A STUDY OF THE MECHANICAL PROPERTIES OF CRUMB RUBBER LIGHTWEIGHT FOAMED CONCRETE WITH DENSITY OF 1100-1200 KG/ M^3

OON KEL LEE

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

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

April 2020

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 : OON KEL LEE

ID No. : 15UEB01502

Date : 22nd April 2020

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"A STUDY OF THE MECHANICAL PROPERTIES OF CRUMB RUBBER LIGHTWEIGHT FOAMED CONCRETE WITH DENSITY OF 1100-1200 KG/M^3"** was prepared by **OON KEL LEE** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : 

Supervisor : Dr. Lee Foo Wei

Date : 22nd April 2020

ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Dr. Lee Foo Wei for his invaluable advice, guidance and his enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to Leon Lim, my senior who guided me throughout this project and taught me a lot about concrete behaviours. Then my friend, Ooi Wei Chien, who sacrificed his time helping me to cast seventeen sets of concrete during the semester break even though he was busy with his post graduate studies. Lastly, my loving parents who had helped and given me encouragement.

ABSTRACT

For the past few decades, the disposal of waste tyres has become a serious environmental problem as a huge amount of scrap tyres are being generated worldwide. Many researchers had been studying this issue and actions had been made. It appears that recycling scrap tyres were the best and most effective solution for disposing of this material due to its economic and ecological advantages. This study was carried out to study on the feasibility of using crumb rubber particles as a partial replacement of fine aggregates in lightweight foamed concrete. Besides, it could be a benchmark for future studies in this field to accommodate a better and more sustainable production of building insulators. The mechanical properties such as the compressive strength, tensile strength and flexural strength of crumb rubber lightweight foamed concrete were tested based on the ASTM standards. Two sizes of crumb rubber particles were used in this study, namely, the granular crumb rubber (1 - 4 mm) and powdered crumb rubber particles (40 mesh). This study has proven that the utilization of granular and powdered crumb rubber in lightweight foamed concrete could affect the mechanical properties like the compressive, splitting tensile and the flexural strength. The highest compression and tensile strengths of 20 % granular crumb rubber lightweight foamed concrete (GCLFC) were reported with a value of 2.930 MPa and 0.399 MPa while the highest flexural strength obtained from 10 % of crumb rubber replacement was 2.248 MPa. The mechanical strength of GCLFC had increased by 10.27 % (compressive), 21.65 % (splitting tensile) and 2.97 % (flexural) compared with the controlled mix specimens. However, as the crumb rubber proportion of GCLFC increases more than 20 %, a significant reduction of mechanical strength was noticed. On the other hand, the powdered crumb rubber lightweight foamed concrete (PCLFC) has the highest compressive and splitting tensile strength at 70 % of crumb rubber proportion with the values of 3.227 MPa and 0.533 MPa whereas the highest flexural strength is at 80 % of crumb rubber proportion with a value of 2.829 MPa. In a nutshell, PCLFC has better improvement in the mechanical strength as it has increased by 3.01 % to 33.87 % (compressive), 2.44 % to 62.5 % (splitting tensile) as well as 6.7 % to 29.6 % (flexural) compared to the controlled mix.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

P	Maximum Load Applied, N
F	Compressive Strength, MPa
A	Cross-section Area of the Concrete Cube, m^2
R	Flexural Strength, MPa
L	Maximum Span Length, mm
b	Average Specimen Width, mm
d	Average Specimen Depth, mm
T	Splitting Tensile Strength, MPa
D	Diameter of the Specimen, m
C_3A	Tricalcium Aluminate
C_2S	Dicalcium Silicate
C_3S	Tricalcium Silicate
C_4AF	Tetra Calcium Alumina Ferrite
MgO	Magnesium Oxide
CaO	Calcium Oxide
LFC	Lightweight Foamed Concrete
GCLFC	Granular Crumb Rubber Lightweight Foamed Concrete
PCLFC	Powdered Crumb Rubber Lightweight Foamed Concrete
OPC	Ordinary Portland Cement

CHAPTER 1

INTRODUCTION

1.1 Background

Concrete is found to be one of the most typical materials in the construction industry. The main components of concrete contain coarse or fine aggregates, Portland cement (limestone) and water. The quality and strength of the concrete vary with respect to the mixing proportion of concrete. Concrete has been used in various applications and it is considered as very affordable, especially in the construction industry (Mehta, 1986). Today, a wide variety of applications have adopted this material, for example, dams, foundations, pavements, storage tanks, bridges, drains and multi-storey buildings. In the construction sector, many industries had shown significant progress throughout the year, together with the development of ready-mixed concrete. (Topçu and Bilir, 2009).

With the growth of concrete technology in the industry, various types of concrete can be found in the market nowadays (Neville and Brooks, 1987). The types of conventional concrete available such as lightweight concrete, high strength concrete, asphalt concrete, crumb rubber lightweight foamed concrete and polymer concrete can be easily obtained from the market. Furthermore, the research and development of the concrete have been widely expanded towards more environmentally-friendly in the past few years (Shetty, 2008). By replacing a portion of aggregates in finer size with recycled waste tyres in concrete can provide adequate strength for the concrete to perform and yet decrease the waste issues (Kaloush, et al., 2005). This alternative way of recycling waste tyres has been strongly recommended. This research had been conducted by many researchers and many findings had been discovered over the past few decades.

The mixture of air-entraining admixture in cement is able to produce lightweight foamed concrete (Amran, et al., 2015). The purpose of air-entraining reagent is to induce tiny air bubbles within the concrete particles. There are several characteristics of lightweight foamed concrete. For instance, it can be easily fabricated, possesses excellent thermal and acoustic insulation. So far, in civil engineering works, the main purpose of this material is used as a filler material. Nonetheless, it has a strong potential of being used as a building material in constructions in terms of its good thermal and acoustic performance.

Even though lightweight foamed concrete contains lower mechanical properties compared to ordinary concrete, it still can serve many purposes in the construction industry (Bing, et al., 2012). For example, in low-rise residential construction, it can be used as the light load walls as well as a partition between rooms. Besides that, they are so much lighter compared to concrete with average weight. Hence, adopting it in structural elements could greatly reduce the column, footing and loading bearing due to a lower structural dead load (Mehta and Monteiro, 2001).

Today, a new development in material technologies had been picked up. It appears that recycled waste tyres could be used in the concrete as it provides several improvements in the ductility, sound absorption, toughness and the freeze-thaw resistance despite the reduction in mechanical properties (Khaloo, et al., 2008). However, there would be a potential improvement in the mechanical properties of concrete when waste tyres are mixed with lightweight foamed concrete (Youssf, et al., 2014). Buildings made of recycled tyre concrete will result in less energy consumption. Moreover, utilising recycled tyres in concrete composites by replacing the fine aggregates partially have the capability of reducing the overall greenhouse gases (GSG) emission on Earth, provide numerous potential economic advantages as well as reducing environmental problems that correlate with the waste tyres as compared to ordinary concrete (Meyer, 2009).

Lastly, to solve the environmental issues related to waste tyres, the study of utilizing crumb rubber particles in lightweight foamed concrete had been carried out and laboratory experiments had been conducted. Besides that, several types of research had been outlining the crumb rubber particles usage in concrete as it has the potential to be used in various applications in the construction field (Benazzouk, 2008).

1.2 Problem Statement

Today, waste material production is soaring at an alarming pace. An approximation of 8 billion waste tyres was produced worldwide today. Not only that, but this situation also became severe as the amount keeps increasing nonstop and it is mirrored in many countries around the globe.

According to Kumar (2013), Malaysia had generated an estimation of 8.2 million waste tyres throughout the years and the total wastes produced in this country could go up to approximately 57,000 tonnes annually. Consequently, sustainable methods on recycling and managing this vast amount of wastes are absolutely essential to prevent any serious pollution from occurring. The environment will be critically polluted if the enormous amount of rubber tyres is not adequately reprocessed and disposed of. Therefore, a few solutions such as reusing tyres from second-hand market and rethreading, recovery of material from chopped, shredded, whole and micronized tyres and recovering of energy can be adopted worldwide (Thomas, et al., 2015).

One of the feasible solutions to the reduction of wastes is using recycled crumb rubber particles in concrete. It helps in the improvement of concrete properties, transforming it to become more flexible as a material (Batayneh, et al., 2008). Besides that, using recycled tyres in construction components is a green alternative for saving the environment and reusing waste (Aiello and Leuzzi, 2010). Throughout the years, extensive research had been made covering the use of crumb rubber particles in ordinary concrete as a filler material (Issa and Salem, 2013). In this study, findings stated that the crumb rubber particles could be used as the replacement for fine aggregates in the lightweight foamed concrete. The effects of crumb rubber contents on the mechanical properties of lightweight foamed concrete are studied.

1.3 Aim and Objectives

This study aims to produce crumb rubber lightweight foamed concrete with a density of 1100 to 1200 kg/m^3.

To attain the aim, there are several objectives required to be listed out:

I. To determine the effect of different proportion (0 – 80 %) of crumb rubber on the mechanical properties, namely the splitting tensile, compressive and flexural strength of crumb rubber lightweight foamed concrete.

II. To obtain the optimum mix proportion of granular and powdered crumb rubber particles in the lightweight foamed concrete based on the highest mechanical strength.

