocity was measured to be 3500m/s on the 56th day. The increase in wave velocity from w/c0.55 to w/c0.60 has a 5% increment, and it can be attributed to the higher water absorption capacity of rubber particles compared to fine aggregate. This is due to the larger surface area of rubber particles requiring more water. The decrease in wave velocity when increasing the w/c ratio from 0.60 to 0.65 in rubberised lightweight foamed concrete can be attributed to the excess rubber content, which leads to the formation of voids caused by the surplus water in the mixture. Scattering will occur due to a void when the P-wave propagates through the medium. Therefore, the wave velocity will increase and decrease in a certain w/c ratio, like the result obtained in this study. Hence, the rubber content, w/c ratio, and curing duration will influence the wave velocity of rubberised lightweight foamed concrete. Hence, from the P-wave velocity results, the rubberised lightweight foamed concrete brings more advantages than the lightweight foamed concrete.

4.5 Correlation between Compressive Strength and P-Wave Parameters

Studying the relationship between the wave parameters obtained through NDT and the compressive strength results obtained through conventional DT is crucial in establishing the efficacy of elastic wave forecasting for the compressive strength of rubberised lightweight foamed concrete. The variables that exhibit a correlation with compressive strength include the amplitude and velocity of the waves. The regression coefficient derived from the correlation analysis between compressive strength and wave amplitude and velocity indicates the parameter's predictive capability for estimating compressive strength.

4.5.1 Correlation Between the Compressive Strength and P-Wave Amplitude

A graph was constructed to illustrate the relationship between the mixed proportion of compressive strength and P-wave amplitude. The correlation between wave amplitude and compressive strength was observed across all mix proportions, ranging from 0% to 70% of acceptable aggregate rubber replacement content. This correlation was examined at several curing periods (1-day, 7-day, 28-day, and 56-day) and with varying w/c ratios. The association could have been visually shown through distinct graphs, limiting the efficacy of observing and analysing the relationship between compressive strength and wave amplitude. The relationship between compressive strength and P-wave amplitude at various w/c ratios is depicted in Figures 4.10, 4.11, 4.12, 4.13, and 4.14.

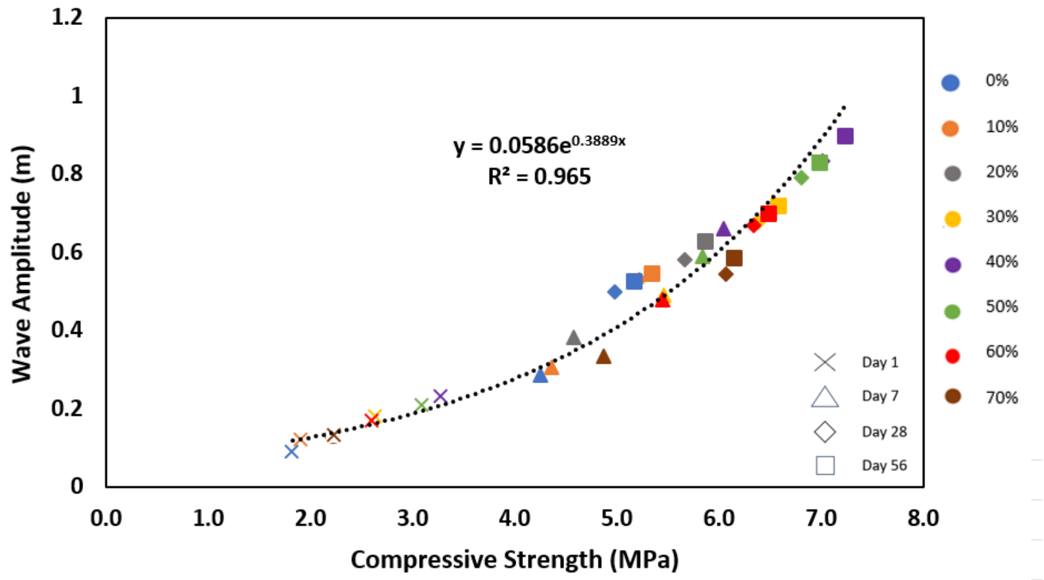

Figure 4.10: Correlation between P-wave Amplitude and Compressive Strength at W/C 0.50 with the Results of Day 1st to 56th of Curing Period

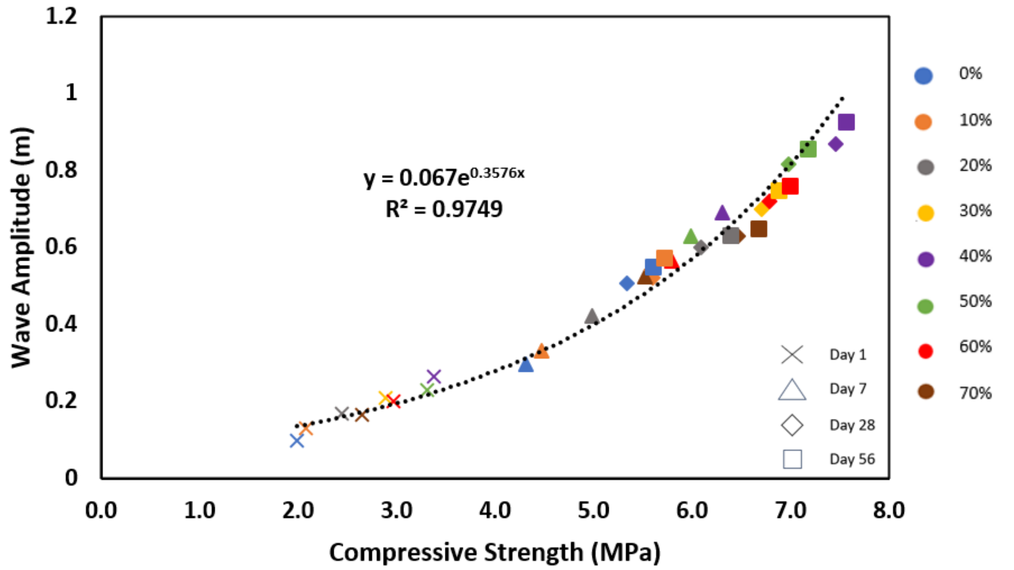

Figure 4.11: Correlation between P-wave Amplitude and Compressive Strength at W/C 0.55 with the Results of Day 1st to 56th of Curing Period

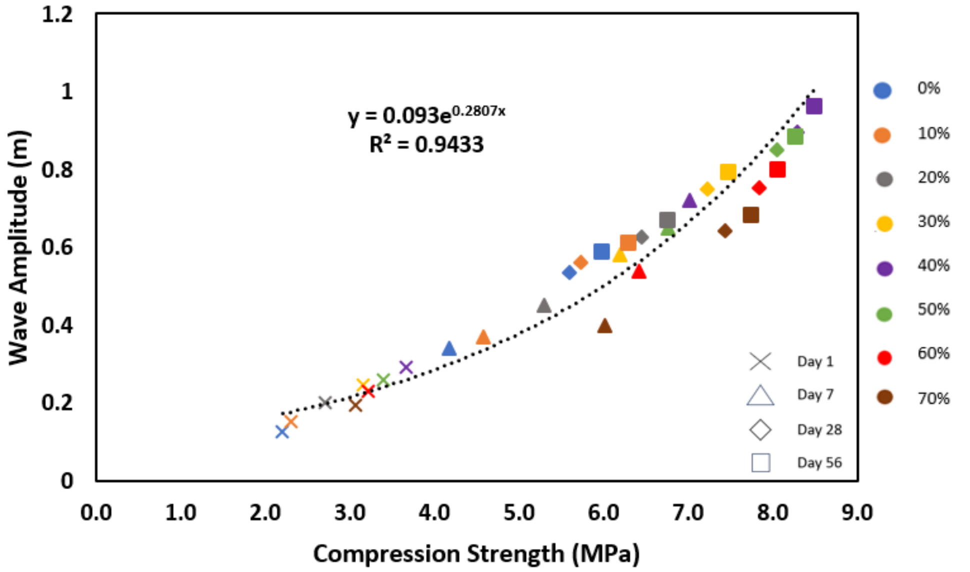

Figure 4.12: Correlation between P-wave Amplitude and Compressive Strength at W/C 0.60 with the Results of Day 1st to 56th of Curing Period

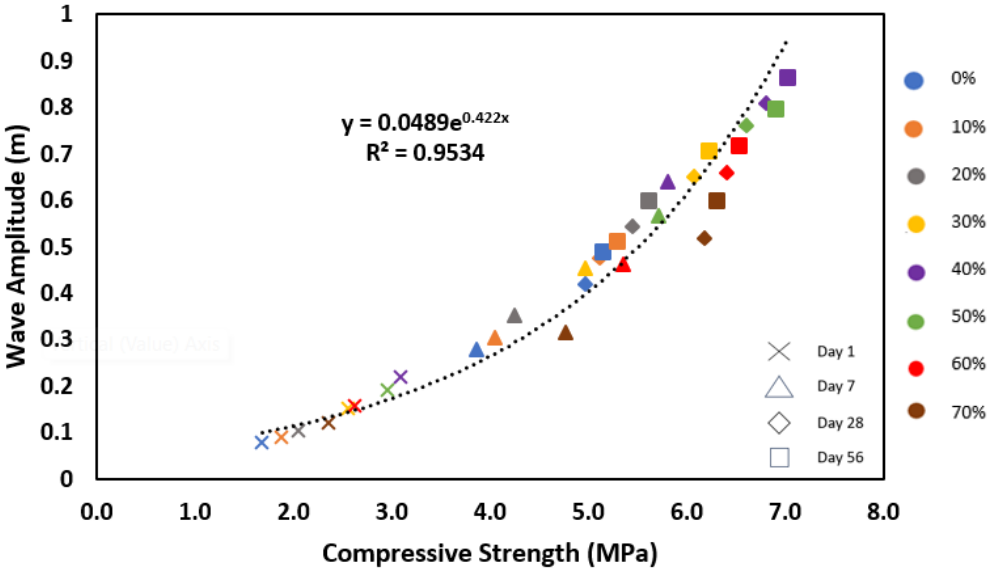

Figure 4.13: Correlation between P-wave Amplitude and Compressive Strength at W/C 0.65 with the Results of Day 1st to 56th of Curing Period

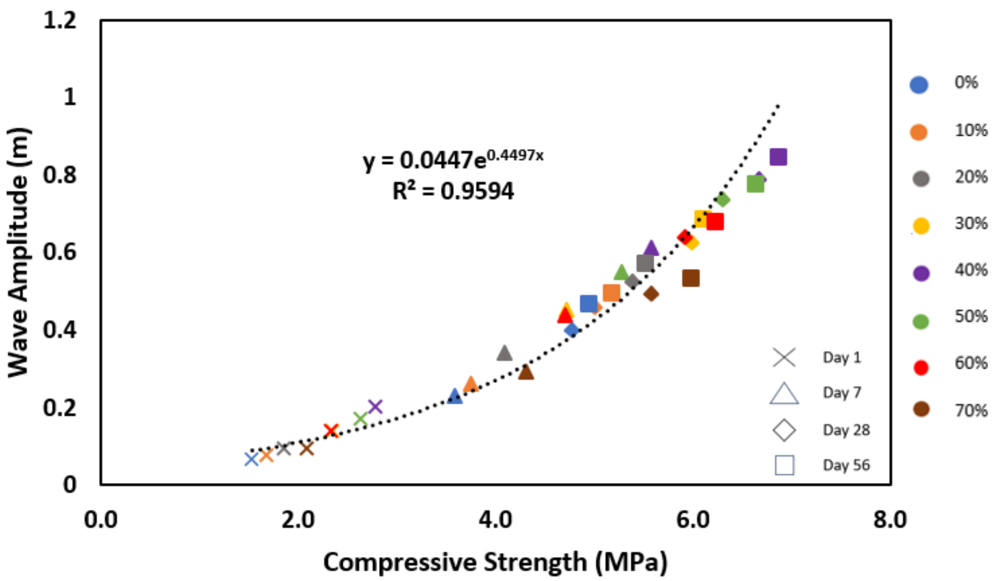

Figure 4.14: Correlation between P-wave Amplitude and Compressive Strength at W/C 0.70 with the Results of Day 1st to 56th of Curing Period

Figure 4.10 shows a positive correlation between wave amplitude and the exponential increase in compressive strength. The amplitude of the P-wave has a positive correlation with the rise in compressive strength. The graphic displays a positive sloping curve representing the trend line indicating the relationship between compressive strength and P-wave amplitude. The analysis of P-waves involves the use of energy levels as a means to indicate the magnitude of the P-wave. The findings indicate a positive correlation between the compressive strength of rubberised lightweight foamed concrete and the energy level of P-waves. This can be attributed to reduced energy dissipation as the P-waves go through regions of higher compressive strength. The equation depicted in each graph represents the trend line that characterises the association between compressive strength and P-wave amplitude. As seen previously, the regression degree spans from 0.9433 to 0.9749. The observed high degree of regression suggests that the amplitude of the P-wave can be effectively utilised as a predictive indicator for the compressive strength of rubberised lightweight foamed concrete.