III. To compare the performance of crumb rubber particle size (1 to 4 mm and 40 mesh) on the mechanical properties, namely the splitting tensile, compressive and flexural strength of crumb rubber lightweight foamed concrete.

1.4 Scope and Limitation of the Study

The current research was performed using a small-scale experimental approach. The scope of this research emphasizes the mechanical strength properties of crumb rubber lightweight foamed concrete with the density ranging from 1100 kg/m^3 to 1200 kg/m^3. Three laboratory tests will be carried out in order to determine the crumb rubber lightweight foamed concrete mechanical properties which are the flexural, compressive and the splitting tensile test. Besides, the reason for conducting these three tests is to find out whether the concrete strength could achieve the ASTM standard and requirements.

To carry out the research, a few limitations have to be justified. Firstly, the water-cement ratio was fixed at 0.60. Next, the fine aggregates will be replaced with two different sizes of crumb rubber particles, which are the granular and powdered crumb rubber. Both had a mix proportion ranging from 0 % to 80 % respectively, with 10 % intervals. These trial mixes were prepared to find out the optimum proportion for the crumb rubber lightweight foamed concrete to perform at its best. Seventeen sets of mixes were produced throughout this experimental work.

Three main concrete tests were conducted after 28 days of water curing treatment. For each proportion of crumb rubber lightweight foamed concrete, the compressive strength test was performed on three cubic specimens with the dimension of 100 mm in length, 100 mm in width and 100 mm in height. Splitting tensile test was carried out with three cylindrical specimens, and the flexural strength was obtained by testing three prism specimens with a dimension of 160 mm (l) x 40 mm (w) x 40 mm (h).

1.5 Significance of Study

For this research, the importance of the study is as follow:

1. To promote the use of rubber particles from waste tyres in concrete. This environmentally-friendly concrete product could help reduce the waste tyres around us as well as reducing the unnecessary waste disposal on Earth.
2. Adding crumb rubber particles in lightweight foamed concrete could minimize the environmental issues regarding waste tyres and improve mechanical strength. Hence, it could be applied in construction elements while achieving ecological and economic advantages.
3. This study can be adopted as a benchmark for future studies in this field to accommodate a better and more sustainable production of building insulators for sound and thermal as well to enhance the green technology and green materials in the construction industry.

1.6 Outline of the Report

A total number of 5 chapters are included in this study.

Chapter 1 covers the introduction of the study, which explains about the crumb rubbers in lightweight foamed concrete. Besides, this chapter also consists of the background, problem statement, aim and objectives, study scope, the significance of the study as well as the report layout.

Chapter 2 is the literature review, which contains the previous researches on lightweight foamed concrete and its applications. The use of silica fume is also explained briefly. Chapter 2 also covers the pros and cons of using crumb rubber particles in concrete mixtures, the properties of crumb rubber lightweight aggregate concrete, materials used for producing crumb rubber lightweight foamed concrete and also the engineering testing.

Chapter 3 is the methodology, which outlines the steps of conducting the tests. This chapter consists of the materials, procedures and the mix proportions of crumb rubber lightweight foamed concrete are stated step by steps. Besides that, the details of the test method and procedures are discussed in this chapter.

Chapter 4 is the data presentation; it consists of the data analysis from the three mechanical property tests that had been carried out. A thorough discussion was conducted in this chapter by comparing the results with the different proportion and different sizes of crumb rubber used in lightweight foamed concrete and its strength.

Chapter 5 concludes the overall study of this research. The conclusion of the objectives for this study and some recommendations to improve the outcomes were discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter contributes an overview of the publication of articles relating to the objectives of this report. Firstly, the use of silica fume is briefly explained and the pros and cons of using crumb rubber in concrete are listed in details. The lightweight foamed concrete and its application is explained clearly. The properties of crumb rubber lightweight aggregate concrete are studied and reviewed. Last but not least, the comparison of materials to produce the crumb rubber lightweight foamed concrete was thoroughly reviewed. Material recovery of adding crumb rubber into lightweight foamed concrete is approached in this study.

2.2 Lightweight Foamed Concrete (LFC)

In this era, lightweight foamed concrete has the potential to be used in various applications. It has a huge advantage of being lighter than normal concrete. The range for its density is 300 to 1800 kg/m^3 (Amarnath, 2013). Besides that, lightweight foamed concrete of different densities can be produced by supervising the foam dosage added into the mixture of concrete. It can be used for the construction of numerous structural buildings, filling grades or the thermal insulation wall.

By comparing with normal concrete, lightweight foamed concrete is mostly used in non-loaded bearing applications as it reduces the dead load of structures such as the steel reinforcement required for beam, slab or column in a building which indirectly reduces the cost of the project and makes the design of supporting structures more economical. Besides, it has the properties of having a good thermal insulation, fire resistance, low density and stiffness.

Nowadays, lightweight foamed concrete is an innovative technology and it is quite popular in the construction field. The high-workability property of lightweight foamed concrete produces a well-bonded body. Hence, concrete will not settle that quickly and no compaction is needed. Besides that, the lightweight foamed concrete does not need imposing lateral forces due to its excellent load distribution and high flow ability under fresh condition. However, the foamed concrete is very sensitive to water ratio, and it could take some time during the mixing phase.

2.3 Applications of Crumb rubber Lightweight Foamed Concrete (CRLFC)

Crumb rubber lightweight foamed concrete is expected to become increasingly well-known in plenty of the construction industry due to its typical properties which include good sound insulation, high thermal insulation and low density. In fact, its great flow ability has provided construction industries to undergo their projects with lesser efforts and also costs. Over the past 20 years, several researchers had outlined some suggestions and the potential usage of crumb rubber lightweight concrete in our daily life. The most beneficial potential for using industrial wastes is the impacts on the environment. Hence, the application of crumb rubber in lightweight foamed concrete is capable of stimulating the economy, especially in construction industries and reducing wastelands (Md Noor, et al., 2016).

Firstly, rubber is a great vibration resisting agent and it has the ability to absorb the impact of forces (Ganjian, et al., 2009). Hence, adding it in lightweight foamed concrete can produce a new type of concrete that can be used as foundation pads, capable of reducing the impact of large forces or in the walls of railway stations to reduce the vibrations and noise of the fast-moving train (Fattuhi and Clark, 1996).

Figure 2.1: Rubber Concrete Pad Foundation (Uddin, 2018).

In addition, the insulation of thermal in concrete panels can be improved significantly by utilising crumb rubber particles in concrete depending on the proportion and particle size (Sunthonpagasit and Duffey, 2004). Researchers had shown that higher levels of sound absorption could be achieved in crumb rubber lightweight foamed concrete and the overall reduction of noise is 36 % (Najim and Hall, 2010). Thus, the usage of crumb rubber lightweight foamed concrete could be considered in highway constructions for their coating and road barriers.

Figure 2.2: Precast Rubber Concrete Road Barrier (Whisper, 2015).

Also, crumb rubber lightweight foamed concrete can be utilised in architectural applications where high strength is not required like the nailing concrete, where only low unit weight is necessary such as in wall panels, as well as in barriers and elements of construction that are subjected to impact forces.

Figure 2.3: Rubber Concrete Wall Panels (Europages, 2017).

Lastly, sound absorptive walls can be produced using crumb rubber foamed concrete. Although this type of wall is expensive compared to normal walls, however, they are more efficient in absorbing sound (Sukontasukul, 2009). For instance, Smart Wall is a concrete panel system that uses rubber particles to replace fine aggregates in its concrete mix. It consists of elements with bulging angled surface designed to lower direct reflections of sound and therefore reduces the noise (Farraq, 2016).

2.4 Advantages of Using Crumb Rubber in Concrete

There are several advantages of using crumb rubber concrete instead of plain concrete. Firstly, it helps to reduce the amount of cracking in roads, bridges and structures. To improve the long-term quality of a structure, it is essential to recognize the use of wastes tyres in construction. Otherwise, the large number of scrap tyres would end up in the landfill (Cierra, 2017). Besides that, although replacing crumb rubber as lightweight aggregates in concrete significantly reduces the strength, nonetheless, many studies conducted by researchers had shown an improvement in certain durability properties of using crumb rubber in concrete mixtures (Pierce and Blackwell, 2003).

Additionally, reducing the weight of concrete can reduce the cost of construction. However, the strength required must be maintained to support the concrete to work. Next, crumb rubber concrete tends to have improved acoustic insulation and thermal conductivity compared to normal concrete. Moreover, using rubber in concrete will enhance the shock resistance, absorption capability, extensibility and ductility of the concrete (Kaloush and Way, 2005). Lastly, crumb rubber is encouraged to be used in concrete as it helps to absorb impacts since rubbers have the capability of softening concrete as well as yielding a greater plastic deformation (Atahan and Yücel, 2012).

2.5 Disadvantages of Using Crumb Rubber in Concrete

Using crumb rubber in concrete has its drawbacks too. Firstly, by increasing the percentage of rubber content in concrete, a significant reduction in the concrete mechanical properties will occur which includes the splitting tensile strength, elasticity modulus, flexural strength and the compressive strength. Therefore, crumb rubber concrete is not encouraged to be applied in structural members where high strength is necessary.