Figure 4.11 displays the P-wave amplitude observed over the day one curing period, ranging from 0.097342m to 0.265118m. On the 56th day, there was an observed rise in the amplitude of the P-waves, with values ranging from 0.548942m to 0.925724m. The observed amplification in magnitude can be attributed to rubberised lightweight foamed concrete undergoing a hardening and hydration process. The strength and hardening of rubberised lightweight foamed concrete increase with an extended curing period. The process of hydration takes place, resulting in the formation of a C-S-H gel. The gel substance effectively occupies the voids inside the rubberised lightweight foamed concrete, resulting in a robust connection between the particles. Consequently, the reduction in porosity leads to an increase in compressive strength throughout the operation. When the P-wave propagates through the medium, a smaller amount of energy is dissipated into the air void space, amplifying the wave's amplitude.

Moreover, it has been observed that there is a direct correlation between the increase in rubber content and the amplification of P-wave amplitude, as well as the enhancement of compressive strength. Figure 4.12 illustrates the range of P-wave amplitudes, varying from 0.589271m to 0.961578m, corresponding to rubber replacement percentages ranging from 0% to 70% throughout a curing time of 56 days. The amplitude of the P-wave exhibits an increase from 0% to 40% in rubber content replacement, ranging from 0.589271m to 0.961578m. However, beyond the 40% rubber replacement content, the compressive strength and P-wave amplitude experience a decline, reaching a value of 0.684866m from 0.961578m. This observed increase in compressive strength and P-wave amplitude can be attributed to the presence of rubber particles that are smaller in size than the fine aggregate. These rubber particles effectively fill the voids within the rubberised lightweight foamed concrete. Consequently, the compressive strength increases, leading to a more rapid dissipation of the P-wave energy into the medium. The energy continues to grow, increasing the amplitude of the P-wave.

However, it has been shown that the compressive strength and P-wave amplitude exhibit a reduction beyond a rubber replacement content of 40%. This decline might be attributed to excessive rubber content in the concrete, which leads to a weaker bonding between the particles in the specimens. The reason for this phenomenon is that fine aggregate exhibits a higher capacity to establish stronger interparticle bonding in comparison to rubber particles. The compressive strength and P-wave amplitude show a decrease with a 40% replacement of rubber content. This decline can be attributed to the weakened bonding within the concrete, which makes it more susceptible to cracking. Consequently, a gap increase occurs, further contributing to the reduction in P-wave amplitude.

4.5.2 Correlation between Compressive Strength and P-Wave Velocity

P-wave velocity and compressive strength were plotted for each w/c ratio at various curing periods, including 1-day, 7-day, 28-day, and 56-day. All mix proportions were used in the analysis. The link between compressive strength and P-wave velocity at various w/c ratios is depicted in Figures 4.15, 4.16, 4.17, 4.18, and 4.19 below.

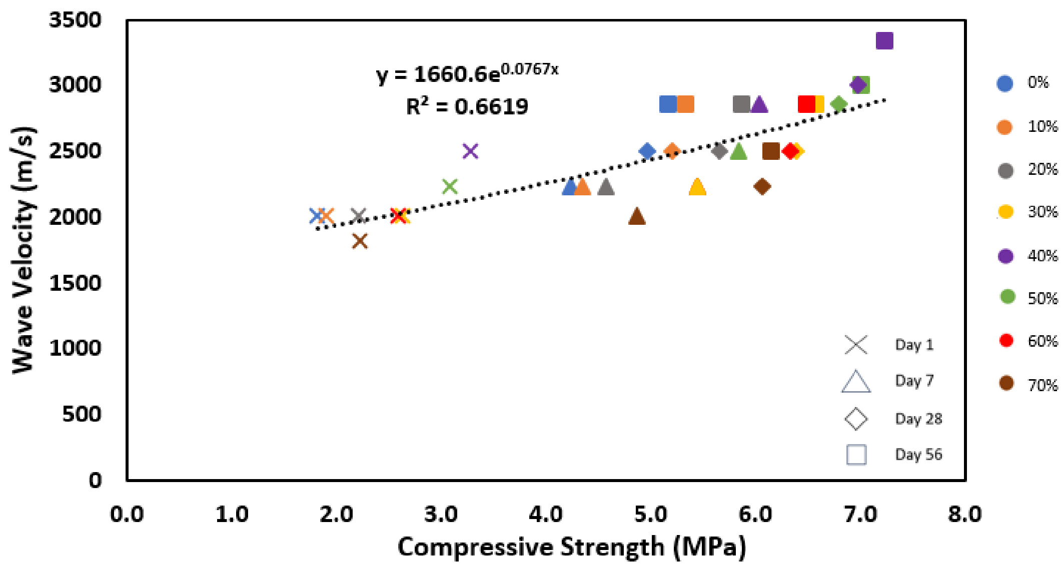

Figure 4.15: Correlation between P-wave Velocity and Compressive Strength at W/C 0.50 with the Results of Day 1st to 56th of Curing Period

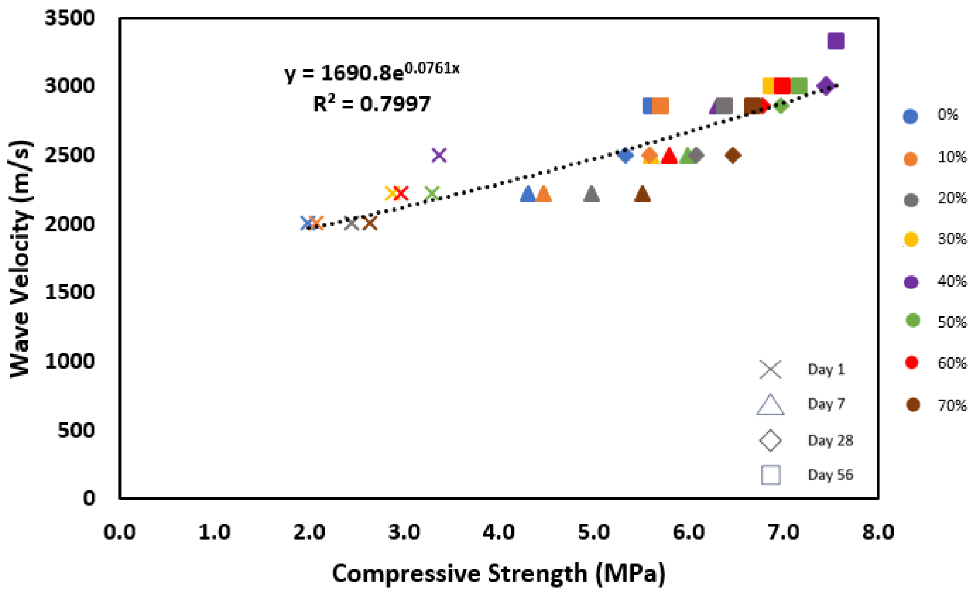

Figure 4.16: Correlation between P-wave Velocity and Compressive Strength at W/C 0.55 with the Results of Day 1st to 56th of Curing Period

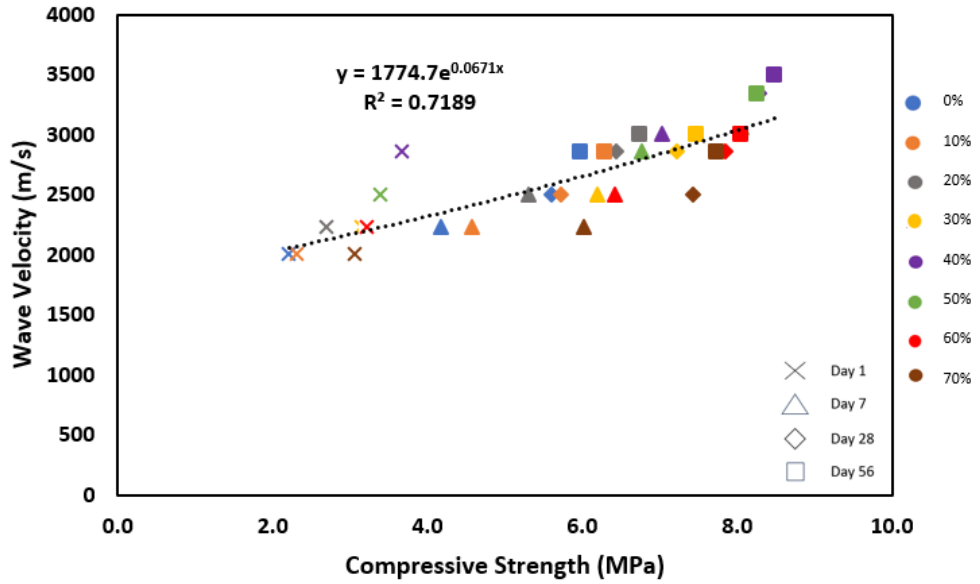

Figure 4.17: Correlation between P-wave Velocity and Compressive Strength at W/C 0.60 with the Results of Day 1st to 56th of Curing Period

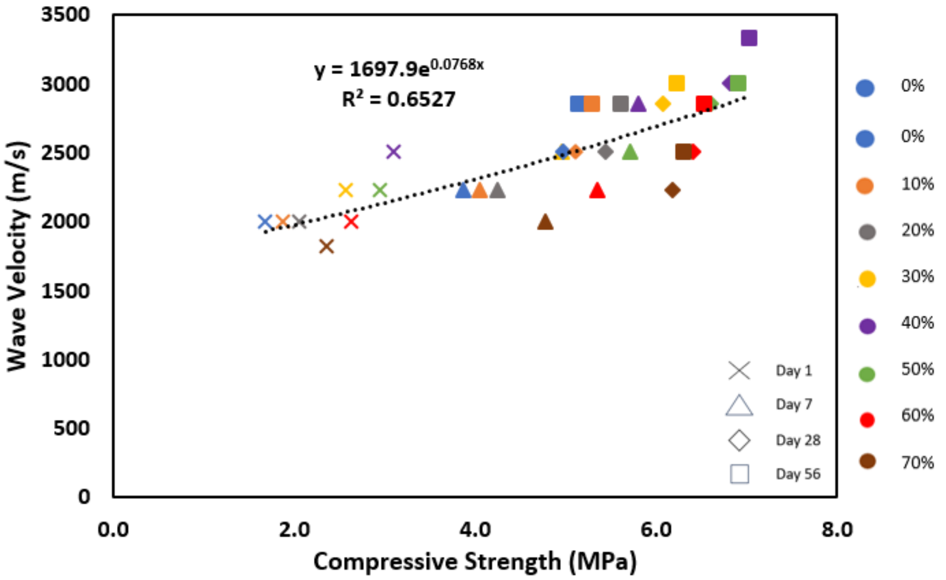

Figure 4.18: Correlation between P-wave Velocity and Compressive Strength at W/C 0.65 with the Results of Day 1st to 56th of Curing Period