Next, according to studies, crumb rubber particles addition could result in a decrease of the slump of concrete (Wang, 2013). Likewise, the concrete workability will also decrease as the rubber particles increases. This may result in the delay of construction works as well as requiring more man power and cost (Fattuhi and Clark, 1996). Figure 2.4 shows a bar graph by Abdullah (2017) on the effect of slump flow versus the percentage of rubber.

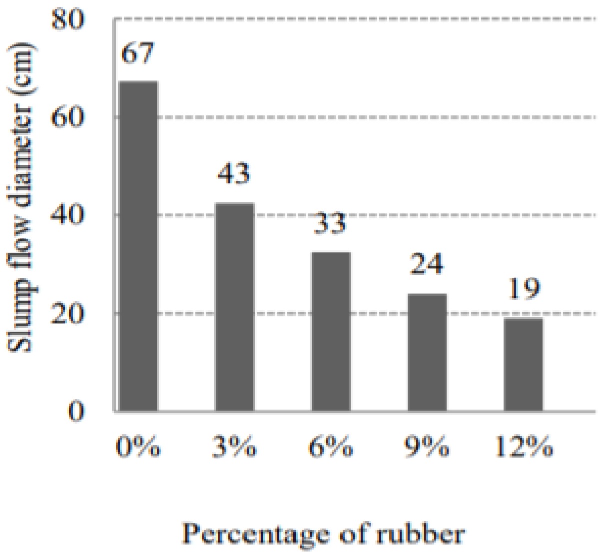

Figure 2.4: The Effect of Slump flow versus The Percentage of Rubber (Abdullah, 2017).

Crumb rubber concrete requires proper lab tests and mix proportioning which may increase the time consumption and budget of the project (Bravo and Brito, 2012). Therefore, crumb rubber concrete is only recommended to be used in non-massive structures such as non-bearing walls, pavements and road curbs.

2.6 Materials

The main materials to produce crumb rubber lightweight foamed concrete include crumb rubber, silica fume, air-entraining agent (foam), water, Type I Ordinary Portland cement (OPC), and lightweight aggregate (sand).

2.6.1 Rubber Aggregates

There are many types of scrap rubber particles. It can be divided into four groups based on its size of particles. The first type is the shredded rubber aggregates. In concrete, shredded rubber aggregates can be served as the coarse aggregates as the crushed limestone and gravel in concrete can be partially replaced with shredded rubbers (Ganjian, et al., 2009). The production of shredded rubber normally comes in various sizes ranging from 73 to 13 mm. In fact, to achieve an optimum volume reduction, both primary and secondary grinding processes are necessary (Read, et al., 1991).

Next, the second type is crumb rubber aggregate. Methods to transform scrap tyres into crumb rubbers include the process of cracker mill, granular process, and the process of micro-mill. The production of crumb rubber particles normally sizes from 5 to 0.5 mm. The preferable type of rubber aggregates to be used in this study as the partial replacement for fine aggregates in the concrete mixture is the crumb rubber because it can be easily obtained in the market.

The third type is ground tyre rubber. Ground rubber size ranges from as course as 19 mm to 0.15 mm fine, it depends on the type of size reduction equipment that is used or the intended applications. The process of obtaining ground rubbers divides into two stages which are magnetic separation and screening process. From these two stages, ground rubbers from various size fractions are retrieved (Heitzman, 1992).

Lastly, the silt rubber aggregate, can also be known as fibre rubber aggregate. Fibre rubber can be produced by cutting the tyre with tyre cutting machines. During the process, the tyre will be silted into half and the side walls from the thread of tyres will be separated. Figure 2.5 shows four types of rubber aggregates, namely shredded, crumb, ground and fibre.

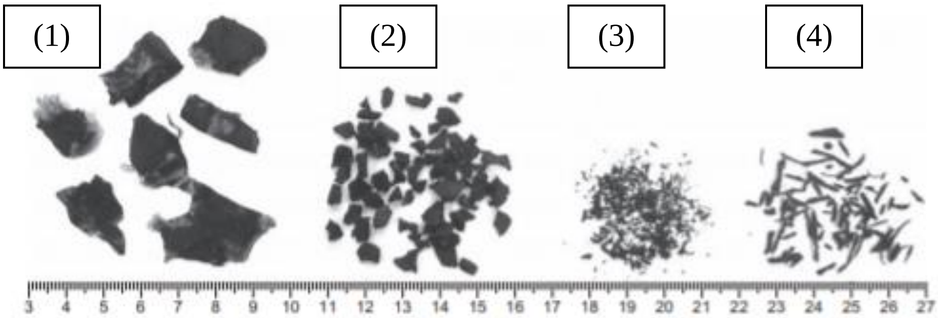

Figure 2.5: Rubber Aggregates: (1) Shredded, (2) Crumb, (3) Ground, and (4) fibre (Nakim, et al., 2010).

According to a study by Siddique and Naik (2004), if the rubber particles are pre-treated or possess a rough surface, the concrete will experience an enhancement in the compressive strength due to the improved bonding developed in the matrix during the phase.

2.6.2 Type I Ordinary Portland cement (OPC)

Various types of Portland cement can be found in the market. It can be classified into six types which are - type I, II, III, IV, V and the White type. In this study, type I- ordinary Portland cement is adopted. Table 2.1 illustrates the general features of Portland cements.

Table 2.1: General Features of Portland Cement.

Features / Types	Classification	Characteristics	Applications
I	General Purpose	High in C_3S for high early strength	General Construction
II	Moderate Sulphate Resistance	Low C_3A content	Structures exposed to soil and water
III	High early Strength	Ground more finely, have more C_3S	Rapid Construction, Cold weather concreting
IV	Low heat of hydration	Very low C_3S content	Massive structures
V	High Sulphate Resistance	Very low C_3A content	Structures exposed to sulphate ions
White	White Colour	No C_4AF, low MgO	Decorative

The most common or general-purpose cement, Ordinary Portland cement (OPC) is usually available in white or grey. According to the ASTM standard C150, the chemical compounds of this type are C_3A, C_2S, C_3S, C_4AF, MgO and free CaO. The high content of C_3S in OPC contributes to the early strength of concrete, but not resistant to sulphate attack and dry shrinkage. Generally, OPC is commonly used in general constructions such as buildings, bridges, pavements and precast concrete.

2.6.3 Aggregate

Aggregates are recognised as inert granular materials which include crushed stones, gravel and sand. To produce concrete, the three most important materials are aggregates, Portland cement and water. To create an excellent concrete mix, the aggregates used must a hard surface, dirt free, strong and free from absorbed chemicals to prevent the concrete from deteriorating. Next, the total volume of concrete consists of 60 to 75 percent of aggregates. Besides, aggregates can be classified into two main groups which are the fine aggregates and coarse aggregates. Table 2.2 illustrates the comparison of aggregates.

Table 2.2: Comparison between Fine and Coarse Aggregate.

No.	Scopes	Coarse Aggregate (CA)	Fine Aggregate (FA)
1	Particles Sizes	Particles that retain on 4.75 mm sieve.	Particles that retain on 0.075 mm sieve and pass through 4.75 mm sieve.
2	Function in Concrete	Act as inert filler material for concrete.	Voids between coarse aggregate are filled up by fine aggregates.
3	Uses	Mainly used in concrete, railway track ballast, etc.	Used in mortar, plaster, concrete, filling of road pavement layers, etc.
4	Source	Dolomite aggregates, crushed gravel or stone, natural disintegration of rock are the major sources of coarse aggregate.	River sand, crushed stone sand, crushed gravel sand is the major sources of fine aggregate.

2.6.4 Silica Fume

Silica fume is the by-product from the alloys that contains silicon during the smelting process. It is usually produced in the electric arc furnaces or the silicon and ferro-silicon industry. Silica fume namely micro-silica, volatilized silica, silica dust or condensed silica is commonly used as pozzolanic admixture in concrete (Siddique and Khan, 2011). Silica fume contributes to the improvement of concrete strength by providing greater volume and more uniform distribution of hydration products (Sharma, et al., 2014). From an economics perspective, silica fume is much more affordable as compared to cement (Ghafoori and Diawara, 2007).

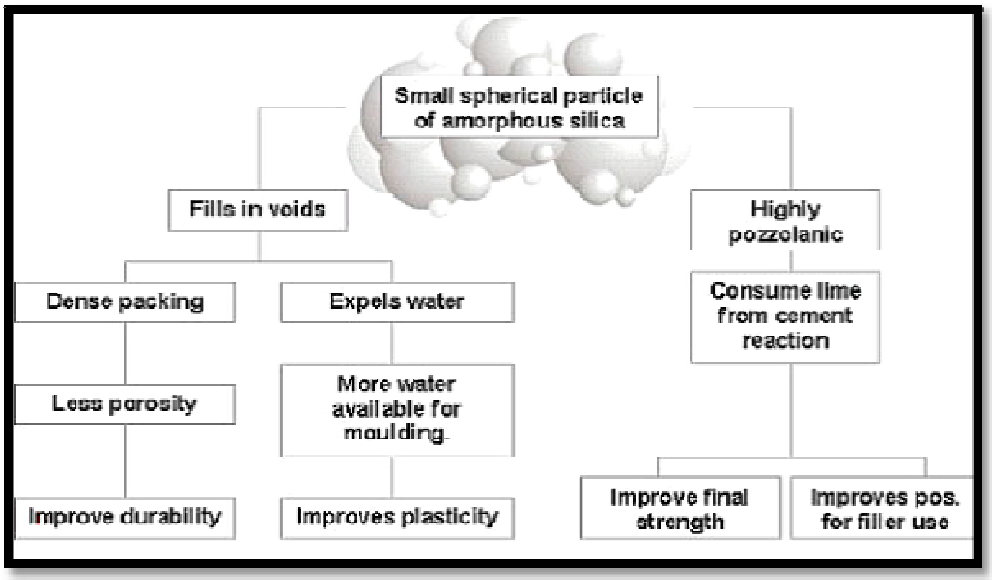

Figure 2.6: Benefits of Silica Fume (Sharm, et al., 2014).