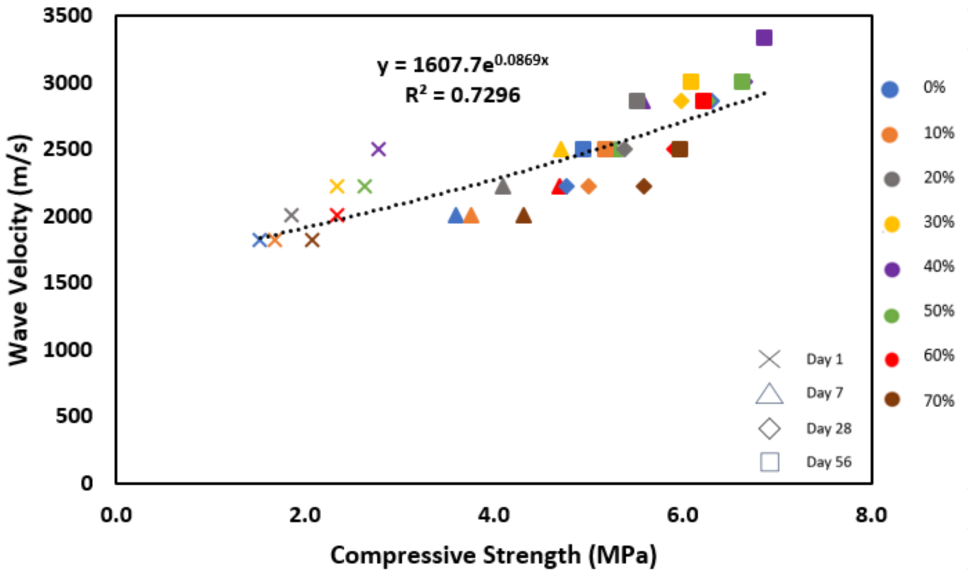

Figure 4.19: Correlation between P-wave Velocity and Compressive Strength at W/C 0.70 with the Results of Day 1st to 56th of Curing Period

The increased compressive strength is directly correlated with the corresponding rise in P-wave velocity. The trend line in the graph exhibits a continuously rising curve, indicating a positive association between P-wave velocity and compressive strength. This correlation can be mathematically represented by the equation depicted on the graph. The regression degree for the association ranges from 0.6527 to 0.7997. The findings of this study suggest that an increased degree of regression demonstrates the suitability of P-wave velocity as a predictive factor for the compressive strength of rubberised lightweight foamed concrete.

During the initial one-day curing period, the P-wave velocity range ranges from 2000 m/s to 2857.143 m/s for a w/c 0.60, as shown in Figure 4.17. The P-wave velocity exhibits an expanded range of values when the curing period is extended. The velocity range observed for the 56th day spans from 2857.143m/s to 3500m/s. The relationship between porosity, voids, P-wave velocity, and compressive strength is significant. The rubberised lightweight foamed concrete undergoes an extended curing period to facilitate its hardening and hydration. Chemical reactions take place between cementitious material and water, resulting in the formation of the C-S-H gel. This gel links the particles together and fills the voids within them. The formation refers to a solid structure that has enhanced compressive strength. P-waves exhibit a higher velocity while propagating through a solid medium than an air medium. Consequently, the velocity of P-waves transmitted through the material increased in direct proportion to the duration of the healing time.

Figure 4.18 demonstrates that during a 56-day curing period, the P-wave velocity range increases from 2500 m/s to 3333.33 m/s when the rubber content is raised from 0% to 70%. The study's findings showed a decrease in the velocity of the P-wave as the proportion of rubber in the medium increased. Furthermore, the creation of air voids resulted in a decrease in both P-wave velocity and compressive strength. The presence of air voids inside the medium will decrease the velocity of the P-wave as it propagates through the medium. Consequently, an increase in rubber replacement leads to a decrease in both the velocity of the P-wave and the compressive strength of the rubberised lightweight foamed concrete.

4.6 Flexural Strength & Splitting Tensile Strength

The present study investigates the flexural strength and splitting tensile strength of rubberised lightweight foamed concrete with a w/c 0.60. To evaluate their tensile strength, the concrete mixture of w/c 0.60 is used as the sample material for casting specimens. The compressive strength exhibits the most desirable outcome when the w/c ratio is 0.60, mainly when the rubber content is 40%. Three different types of rubber content specimens were utilised to assess the effects of varying rubber content percentages. The specimens had three different rubber content percentages: 0% (control), 40%, and 70% with the w/c 0.60. Figures 4.20 and 4.21 depict the graph in order to enhance comprehension of the graph's pattern. Figure 4.20 shows the higher flexural strength of 1.64MPa of 40% rubber content followed by 1.52MPa of 70% rubber content, and the lowest is the control mixture with a value of 1.46. However, Figure 4.21 shows the splitting tensile strength of 40% rubber content with a higher value of 0.90MPa followed by 70% rubber content with a value of 0.83MPa, and the lowest splitting tensile strength is the control mixture of 0.74MPa.

	0	40	70
W/C 0.60	1.46	1.64	1.52

Figure 4.20: Flexural Strength Result on the 28th Day

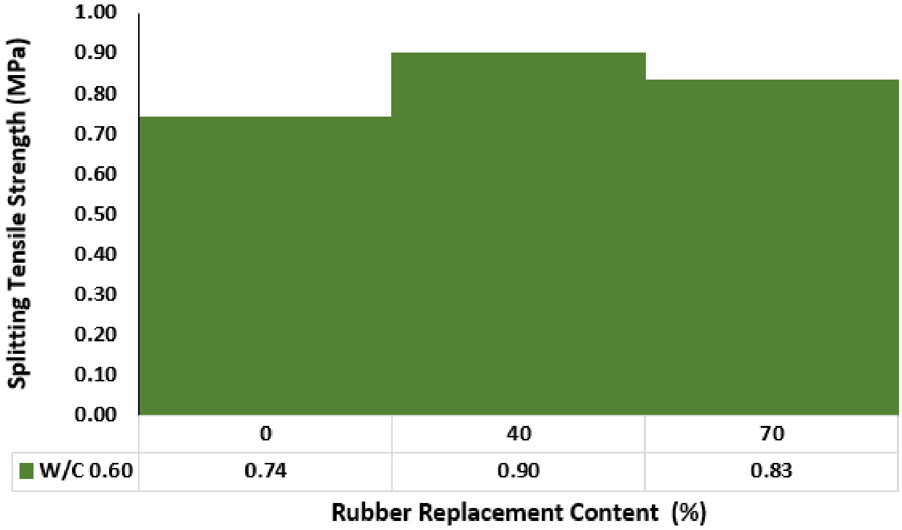

Figure 4.21: Splitting Tensile Strength Result on the 28th Day

Figures 4.20 and 4.21 depict the results of flexural strength and splitting tensile strength, respectively, after a 28-day curing period. As demonstrated, the flexural strength and splitting tensile strength exhibit an increasing trend from 0% to 40% rubber content, followed by a subsequent decrease at 70%. Theoretically, increased rubber content is associated with decreased flexural and splitting tensile strength. However, this study demonstrates that a rubber component of 40% yields the most ideal outcome compared to other percentages. This phenomenon occurs because of the relatively smaller size of the rubber particles in comparison to the fine aggregate. The reduction in rubber particle size can contribute to the effective filling of voids within the mixture, enhancing the concrete's density. However, adding rubber material led to a notable enhancement in flexural and flexural strength, ranging from 0% to 40%.

Nevertheless, an excessive amount of rubber particles in the concrete mixture can have an adverse effect on the bonding between these particles. The fine aggregate exhibits a greater capacity for establishing robust interparticle bonds, whereas the rubber, owing to its inherent softness, is limited to forming weaker interparticle bonds. The decrease in concrete strength may be observed in Figure 4.20 and Figure 4.21. Rubber particles possess a distinct feature, namely elasticity. Compared to the control samples, the utilisation of rubber elasticity can contribute to the improvement of deflection in rubberised lightweight foamed concrete prior to failure. Hence, an increase in the proportion of rubber content is associated with a reduction in strength. However, incorporating rubber of smaller particle sizes using a suitable technique can enhance the strength of rubber concrete (Roychand, et al., 2020).

4.7 Summary

This chapter comprehensively analyses the compressive strength achieved through conventional NDT and the P-wave characteristics obtained through NDT method. The NDT yields parameters such as P-wave amplitude and velocity. The rubber content, curing period, and w/c ratio significantly influence the compressive strength, P-wave amplitude, and velocity. The relationship between compressive strength and P-wave amplitude, as well as the relationship between compressive strength and P-wave velocity, has been graphed and examined. Based on the correlation graph, it can be observed that both P-wave amplitude and P-wave velocity exhibit a higher degree of regression. The regression coefficients for P-wave amplitude range from 0.9433 to 0.9749, whereas the regression coefficients for P-wave velocity range from 0.6619 to 0.7997. The regression coefficients of P-wave amplitude exhibit values exceeding 0.8, which suggests that the selected parameters possess a high level of suitability for predicting the compressive strength of rubberised lightweight foamed concrete. Nevertheless, the regression coefficients of P-wave velocity exhibit values below 0.8, suggesting that these parameters are less suitable for predicting the compressive strength of rubberised lightweight foamed concrete. Hence, it may be suggested that the reliability of the P-wave amplitude surpasses that of the P-wave velocity owing to its more significant degree of regression.