According to a study, Rasol (2015) mentioned that the application of silica fume in concrete is able to increase the tensile, flexural strength and modulus of elasticity of the concrete. Besides, silica fume is capable of reducing the voids in concrete resulting in the concrete to have extremely low permeability against water and chloride intrusion. Premkumar, et al., (2019) stated that compressive strength, tensile strength and flexural strength of normal concrete at 28 days, had 10 % to 20 % of increment with the 10 % silica fume replacement. Ghutke and Bhandari (2014) observed the effect of silica fume on concrete and discovered that 10% to 15 % replacement of silica fume showed the optimum compressive strength gain at 3, 7 and 28 days.

Furthermore, Amarkhail (2015) studied the influence of silica fume on properties of high strength concrete and proved that 10 % and 15 % replacement of silica fume achieved the highest compressive strength and the highest flexural strength respectively. Mydin, et al., (2014) justified that 15 % replacement of silica fume in concrete produced the highest strength in compressive, flexural and tensile strength. Srivasta, et al., (2014) proved that normal concrete with 5 % of silica replacement enhanced the compressive strength by 18 %. Following a study by Gopi and Chamberlin (2019), the results showed the compressive, tensile and flexural strength of the concrete achieved its maximum value when the cement is replaced with 6 % of silica fume and 15 % of fly ash.

2.6.5 Air-entraining agent

Air bubbles can be formed by adding an air-entraining agent into the concrete mix. The purpose of it is usually to improve the resistance to freezing and thawing or salt scaling. Not only that, it also helps to improve workability. Air itself does not provide any strength; therefore, additional cement is usually necessary to compensate for the strength; otherwise, it might be lost.

Foaming agents can be divided into two types, such as synthetic and protein foaming agents. Both of them will make a massive difference in the mechanical results or the resistance properties of concrete. Foaming agents are required to produce lightweight cellular concrete. Besides, one of the purposes of introducing it into the concrete mix is to reduce the concrete weight.

Protein-based foaming agents have better performance in strength, whereas the synthetic-based foaming agent is much cheaper, can be stored longer and easier to handle. Besides, hydrolysed protein foaming agents require more energy compared to synthetic-based foaming agents in synthesising bubble foams (Sari and Sani, 2017).

Even without the addition of foaming admixtures, the crumb rubber concrete mixture contains higher air content than controlled mixture (Fedroff, 1996). The reason is that rubber particles can entrap air due to their non-polar properties (Siddique and Tarun, 2004).

2.7 The Properties of Crumb Rubber Lightweight Aggregate Concrete

The behaviour of concrete could be greatly affected by replacing the fine aggregates with crumb rubbers. There are many articles concerning about this. The majority of studies showed that the flexural strength, splitting tensile strength, elasticity modulus and compressive strength of concrete decreases as the percentage of crumb rubber particle content increases. However, the impact and the resistance of freeze-thaw are found to be improving with the increasing percentage of rubber particle content.

2.7.1 Compressive Strength

According to a study by Lv (2015), a lab experiment had been conducted on the effects of lightweight concrete after adding the crumb rubber particles. Based on the results, it shows that there will be a significant decrease in the compressive strength when the rubber replacement level increases from 0 to 100 %. It decreases approximately from 40.0 MPa to 8.0 MPa while increasing in age. On day 28, there is roughly 83 % of strength reduction. The potential explanation for this reduction in strength could be due to the increasing rubber contents that lead to the reduction of solid load-carrying materials.

Besides that, the strength reduction may be due to the cement paste and the rubber particle boundaries adhesion forces between them that is gradually reducing, causing an increase in the volume of the interface transition zone and the weak phase. Therefore, it is recommended to use a silane coupling agent around rubber particles as a cementitious coating layer to enhance the performance of bonding between cement hydration products and rubber particles. The graph of the compressive strength against the replacement level of rubber content in concrete is illustrated in Figure 2.7 for 7, 14 and 28 days respectively.

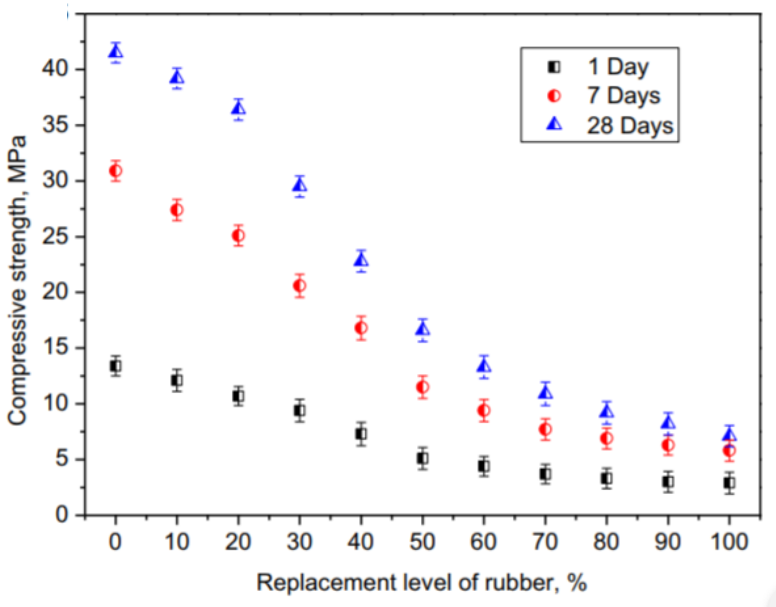

Figure 2.7: The Compressive Strength versus Replacement Level of Rubber (Lv, 2015).

2.7.2 Splitting Tensile Strength

Next, the splitting tensile strength has been studied to drop as well when there is an increase in the replacement percentage of rubber particles. According to Zhou (2015), when rubber content in concrete increases, the splitting tensile strength of the concrete decreases regardless of the ratio of water to cement used in the mixture of concrete.

Figure 2.8 illustrates the changes of splitting tensile strength against the replacement level of rubber particles at three different days, (day 1, 7 and 28). From the graph, at 1, 7 and 28 days, the tensile strength of concrete reduced as the rubber particles content in the mixture increased. The splitting tensile strength of concrete at 28 days reduced the most compared to 1 and 7 days. The reason behind this is because during the early age, the full utilization of the concrete strength had not been achieved; hence the splitting tensile strength of crumb rubber lightweight concrete is fully dependent on the hardened cement paste strength and interface bonding.

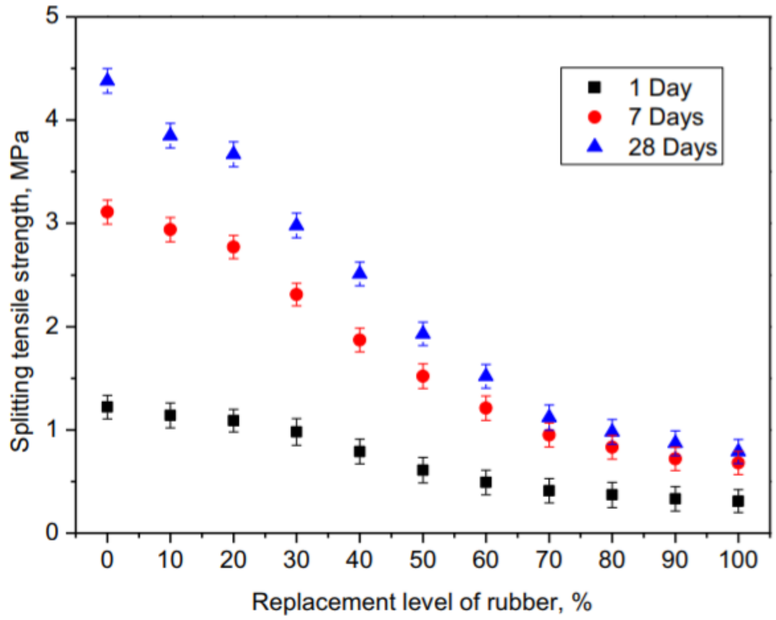

Figure 2.8: The Splitting Tensile Strength against The Level of Replacement of Rubber (Lv, 2015).

2.7.3 Flexural Strength

Similarly, based on studies, the usage of rubber particles in concrete will cause the flexural strength of concrete to undergo reduction, as shown in Figure 2.9. However, although the flexural strength decreases, the high deformations of rubber particles will prevent the crumb rubber concrete specimen from collapsing suddenly during the flexural test (Liu, et al., 2013). In addition, at 28 days, the rate of decreasing in the concrete flexural strength will be slower because the rubber particles in the mixes are evenly distributed. Thus, preventing cracks from developing. Besides, there will be a decrement in the brittleness index as rubber is added after 15 % and a transition from brittle-ductile behaviour is showed (Topcu, et al., 1997).

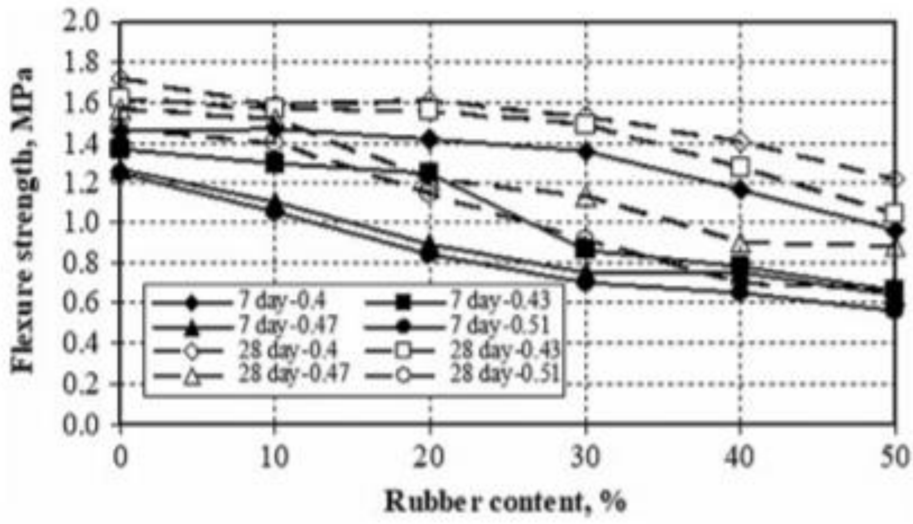

Figure 2.9: The Flexural Strength versus Rubber Content (Topcu, et al., 1997).

2.7.4 Impact Resistance

The impact is a complicated dynamic phenomenon which includes the fracturing of tensile and crushing of shear failure. Using rubber aggregates in the concrete mixture can be beneficial in both the impact and static condition. Based on studies, with the addition of crumb rubber particles into the concrete, an increment of impact resistance will occur as the material is capable of absorbing shock or energy.

A drop weight impact test had been proposed by ACI Committee (2005) to determine the resistance of impact by demonstrating the relative brittleness as well as quantifying the concrete impact resistance. The steps are simple yet economical. Therefore, it is widely used.

Besides that, Sallam, et al. (2008) had conducted a test on the usage of recycled tyre rubber particles in normal concrete to identify the impact resistance. According to the test results, when lightweight concrete (LWC) is under an impact load, the presence of rubber particles in concrete increases the crack initiation resistance.

2.7.5 Modulus of Elasticity

Other than that, several studies had proven that the elastic modulus is bound to decrease as the percentage of rubber particles in concrete increases. In a test conducted by Benazzouk, et al. (2008), as the ratio of rubber particle increase, elasticity dynamics modulus starts decreasing, as shown in Table 2.3.

Table 2.3: The Ratio of Rubber versus Elasticity Dynamic Modulus (Benazzouk et al., 2018).

Rubber particles (%)	Dry unit weight (kg/m^3)	Air (%)	Elasticity Dynamic Modulus (GPa)
50	1150	17.0	9.5
40	1300	14.0	11.5
30	1473	11.8	13.0
20	1620	8.7	14.0
10	1740	5.0	20.0
0	1910	2.0	25.0

The static elasticity modulus has quite an effect on the performance and serviceability of concrete buildings. By comparing with the normal lightweight concrete, the rigidity of lightweight aggregate concrete containing rubber contents is much lower. According to Table 2.3, at 28 days, the rate of replacement for rubber particles increases from 0 % to 100 % and this results in a declination of modulus from 25 to 9.5 GPa. The reason behind this is because the elasticity modulus of rubber aggregate with respect to the mineral aggregate is low. Therefore, they do not contribute much on the resistance to externally applied loads but only act as large pores.

2.7.6 Freeze-thaw resistance

Moreover, Paine and Dhir (2010) had studied the feasibility of using granulated rubber in concrete construction technology. Based on their research, the freeze-thaw resistance of concrete improves as granulated rubber is used. In fact, the addition of crumb rubber particles in concrete at a proportion of 20 % by mass had shown a positive result with an increment of 40.96 % for the freeze-thaw resistance compared to the concrete without crumb rubber particles (Girkas and Nagrockiene, 2017). Figure 2.10 shows the results of freeze-thaw resistance with different composition of concrete.

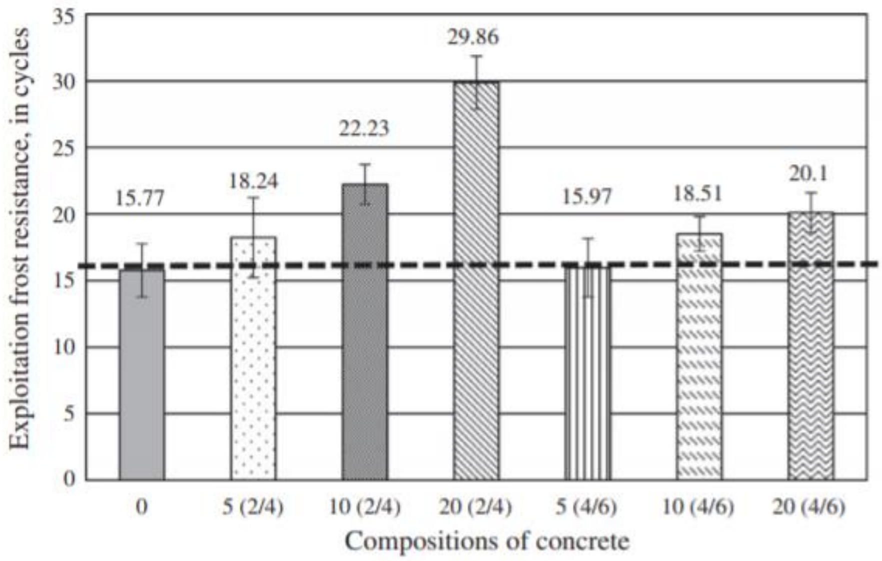

Figure 2.10: Result of Freeze-thaw Resistance (Girkas and Nagrockiene, 2017).

2.8 Summary

Overall, the conclusion of this literature review can be summarized as follows: Crumb rubber lightweight foamed concrete consists of fine aggregates, water, rubber particles and also air voids by the foaming agent in the cement paste. Crumb rubber lightweight foamed concrete (CRLFC) can be created by using foaming agents or pre-air entraining method.

Next, crumb rubber lightweight concrete has low density, low-thermal conductivity, good sound insulation and can be cast easily. Besides that, due to the natural characteristics of rubber particles, crumb rubber lightweight concrete has the ability to absorb impact forces. Compared to normal concrete, the compressive and tensile strength of the lightweight concrete with rubber particles is lower due to its density; however, under certain condition, people still choosing it over the normal concrete because of its massive properties such as the ability to absorb sound and thermal.

Lastly, rubber particles can reduce the weight of concrete. The crumb rubber particles are used to partially replace the fine aggregates in the concrete. The case study on the performance of the crumb rubber lightweight concrete has been reviewed and discussed. Although the mechanical strength of crumb rubber lightweight concrete is low, many applications had adopted this material due to its ability to resist higher impact and able to withstand the immensely adverse forces of the freeze-thaw cycle.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The main focus in the current chapter was on the procedures and methods of the study, which include the preparation of materials to produce crumb rubber lightweight foamed concrete, mix proportions and procedures, curing process, and then followed by the details of test procedures for concrete specimens. Figure 3.1 shows the flow chart of the overall research.

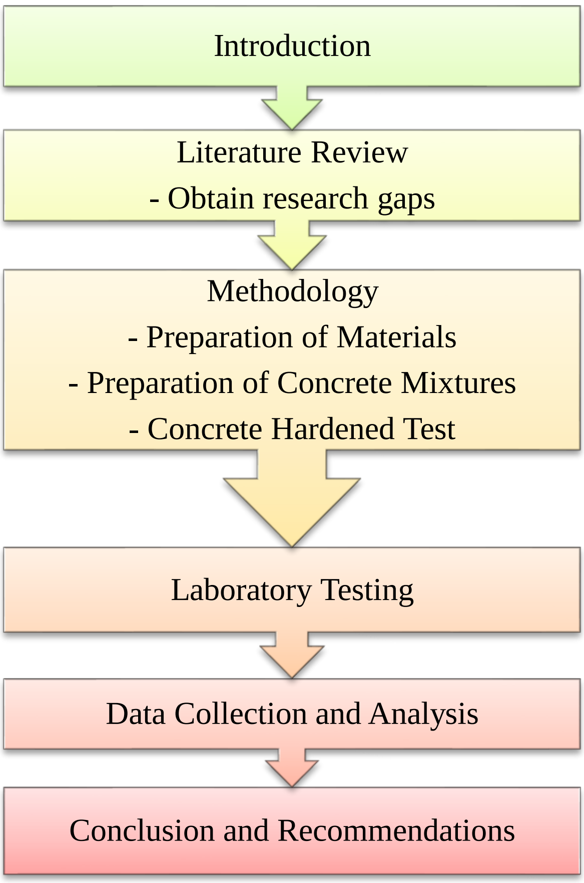

Figure 3.1: Flow Chart of Overall Research.