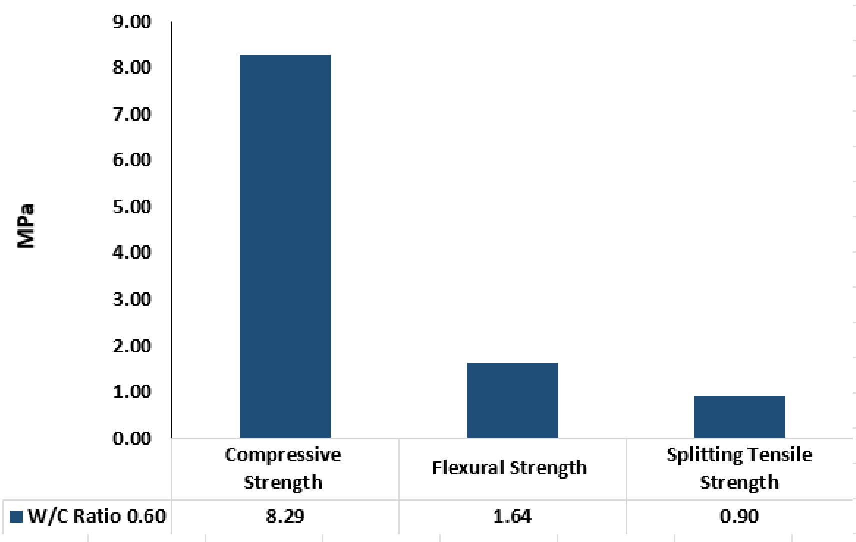

Figure 4.22: Mechanical Strength of the Rubberised Lightweight Foamed Concrete of W/C 0.60 with 40% Rubber Content

Figure 4.22 summarises the mechanical strength of the rubberised lightweight foamed concrete of w/c 0.60 with 40% rubber content. The results show that w/c 0.60 with 40% rubber content obtained the optimal results. Therefore, the rubberised lightweight concrete with a desirable mix proportion will produce better mechanical strength than the lightweight foamed concrete for this research's 1350kg/m^3 density.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Throughout the entirety of this study, four different tests were conducted on rubberised lightweight foamed concrete. These tests included traditional DT to determine compression strength, NDT method to assess compressive strength, flexural strength, and splitting tensile strength tests. The conventional DT approach involves using a compression testing machine, which yields compressive strength as the resultant outcome. The ultrasonic pulse velocity test, an elastic wave method, is a NDT method. Two P-wave characteristics have been acquired, namely P-wave amplitude and P-wave velocity. The outcomes strongly correlate with several factors, such as the rubber content, w/c ratio, and duration of the curing process. The maximum compressive strength, P-wave velocity, and P-wave amplitude values are achieved when the mix percentage undergoes an extended curing period and has a w/c ratio of 0.60, specifically with specimens containing 40% rubber content. A correlation exists between the amplitude and velocity of the P-wave and the compressive strength. The observed connection indicates a strong regression relationship between the P-wave amplitude parameters and the ability to forecast the compressive strength of rubberised lightweight foamed concrete. Nevertheless, despite the good regression degree shown in the association of P-wave velocity parameters, these parameters may not be very suitable for accurately predicting the compressive strength of rubberised lightweight foamed concrete. The reliability of the P-wave amplitude has a higher accuracy due to its higher regression degree, ranging from 0.9433 to 0.9749, compared to the P-wave velocity, which ranges from 0.6619 to 0.7997. The exponential equation derived from the correlation allows for the prediction of compressive strength by including the P-wave parameter. The flexural and splitting tensile strength tests yielded identical optimal flexural and splitting tensile strength values. The achieved values were 1.64MPa and 0.90MPa, respectively. The strengths of the specimens were determined by utilising a mixture of w/c ratio of 0.60, with a rubber content of 40%. In conclusion, the application of the non-destructive elastic wave method demonstrates its efficacy in predicting the compressive strength of rubberised lightweight foam concrete, primarily attributed to its higher regression degree. The study found that the specimens with a w/c ratio of 0.60 and a rubber content of 40% exhibited the highest level of strength compared to other rubber content percentage and w/c ratios. Therefore, the result proves that the rubberised lightweight foamed concrete has excellent mechanical strength than the lightweight foamed concrete.

5.2 Recommendations

A recommendation for future improvement for the study is employing oven drying as a method for drying the rubberised lightweight foamed concrete, compared to air drying, due to the possible influence of weather conditions on the air-drying temperature. In a rain situation, the temperature will likely be lower, unlike a state of complete dryness. Oven drying facilitates the establishment of a fixed temperature, ensuring a uniform drying of all concrete cube specimens. Consequently, it enhances the precision of the outcome. Next, the vebe test applies to the fresh concrete investigation, providing a more comprehensive analysis of the concrete mixture's appropriate mixing and ability to fulfil the specified specifications and performance requirements. Additionally, instead of manually hitting the concrete cube specimen with the pendulum, the elastic wave method uses a steel ball with a fixed position and angle. The variability in manually hitting the concrete cube specimen results from differences in the angle, position, and force applied, as it is challenging to consistently duplicate these factors for each hit. Employing a steel ball held in a stationary position and at a set angle makes it possible to maintain a consistent force exerted on the concrete cube specimen. As a result, the result's accuracy improves. One potential method for enhancing the precision of the outcome is to augment the quantity of samples utilised for each test. Scanning electron microscopy (SEM) can enhance the investigation of concrete specimens. SEM studies are valuable because they generate high-resolution pictures that facilitate in-depth analysis of tangible characteristics, including investigating the material's internal structure. This study enhances the comprehension and visualisation of the impact of crumb rubber on the properties of rubberised lightweight foamed materials.

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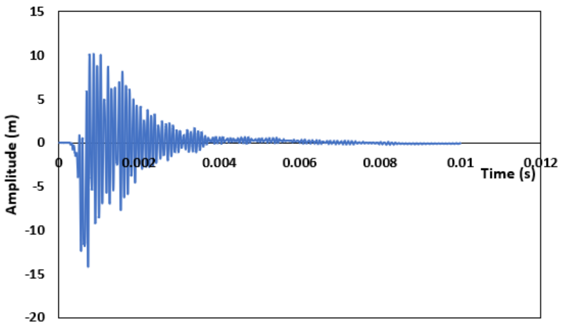
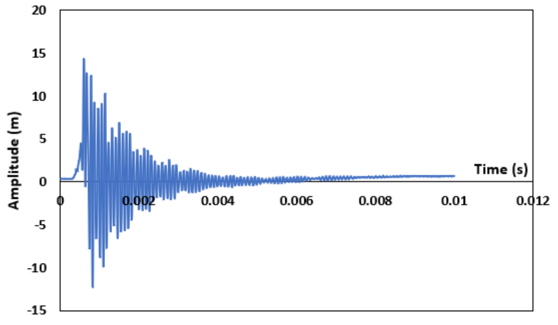
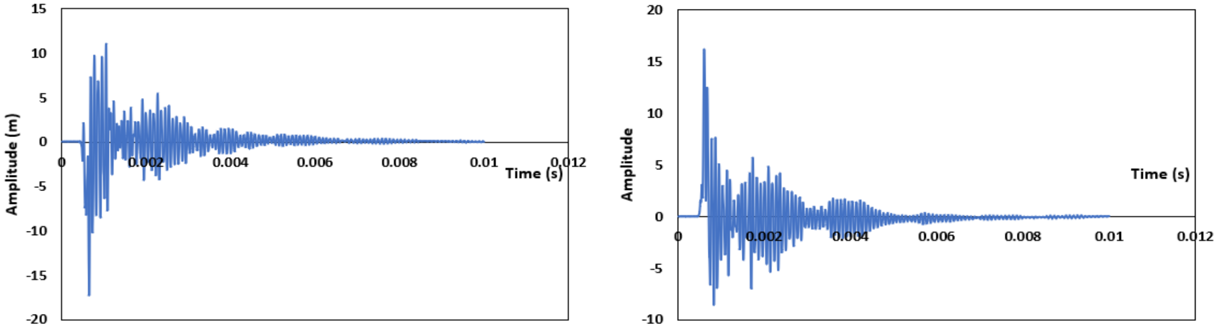
APPENDICES

Appendix A NDT Results Obtained from LabView Signal Express 2011

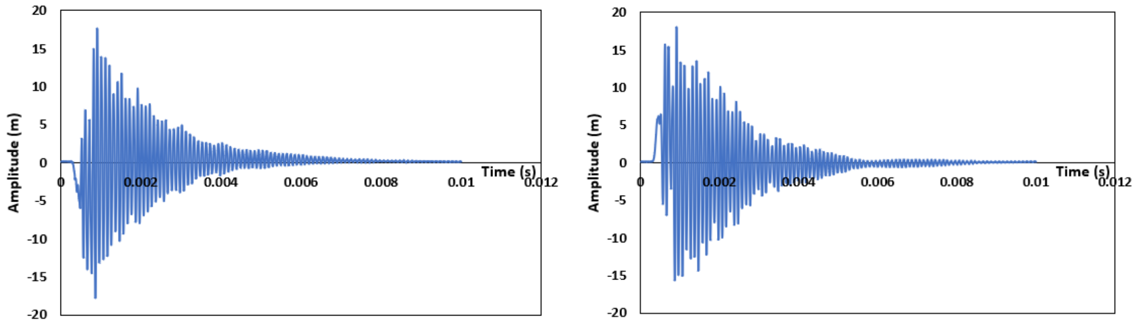




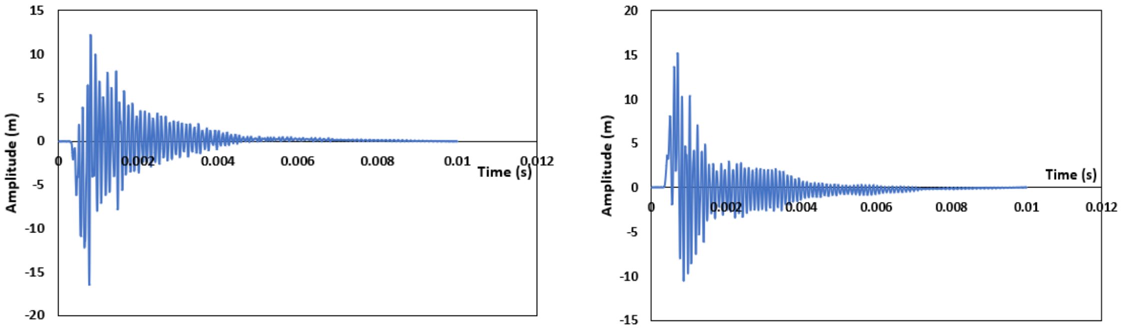
Appendix A-1: W/C 0.50 (Control) Result from NDT Test in Day 56



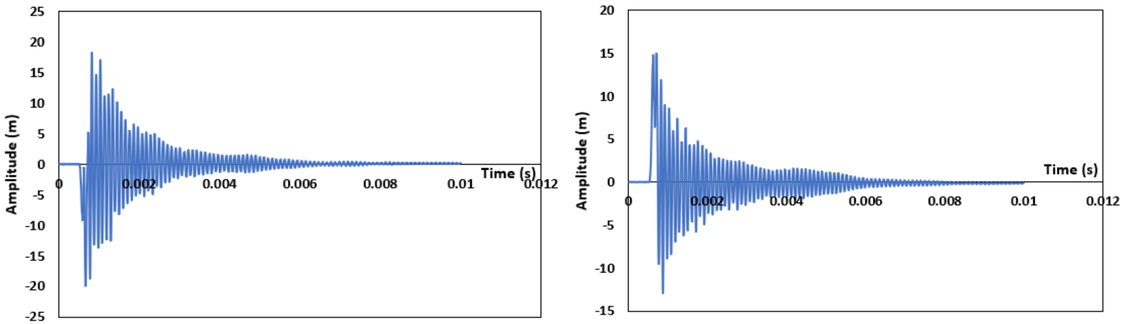
Appendix A-2: W/C 0.50 (10% Rubber Content) Result from NDT Test in Day 56