3.2 Raw Materials

Ordinary Portland cement (OPC), silica fume, fine aggregate (sand), rubber particles in the form of granular shape and powdered, foaming agent and also water which will then be mixed together in order to produce crumb rubber lightweight foamed concrete specimens with a density of 1100 – 1200 kg/m^3.

3.2.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement with the brand of ‘Orang Kuat’ from Yeoh Tiong Lay Sdn. Bhd was selected in this study. Based on ASTM C150, the OPC was sieved through a 600 μm (No.30) sieve to screen out the hydrated clinker in the cement. After that, the excessive sieved cement was stored under an air-tight container to avoid the hydration process of cement with humid air in surroundings. Figure 3.2 shows the Ordinary Portland cement brand used.

Figure 3.2: The Ordinary Portland Cement, ‘Orang Kuat’ brand from YTL Sdn. Bhd.

3.2.2 Silica Fume

Silica fume was added into the mix proportion. In this study, Scancem Materials silica fume with a density of 430 kg/m^3 was used. At first, the silica fume was sieved through a sieve with openings of 600 μm (No.30). Then, excessive sieved silica fume was stored in an airtight container to prevent moisture from the surroundings to damp the silica fume. After that, 10 % of OPC will be replaced with silica fume in terms of mass (kilogram). For instance, 4 kg of cementitious material contains 3.6 kg of OPC and 0.4 kg of silica fume. Figure 3.3 illustrates the sieved silica fume of Scancem Materials.

Figure 3.3: Silica Fume from Scancem Materials.

3.2.3 Fine Aggregate

The categories of fine aggregates include sand as well. The sand was oven-dried at the beginning for at least 24 hours at the temperature of 105 °C to remove the unnecessary moisture in the sand. After that, 600 μm (No.30) passing sieve was used to sieve the dried sand and kept in a container. Figure 3.4 shows the sieved sand in a container.

Figure 3.4: Sieved Sand in a Container.

3.2.4 Crumb Rubber

Crumb rubber was used in this study to replace the sand partially. There are two different sizes of crumb rubber in this study, which are the granular and powdered crumb rubbers. Granular crumb rubber particles were sieved between the ranges of 0.075 mm - 4.75 mm (No.4 and No.200 sieve) sieve whereas powdered crumb rubber comes in the size of 40 mesh. Figure 3.5 and 3.6 illustrate the crumb rubber for the laboratory work.

Figure 3.5: Granular Crumb Rubber Particles.

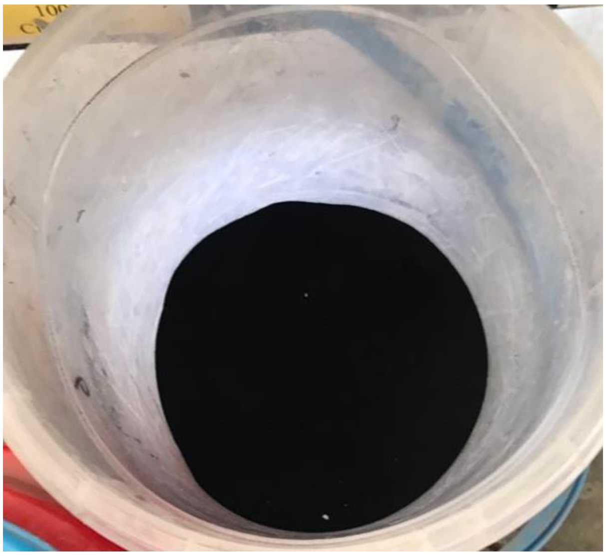

Figure 3.6: Powdered Crumb Rubber Particles.

3.2.5 Foaming Agent

In this study, SikaAER$^{@}$ - 50/50 had been chosen to be used as the air-entraining agent due to its strong air-entraining properties. Figure 3.7 shows the SikaAER$^{@}$ - 50/50, a strong air-entraining admixture, which is also known as a foaming agent to produce foam when mixed with water and pressurized in the foam generator.

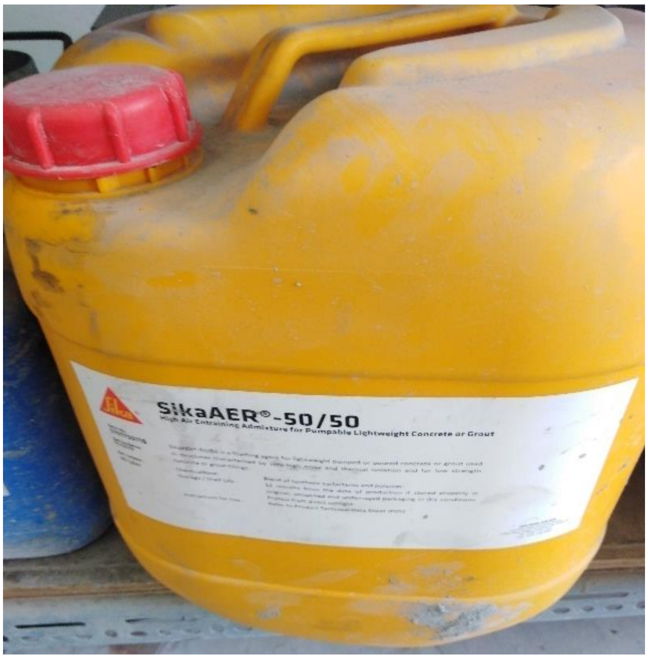

Figure 3.7: The Foaming Agent - SikaAER$^{@}$ - 50/50.

The mixture of foaming agent and water into the foam generator under the pressure of 0.5 MPa was used to produce foam with desired density. The ratio of a foaming agent to water was around 1:20 and the density of the produced foam was approximately 45 ± 5 kg/m^3. After that, the stabilized foam was induced and dispensed out through the nozzle. Figure 3.8 shows the foam generator and Figure 3.9 illustrates the generated foam.

Figure 3.8: Foam Generator.

Figure 3.9: Generated Foam.

3.2.6 Water

Water is one of the most important components used to mix the concrete and for water curing stage. Throughout this research, tap water was used. The negative effect of cement hydration and the durability can be avoided by making sure the pH value of water was normal and free from impurities.

3.3 Mould

Three types of concrete moulds were used in this research:

1. 100 mm x 100 mm x 100 mm cube for the compressive strength test.
2. 200 mm (H), diameter 100 mm cylinders for the splitting tensile strength test, and
3. 40 mm x 40 mm x 160 mm prism for the flexural strength test.

Before using the moulds, the moulds were cleaned and checked to assure that they are free from concrete residues from previous work. The pressure cleaner was used to help in cleaning the moulds. After that, the moulds were covered with a layer of oil before pouring the concrete into it to ease the work of demoulding.

3.4 Mix Proportions

In this study, 16 sets of mix proportions of crumb rubber lightweight foamed concrete and 1 controlled mix (CLFC - 0) were produced.

Firstly, the controlled mix did not contain either granular or powdered crumb rubber particles. It is set as the reference for the other mix proportions. Next, there were eight sets of granular crumb rubber lightweight foamed concrete (GCLFC) while the remaining eight sets were powdered crumb rubber lightweight foamed concrete (PCLFC). The proportion of granular and powdered crumb rubber particles range from 10 % - 80 % with an interval of 10 % respectively.

Besides that, the water-cement ratio was fixed at 0.60 for each mix proportion of the crumb rubber lightweight foamed concrete. The designations of granular crumb rubber lightweight foamed concrete and powdered crumb rubber lightweight foamed concrete is reported in Table 3.1 and Table 3.2 respectively.

Table 3.1: Granular Crumb Rubber Lightweight Foamed Concrete (GCLFC) Design Mix.

Designation	Replacement of Rubber Particles (%)	Water/Cement Ratio
GCLFC – 10	10	0.60
GCLFC – 20	20	0.60
GCLFC – 30	30	0.60
GCLFC – 40	40	0.60
GCLFC – 50	50	0.60
GCLFC – 60	60	0.60
GCLFC – 70	70	0.60
GCLFC – 80	80	0.60

Table 3.2: Powdered Crumb Rubber Lightweight Foamed Concrete (PCLFC) Design Mix.

Designation	Replacement of Rubber Particles (%)	Water/Cement Ratio
PCLFC – 10	10	0.60
PCLFC – 20	20	0.60
PCLFC – 30	30	0.60
PCLFC – 40	40	0.60
PCLFC – 50	50	0.60
PCLFC – 60	60	0.60
PCLFC – 70	70	0.60
PCLFC – 80	80	0.60

The mix proportioning begins with the selection of the unit weight of the concrete (wet density), the cement content, and the water-cement ratio. Next, the mix is proportioned by the method of absolute volumes. Silica fume was used as a cementitious material which replaces 10 % of the cement by weight and the W/C ratio was fixed at 0.6.