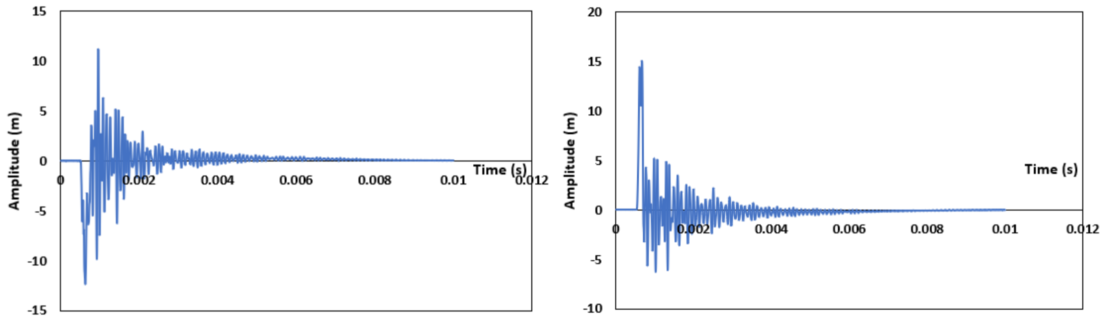
Appendix A-3: W/C 0.50 (20% Rubber Content) Result from NDT Test in Day 56



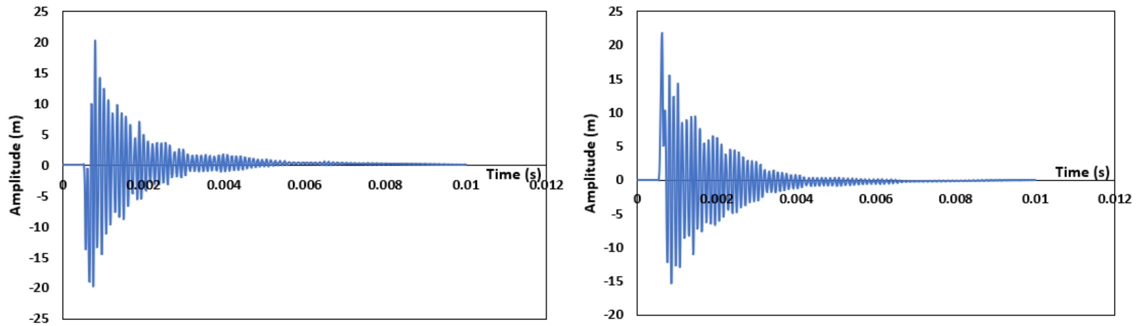
Appendix A-4: W/C 0.50 (30% Rubber Content) Result from NDT Test in Day 56



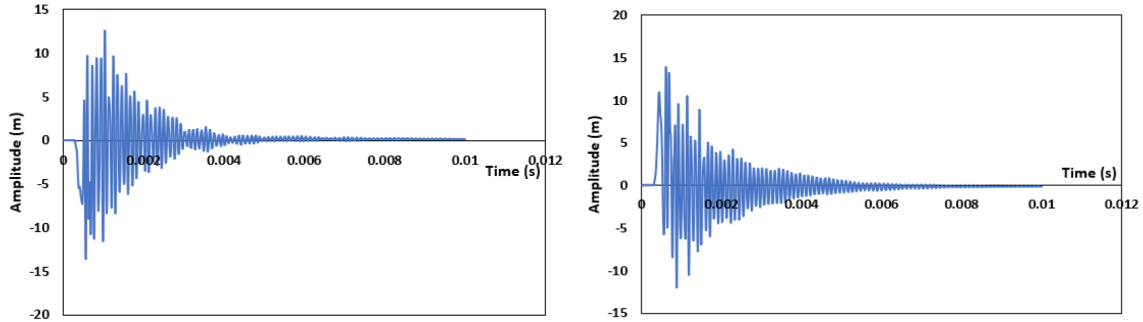
Appendix A-5: W/C 0.50 (40% Rubber Content) Result from NDT Test in Day 56



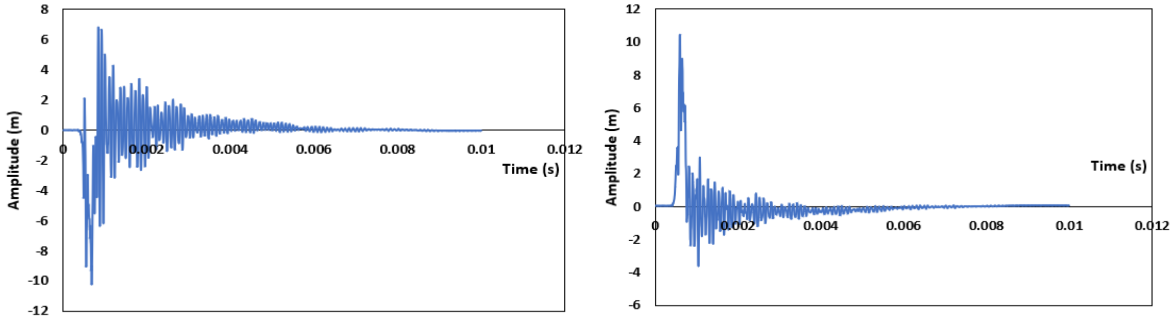
Appendix A-6: W/C 0.50 (50% Rubber Content) Result from NDT Test in Day 56



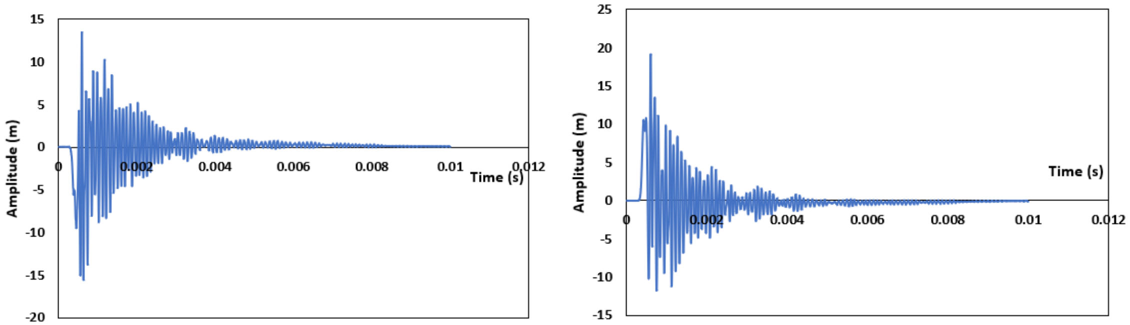
Appendix A-7: W/C 0.50 (60% Rubber Content) Result from NDT Test in Day 56



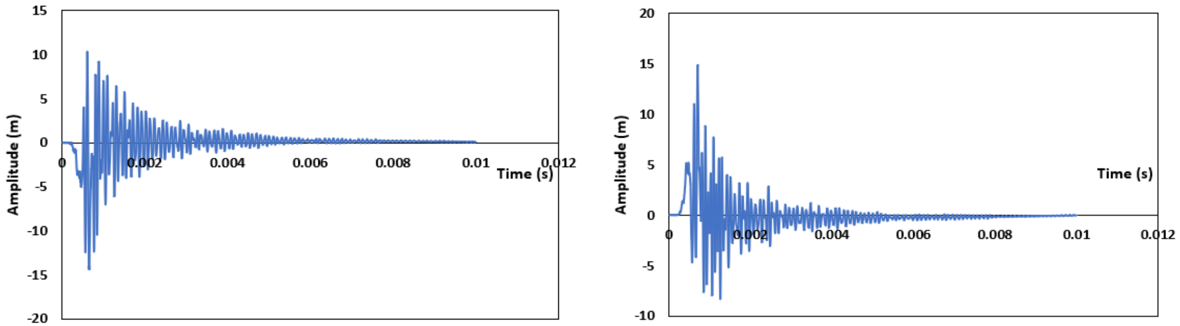
Appendix A-8: W/C 0.50 (70% Rubber Content) Result from NDT Test in Day 56



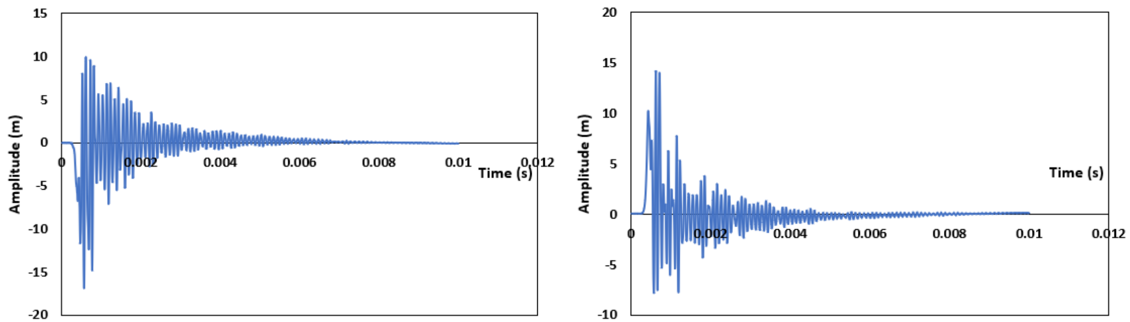
Appendix A-9: W/C 0.55 (Control) Result from NDT Test in Day 56



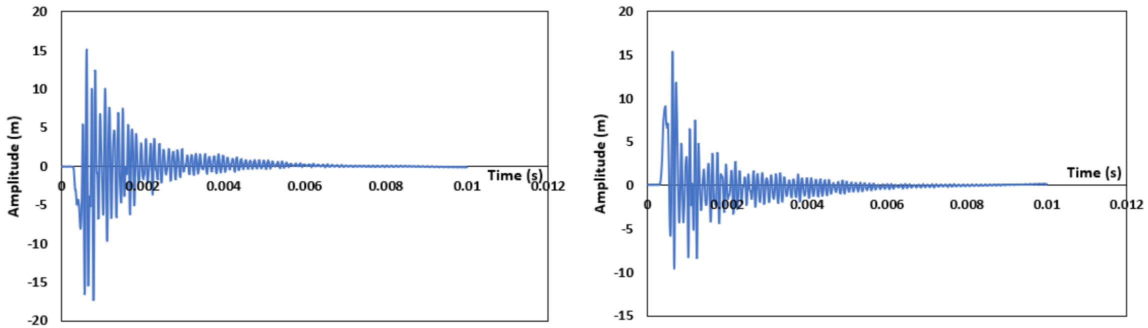
Appendix A-10: W/C 0.55 (10% Rubber Content) Result from NDT Test in Day 56



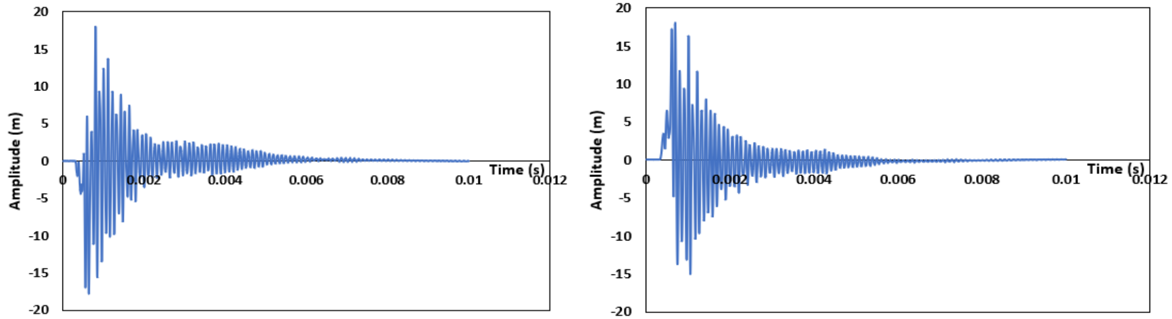
Appendix A-11: W/C 0.55 (20% Rubber Content) Result from NDT Test in Day 56



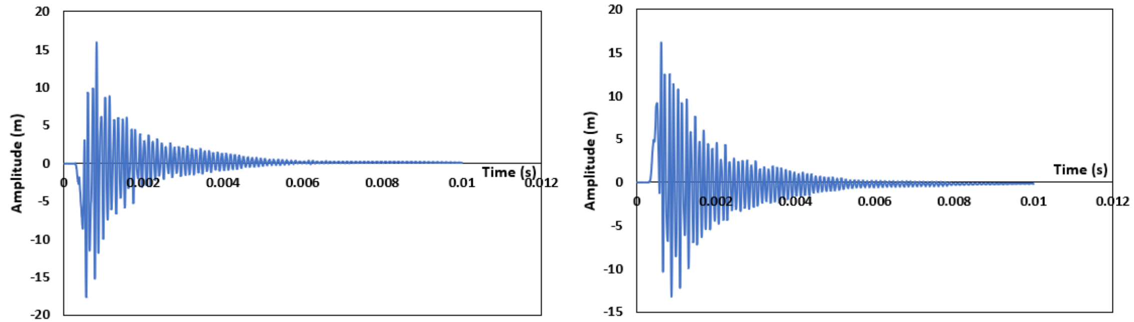
Appendix A-12: W/C 0.55 (30% Rubber Content) Result from NDT Test in Day 56



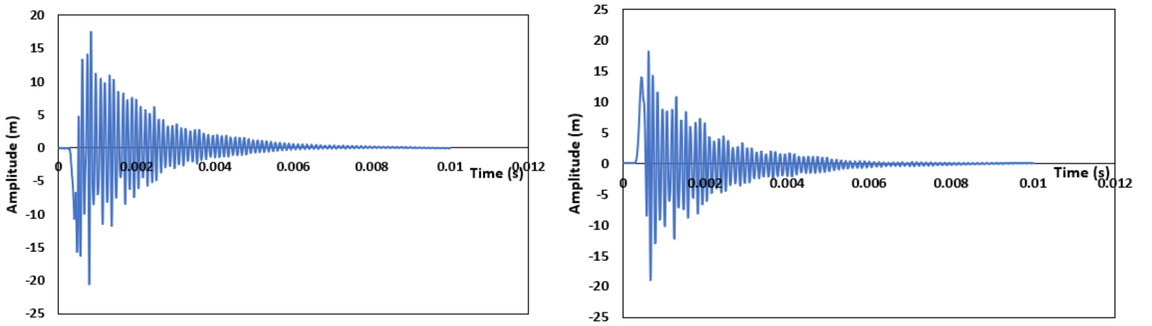
Appendix A-13: W/C 0.55 (40% Rubber Content) Result from NDT Test in Day 56



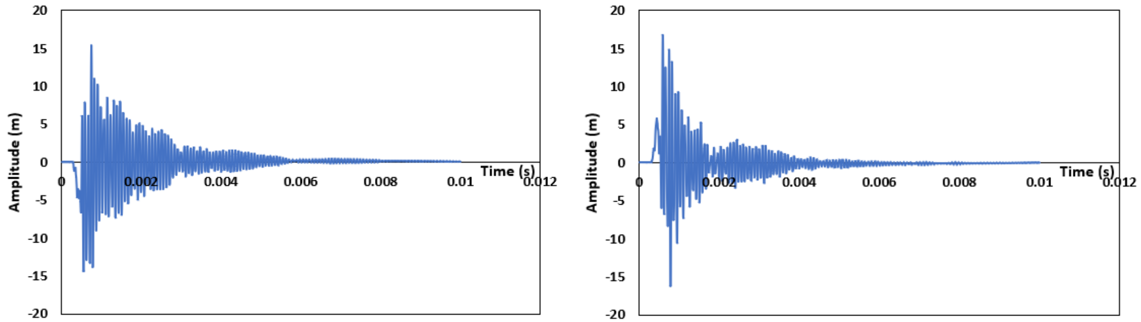
Appendix A-14: W/C 0.55 (50% Rubber Content) Result from NDT Test in Day 56



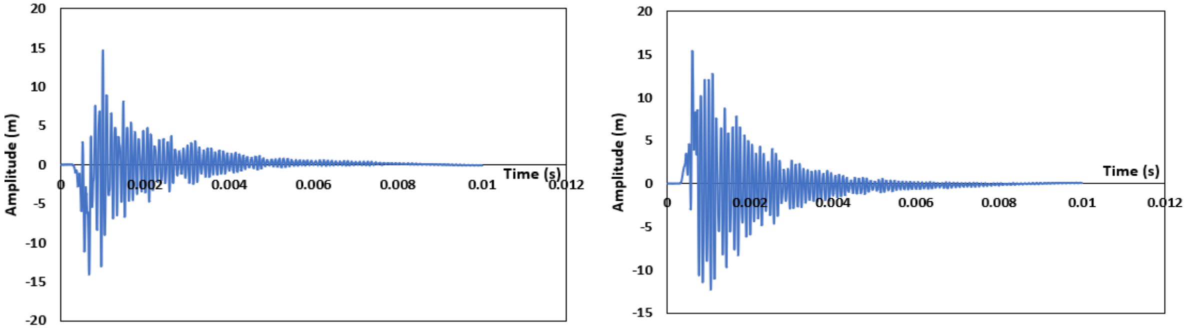
Appendix A-15: W/C 0.55 (60% Rubber Content) Result from NDT Test in Day 56



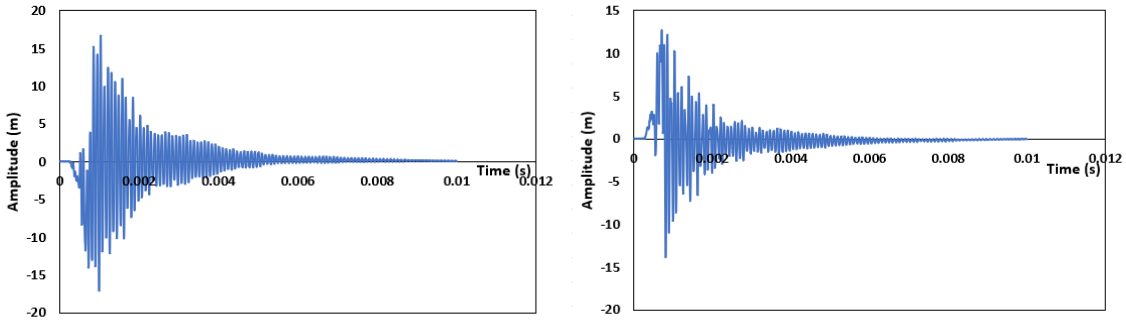
Appendix A-16: W/C 0.55 (70% Rubber Content) Result from NDT Test in Day 56



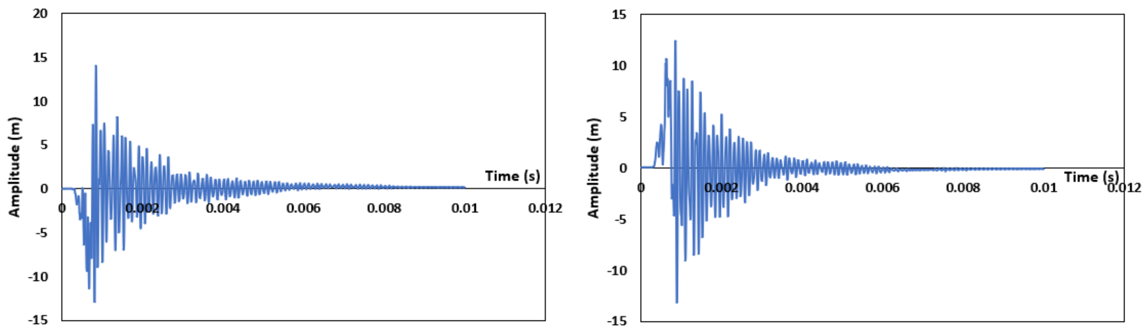
Appendix A-17: W/C 0.60 (Control) Result from NDT Test in Day 56



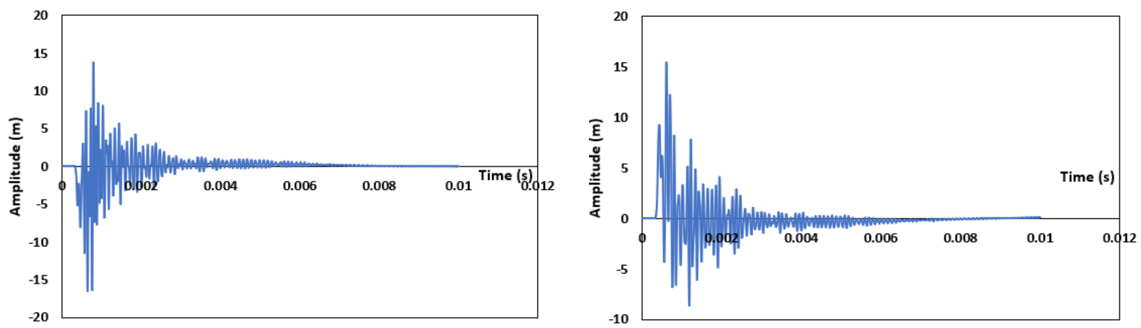
Appendix A-18: W/C 0.60 (10% Rubber Content) Result from NDT Test in Day 56



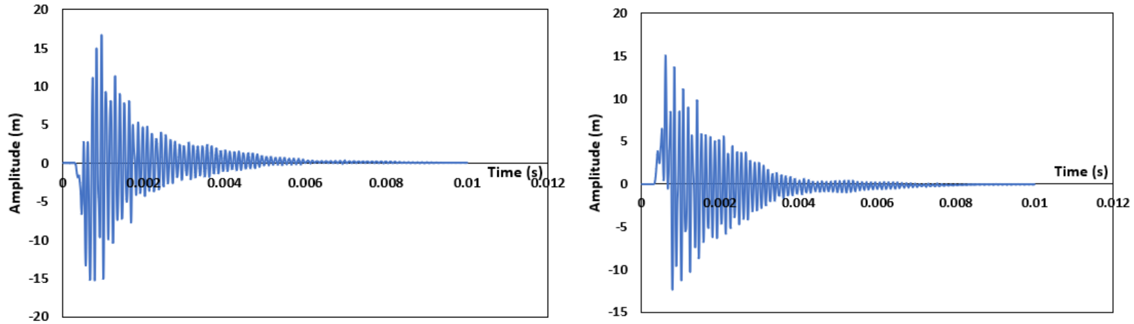
Appendix A-19: W/C 0.60 (20% Rubber Content) Result from NDT Test in Day 56



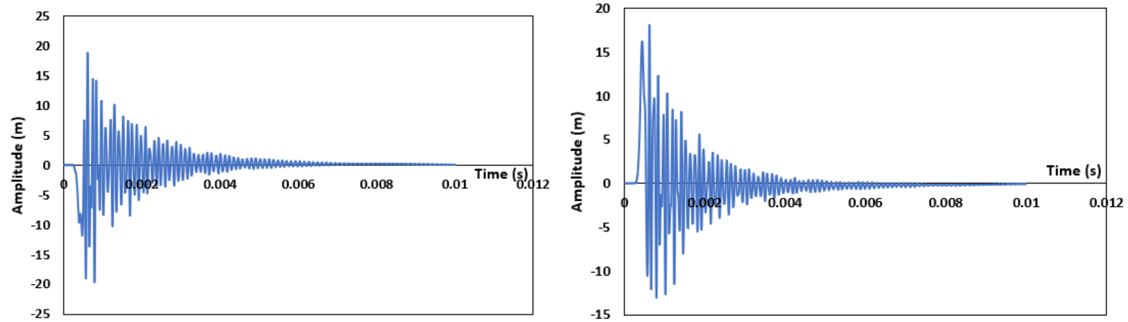
Appendix A-20: W/C 0.60 (30% Rubber Content) Result from NDT Test in Day 56