The partial replacement of sand in lightweight foamed concrete with crumb rubber particles leads to a reduction of density due to its lower specific gravity of crumb rubber (1150 kg/m^3) compared to sand (2650 kg/m^3). The crumb rubber lightweight foamed concrete actual material density is reported in Table 3.3. The density of all mixes should be equal, which is 1150 kg/m^3.

Table 3.3: The Actual Density of Materials in Concrete Mixture for GCLFC and PCLFC.

Concrete Mixtures		Cement (kg/m^3)	Silica Fume (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Crumb Rubber (kg/m^3)		Foam (kg/m^3)	Fresh Density (kg/m^3)
						GCLFC	PCLFC		
CLFC- 0		392.66	43.63	436.29	261.78	0.00	0.00	15.64	1150.00
GCLFC- 10	PCLFC – 10	401.95	44.66	401.95	267.96	18.54	18.54	14.94	1150.00
GCLFC- 20	PCLFC – 20	411.68	45.74	365.94	274.45	37.97	37.97	14.21	1150.00
GCLFC- 30	PCLFC – 30	421.89	46.88	328.14	281.26	58.38	58.38	13.45	1150.00
GCLFC- 40	PCLFC – 40	432.63	48.07	288.42	288.42	79.81	79.81	12.65	1150.00
GCLFC- 50	PCLFC – 50	443.92	49.32	246.62	295.95	102.37	102.37	11.80	1150.00
GCLFC- 60	PCLFC – 60	455.83	50.65	202.59	303.88	126.14	126.14	10.91	1150.00
GCLFC- 70	PCLFC – 70	468.38	52.04	156.13	312.26	151.22	151.22	9.97	1150.00
GCLFC- 80	PCLFC – 80	481.65	53.52	107.03	321.10	177.72	177.72	8.98	1150.00

3.5 Mixing Procedure

Generally, the steps to produce the crumb rubber lightweight foamed concrete are almost similar to the steps in producing the normal concrete. The only difference is the addition of the foaming agent and the crumb rubber particles in concrete. The mixing procedures for preparing CLFC - 0, GCLFC and PCLFC were similar except for the replacement percentage of sand and crumb rubber.

First of all, a ball mixer was prepared and the dry mix was carried out in the mixer, which includes cement, silica fume, sand and crumb rubber particles. The materials were weighted accordingly to the mix proportion before they are mixed thoroughly in the mixer. Once the mixture was evenly mixed, water was weighted accurately and added gently into the mixing bowl until it achieved the desired water-cement ratio. The foam was produced in the foam generator and the volume of a foaming agent to water ratio was 1:20. Then, the foaming agent was added into the wet mixture until it attained the desired density of 1100 - 1200 kg/m^3.

After mixing, the fresh crumb rubber lightweight foamed concrete was poured, spread evenly and compacted in the prepared moulds.

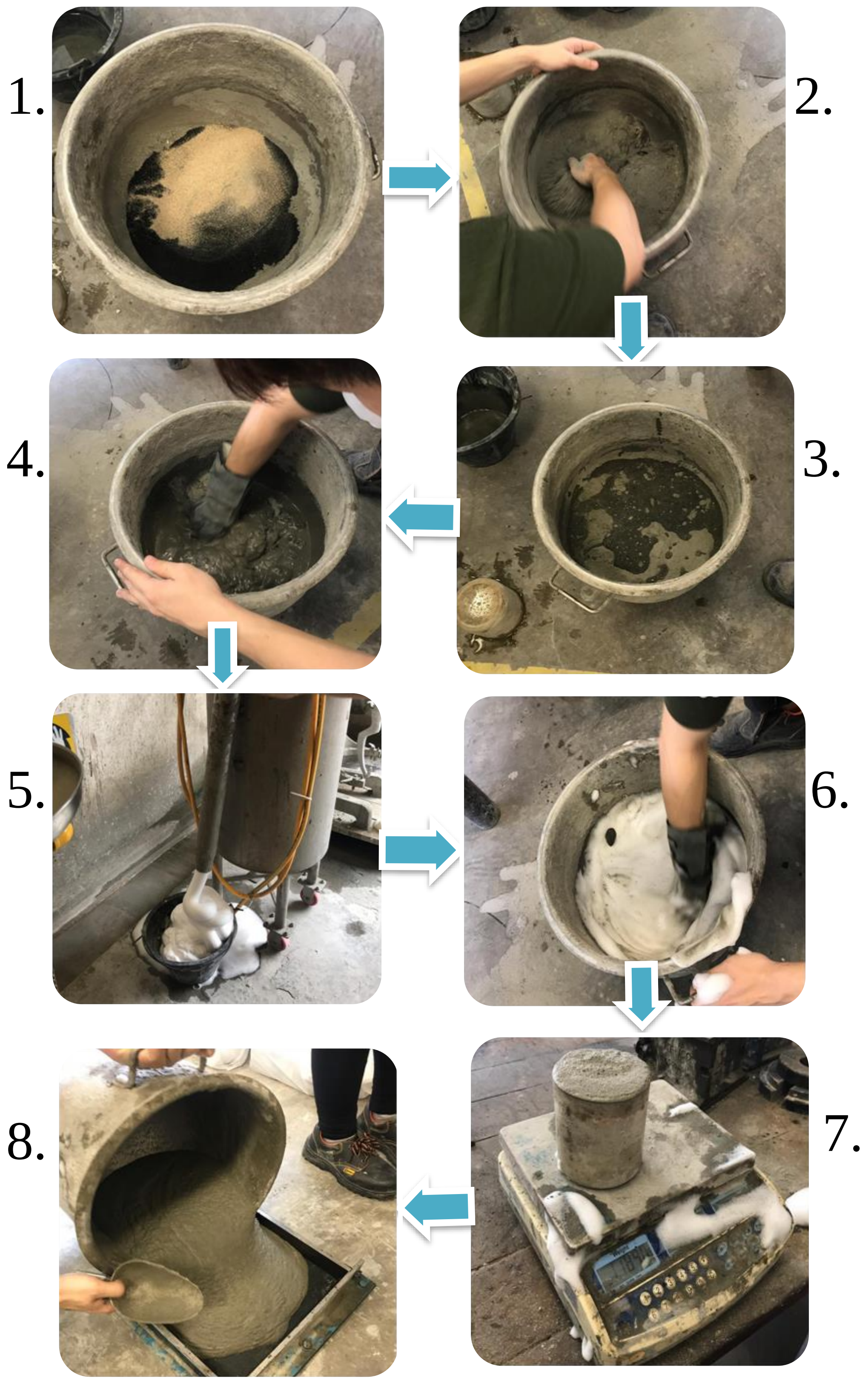

Figure 3.10: Flow of The Mixing Procedures of Crumb Rubber Lightweight Foamed Concrete.

3.6 Casting

After achieving the desired density for the concrete, the wet mixture was cast into three different concrete moulds. The first mould was the cube mould for compressive strength test with a dimension of 100 mm x 100 mm x 100 mm, the second mould was the 200 mm (H) x diameter 100 mm cylindrical mould for splitting tensile strength test and lastly, 40 mm x 40 mm x 160 mm prism mould for flexural strength test. Then, the excessive fresh concrete at the top surface of the mould was removed and levelled after 15 minutes of casting. Next, the fresh concrete was left for 24 hours to set and harden before it was removed from its mould. After that, the concrete was incubated into the water tank for curing purposes.

Figure 3.11: Casting of Concrete.

3.7 Curing

The concrete samples were cured in the water tank to enhance the hydration process of the samples. An optimum duration of 28 days was required for the concrete to undergo a chemical reaction with water so that an ideal concrete strength could be achieved. The temperature of water in the water tank for curing purposes was controlled within the range of 25 to 28 ^{o}C. The specimens were cured for 28 days. Figure 3.12 shows the specimens to be cured in the water tank.

Figure 3.12: Curing Process of Concrete Specimens.

3.7.1 Density Test

The fresh density test was carried out in accordance with ASTM C138 by using a container (1 litre). Figure 3.13 shows the wet density test. The weight of the container was weighted by using the electronic weighing machine.

Figure 3.13: Fresh Density Test of Fresh Concrete.

First, the container was completely filled with fresh concrete. Next, the side of the container was slightly tapped for consolidation purposes. After filling the container, the excess fresh concrete at the top of the container was wiped out to ensure the surface was flat. Then, the container containing the fresh concrete was weighted and the density was recorded. The steps were repeated to obtain the average result. The fresh density was calculated based on the equation (3.1).

$$Density = \frac{Mass}{Volume} \tag{3.1}$$

3.8 Hardened Concrete Test

After curing the concrete specimens for 28 days, the following tests were carried out to determine the mechanical properties of the crumb rubber lightweight foamed concrete. Before that, all the specimens were dried in the oven so that the moisture of the concrete surface can be removed.

3.8.1 Compressive Strength

The compressive strength test was carried out based on BS EN 12390-3 (2002), by testing cube specimens with dimension 100 mm x 100 mm x 100 mm. The compression machine (AD 300/EL Digital Readout 3000 kN) was used to carry out the concrete compression test. Figure 3.14 illustrates the compression machine, and the position of the concrete cube before the force is applied.

Figure 3.14: Compression Test in Compression Machine AD 300/EL Digital Readout 3000 kN.