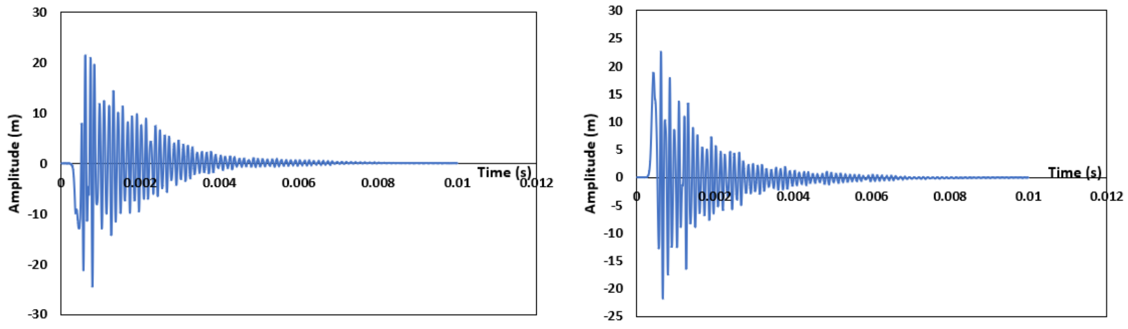
Appendix A-21: W/C 0.60 (40% Rubber Content) Result from NDT Test in Day 56



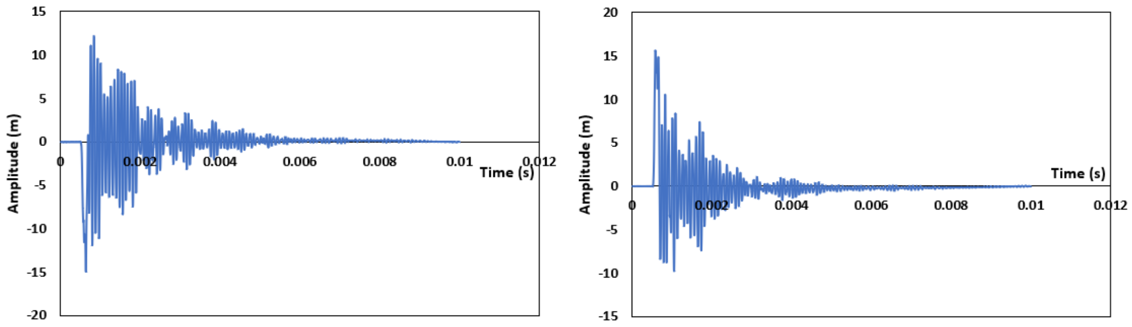
Appendix A-22: W/C 0.60 (50% Rubber Content) Result from NDT Test in Day 56



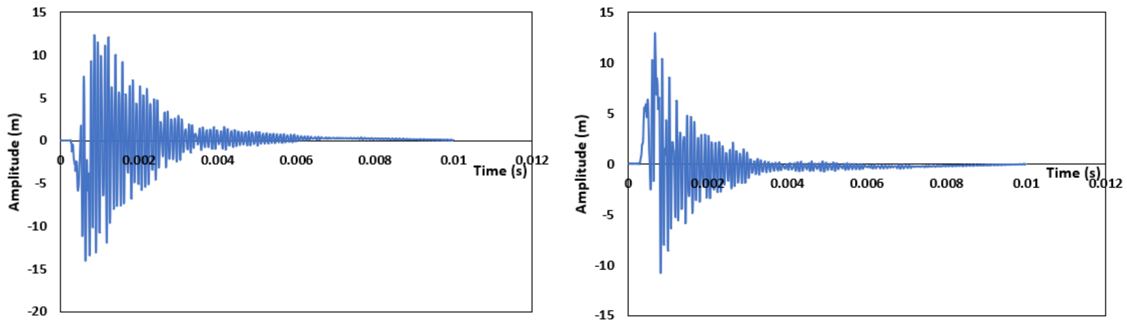
Appendix A-23: W/C 0.60 (60% Rubber Content) Result from NDT Test in Day 56



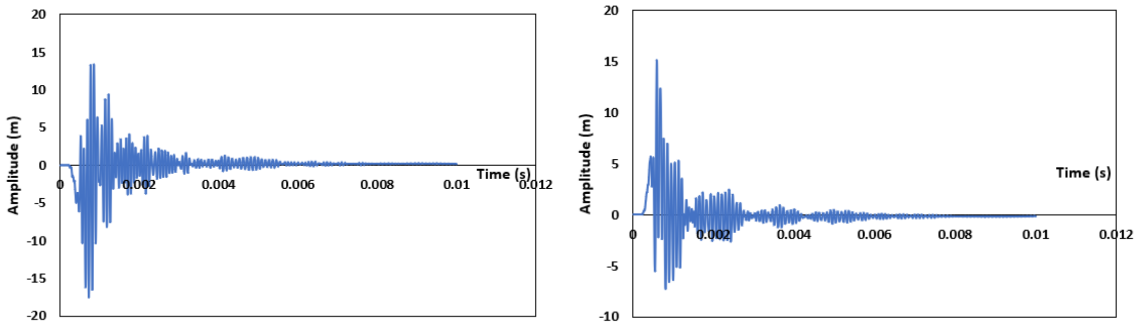
Appendix A-24: W/C 0.60 (70% Rubber Content) Result from NDT Test in Day 56



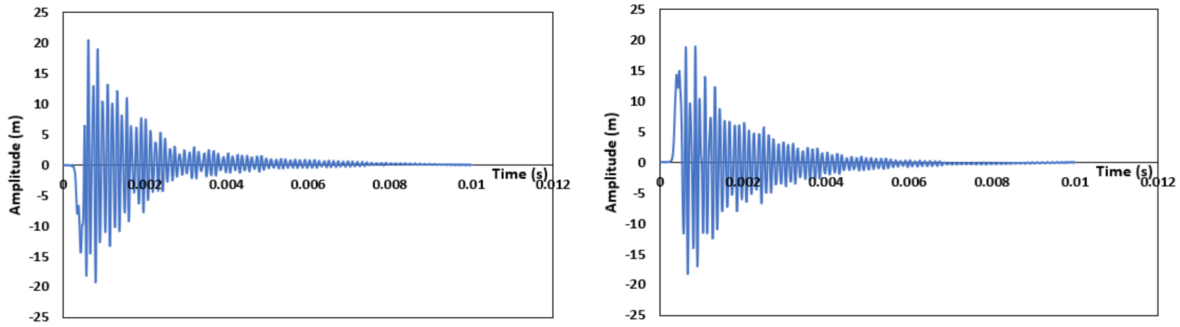
Appendix A-25: W/C 0.65 (Control) Result from NDT Test in Day 56



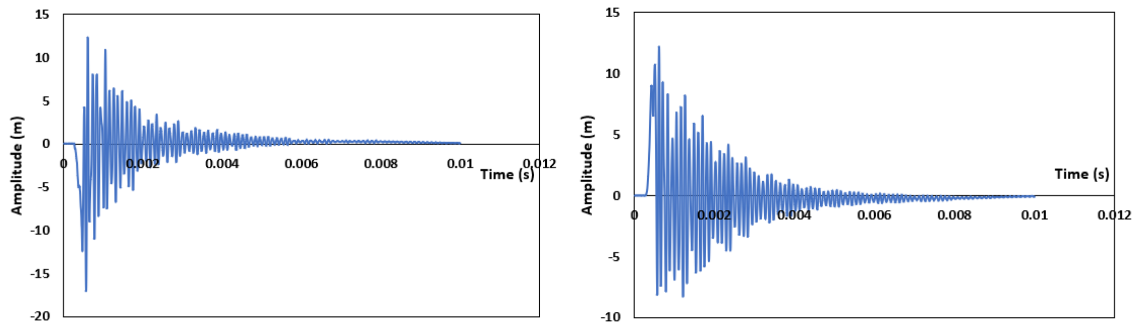
Appendix A-26: W/C 0.65 (10% Rubber Content) Result from NDT Test in Day 56



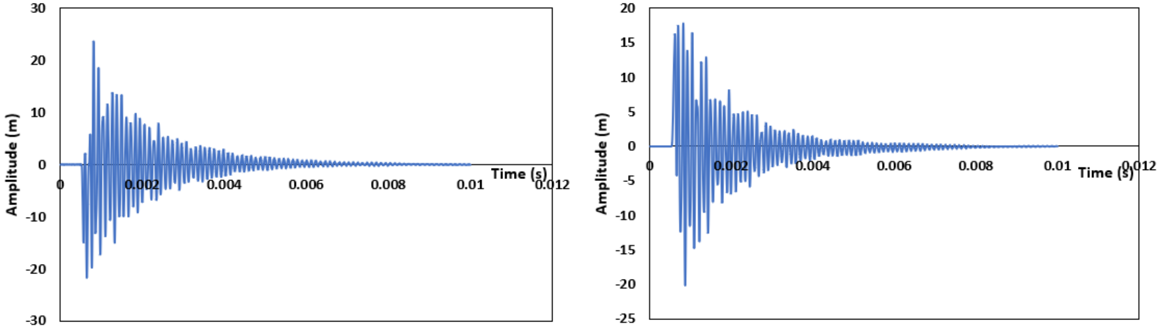
Appendix A-27: W/C 0.65 (20% Rubber Content) Result from NDT Test in Day 56



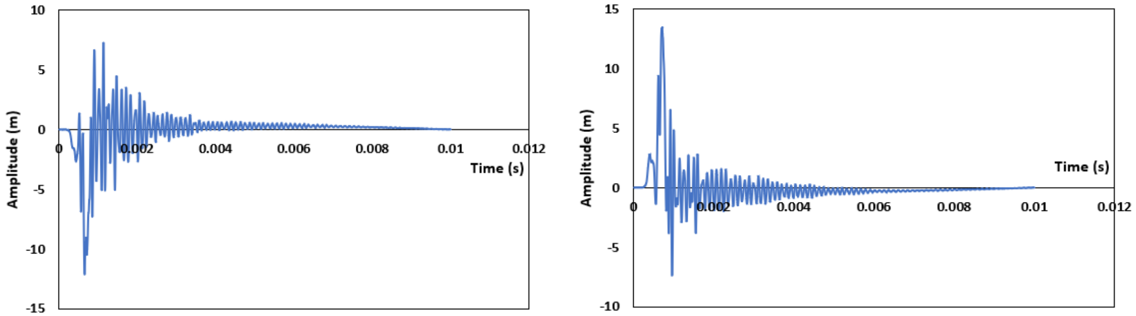
Appendix A-28: W/C 0.65 (30% Rubber Content) Result from NDT Test in Day 56



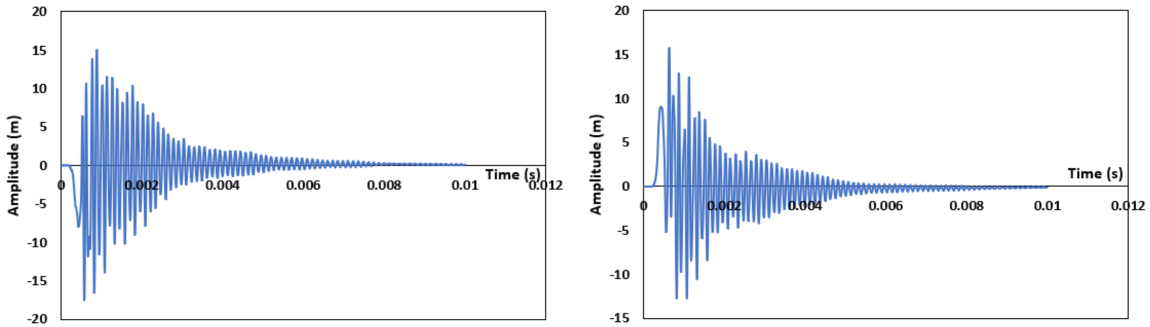
Appendix A-29: W/C 0.65 (40% Rubber Content) Result from NDT Test in Day 56



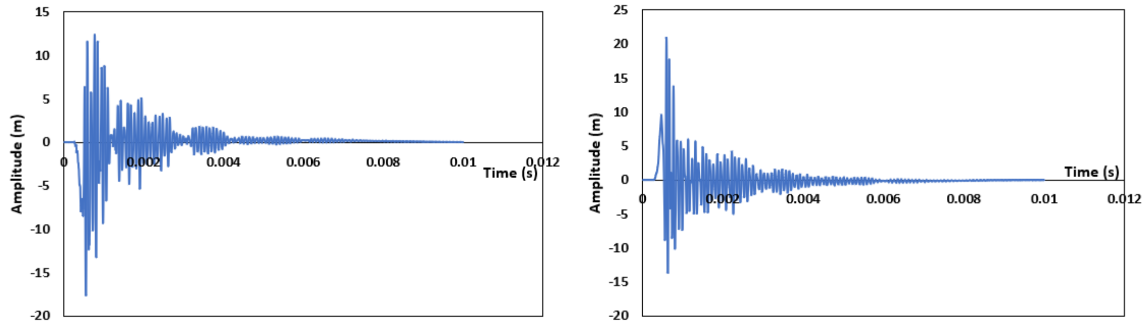
Appendix A-30: W/C 0.65 (50% Rubber Content) Result from NDT Test in Day 56



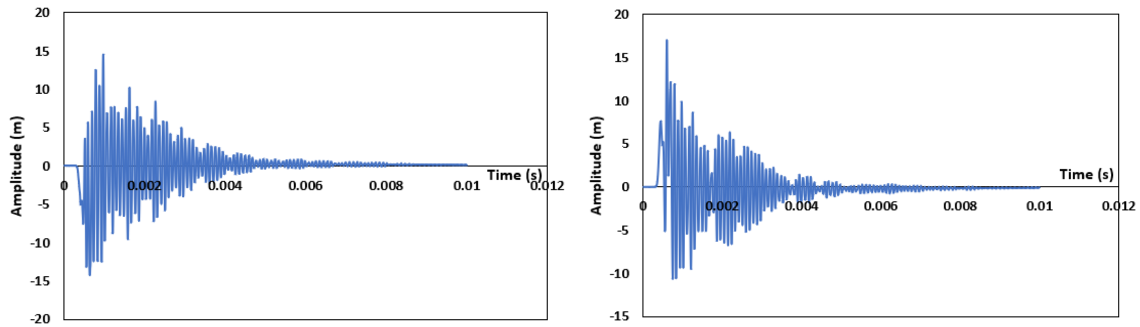
Appendix A-31: W/C 0.65 (60% Rubber Content) Result from NDT Test in Day 56



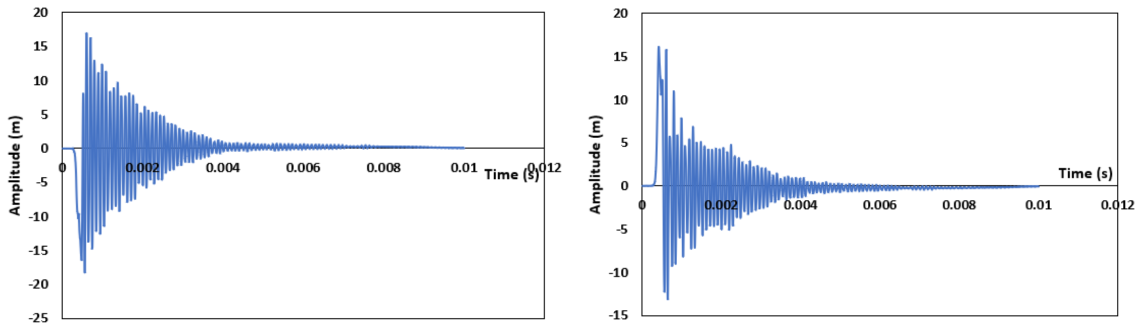
Appendix A-32: W/C 0.65 (70% Rubber Content) Result from NDT Test in Day 56



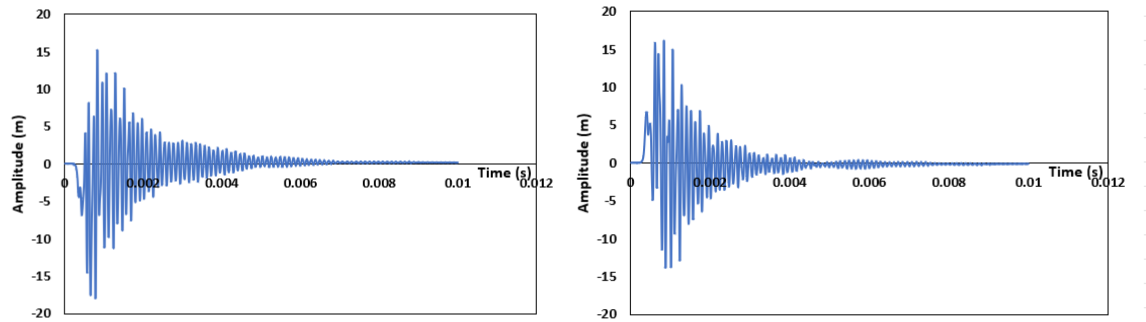
Appendix A-33: W/C 0.70 (Control) Result from NDT Test in Day 56



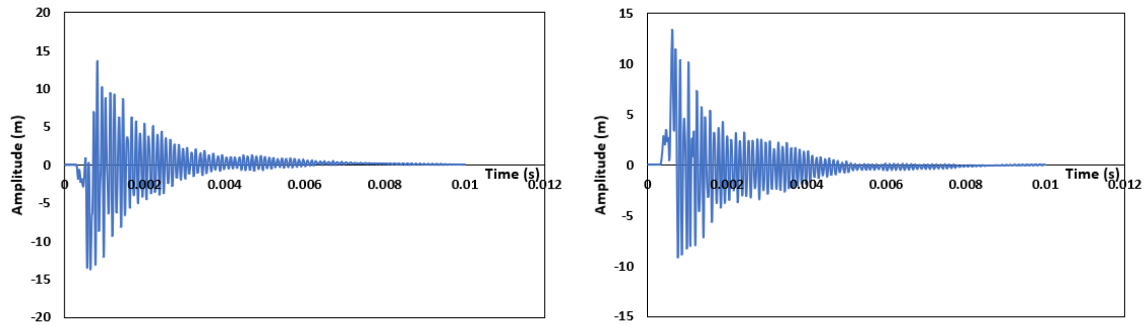
Appendix A-34: W/C 0.70 (10% Rubber Content) Result from NDT Test in Day 56



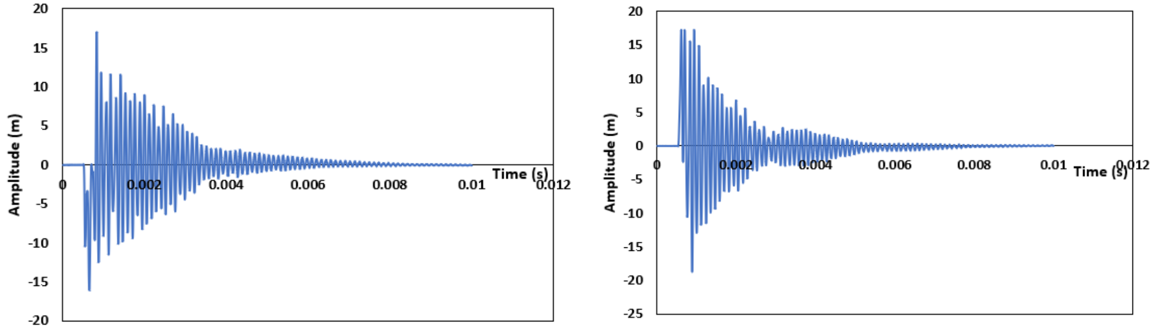
Appendix A-35: W/C 0.70 (20% Rubber Content) Result from NDT Test in Day 56



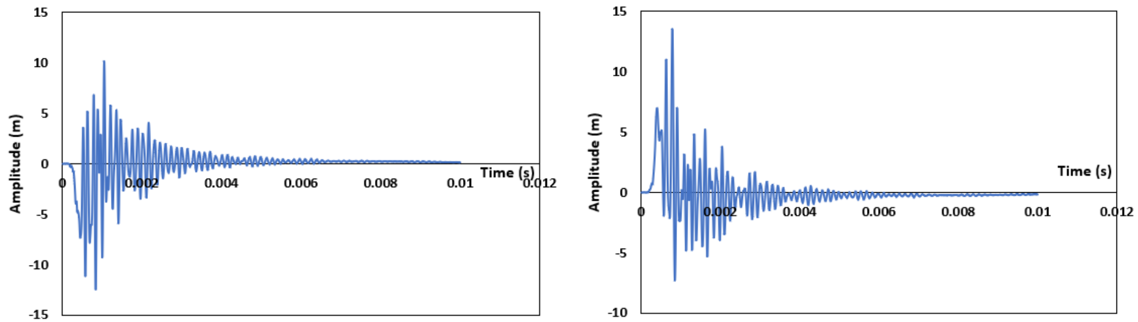
Appendix A-36: W/C 0.70 (30% Rubber Content) Result from NDT Test in Day 56



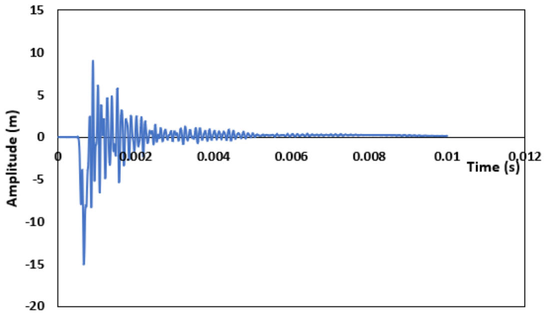
Appendix A-37: W/C 0.70 (40% Rubber Content) Result from NDT Test in Day 56

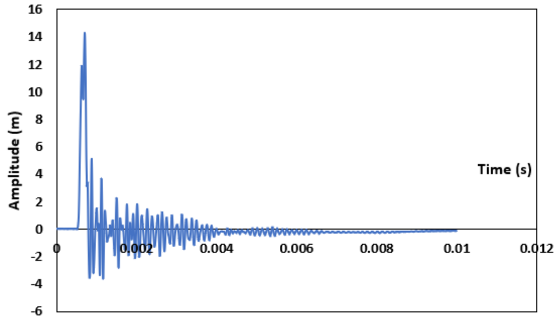


Appendix A-38: W/C 0.70 (50% Rubber Content) Result from NDT Test in Day 56



Appendix A-39: W/C 0.70 (60% Rubber Content) Result from NDT Test in Day 56





Appendix A-40: W/C 0.70 (70% Rubber Content) Result from NDT Test in Day 56