The concrete cubes were measured and recorded before the commencement of the compressive strength test. The concrete cubes were then placed on the centre of the compression machine. A constant axial load of 0.2 kN/s was applied on the concrete until the fracture point. The optimum reading from the machine was then recorded. After that, the steps were repeated to obtain the results for the next two concrete cubes. An average value was obtained for the calculation.

Equation (3.2) demonstrates the calculation of compressive strength for the crumb rubber lightweight foamed concrete.

$$Compressive\ Strength, F = \frac{Load\ (P)}{Cross{-}Sectional\ Area(A)} \tag{3.2}$$

where

F = Compressive strength, MPa

P = load applied by the machine, N

A = cross-section area of the concrete cube, m^2

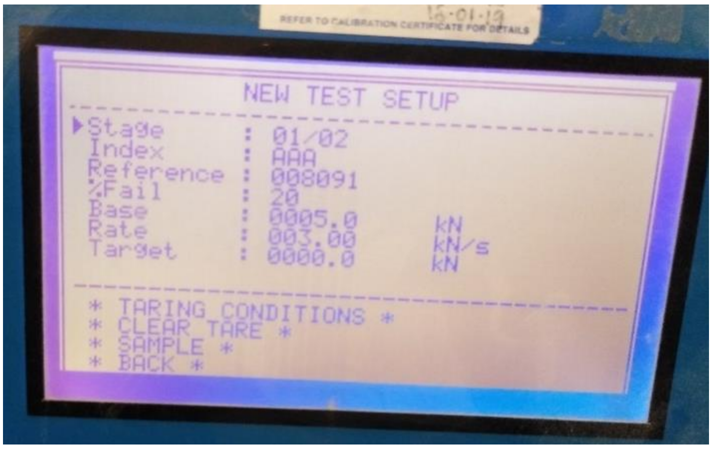

Figure 3.15: The Machine Setup for the Rate of Compressive Strength.

3.8.2 Splitting Tensile Strength

The splitting tensile test was applied in this study to obtain the tensile strengths of the concrete. The steps to carry out the test were almost the same as the previous compression test, except this time a cylindrical specimen was used instead of a cube specimen. After 28 days of curing, the specimens were removed from the water tank and oven-dried. A diametrical line at both ends of the specimen was drawn to ensure that they are on the same axial axis.

Figure 3.16 shows the placing of a cylindrical specimen for splitting tensile test. Before carrying out the test, the dimension and the weight of the specimens were recorded. Two plywood bearing strips were placed at the top and bottom surface of the specimen to ensure an even distribution of loading.

Figure 3.16: The Placing of Cylindrical Specimen for Splitting Tensile Strength Test.

After that, load was applied continuously at a rate of 0.2 kN/s until cracking occur. The breaking load (P) was then recorded. To calculate the splitting tensile strength of the specimen, equation 3.3 was used:

$$T = \frac{2P}{\pi LD} \tag{3.3}$$

where

T = splitting tensile strength, MPa
P= maximum applied load indicated by the testing machine, N
D= diameter of the specimen, m
L= length of the specimen, m

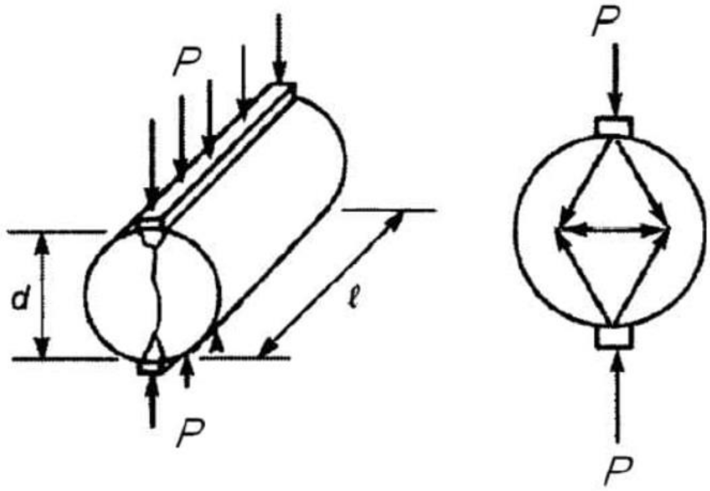

Figure 3.17: Illustration of The Tensile Test on Concrete (Hamakareem, 2016).

3.8.3 Flexural Strength

The flexural strength is also known as the modulus of rupture. In this study, prism specimens were used to carry out the test. The flexural test was done based on the guidelines of ASTM C496 standard. Figure 3.18 shows the size of the mould (40 mm x 40 mm x 160 mm) of the concrete prism specimen to be tested.

Figure 3.18: Prism Mould.

Before the test was carried out, the prism specimens were oven-dried for 24 hours. Then, it was horizontally placed on the machine based on Figure 3.19. A continuous loading was applied at the middle of the prism specimen at a rate of 0.2 kN/s until the failure point occurred. After that, the test was repeated for the other two specimens and the results were averaged and recorded.

Figure 3.19: The Concrete Set Up on the Flexural Machine.

To calculate the flexural strength of the prism specimen, Equation (3.4) was used:

$$R = 3PL/2bd^2 \qquad (3.4)$$

where

Load and Flexural Strength

- P = Maximum Load Applied Indicated by Compression Machine (N)
- R = Flexural Strength (MPa)

Dimensions

- L = Maximum Span Length (mm)
- b = Average Specimen Width (mm)
- d = Average Specimen Depth (mm)

3.9 Summary

Overall, the procedures were separated into two stages. The first stage was the casting of crumb rubber lightweight foamed concrete in various moulds, which are the cube, cylindrical and prism moulds. Firstly, a sieve analysis was conducted to analyse the properties of the materials. Next, crumb rubber lightweight foamed concrete specimens were produced by adding the foaming agent until the concrete had achieved the desired density of 1100 to 1200 kg/m^3. A total of 17 different mix proportions of crumb rubber lightweight foamed concrete were produced with different percentages of crumb rubber replacement. They are 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 % and 80 % for both granular and powdered crumb rubber lightweight foamed concrete. After that, fresh density measurements were conducted to test the fresh concrete properties.

The second stage was the testing stage, where compressive strength test, flexural strength test and splitting tensile strength test were carried out to test the crumb rubber lightweight foamed concrete after 28 days of curing. After that, the results and data were collected for the comparison of the mechanical strength of granular and powdered crumb rubber lightweight foamed concrete.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the outcome of this study, which is essential to justify the feasibility of using crumb rubber particles in lightweight foamed concrete to further increase the mechanical strength. Three main mechanical strength tests were carried out, namely the compressive strength test, flexural strength test and the splitting tensile strength test. In addition, the comparison of mechanical strength between two different sizes of crumb rubber particles in concrete, that are granular (GCLFC) and powdered (PCLFC) crumb rubber lightweight foamed concrete was recorded and presented. All concrete samples were cured in water for 28 days before testing. Finally, the interpretation of result data was discussed as well.

4.2 Mechanical Properties Test

Three main tests were conducted in this study to obtain the mechanical properties of the crumb rubber lightweight foamed concrete. The tests include the flexural strength test, compressive strength test and the splitting tensile strength test. A total of 17 sets of fresh concrete mixtures were produced with different percentages of granular and powdered crumb rubber replacement ranging from 0% to 80% respectively. The average value was calculated to achieve the accuracy and consistency of the result.

Hypothetically, the presence of crumb rubber itself in concrete will consequently diminish the mechanical strength as the cement paste and the crumb rubber particle boundaries adhesion forces between them are gradually reducing, causing an increase in the volume of the interface transition zone (Sofi, 2018). However, by introducing crumb rubber in lightweight foamed concrete could enhance the strength in terms of mechanical properties. The reasons for this phenomenon will be discussed in the following subtopics.

4.2.1 Compressive Strength Test

The compressive strength test is one of the most important tests in the construction industry to evaluate the quality and grading of concrete. A total of 51 concrete cube samples with a dimension of (100 x 100 x 100) mm were cast in this study for compressive strength testing. The 51 cube samples consist of both granular (GCLFC) and powdered (PCLFC) crumb rubber lightweight foamed concrete with different percentages of crumb rubber replacement. The compressive strength was obtained by taking the maximum load (P) of a cube divided by the surface area (A) of contact. Three cube samples were tested for each set. Table 4.1 and 4.2 show the result of the compressive strength test of GCLFC and PCLFC while Figure 4.1 and 4.2 illustrate the bar chart of the averaged compressive strength for both GCLFC and PCLFC.

Table 4.1: The Result of Compressive Strength Test of GCLFC.

Specimen Designation	Compressive Strength (MPa)			
	A	**B**	**C**	**Avg.**
CLFC - 0	2.670	2.580	2.720	2.657
GCLFC - 10	2.770	2.710	2.850	2.777
GCLFC - 20	3.190	2.650	2.950	**2.930**
GCLFC - 30	2.600	2.670	2.710	2.660
GCLFC - 40	2.470	2.520	2.600	2.530
GCLFC - 50	2.250	2.390	2.470	2.440
GCLFC - 60	2.410	2.360	2.540	2.437
GCLFC - 70	2.220	2.650	2.180	2.350
GCLFC - 80	1.970	2.470	2.390	2.277

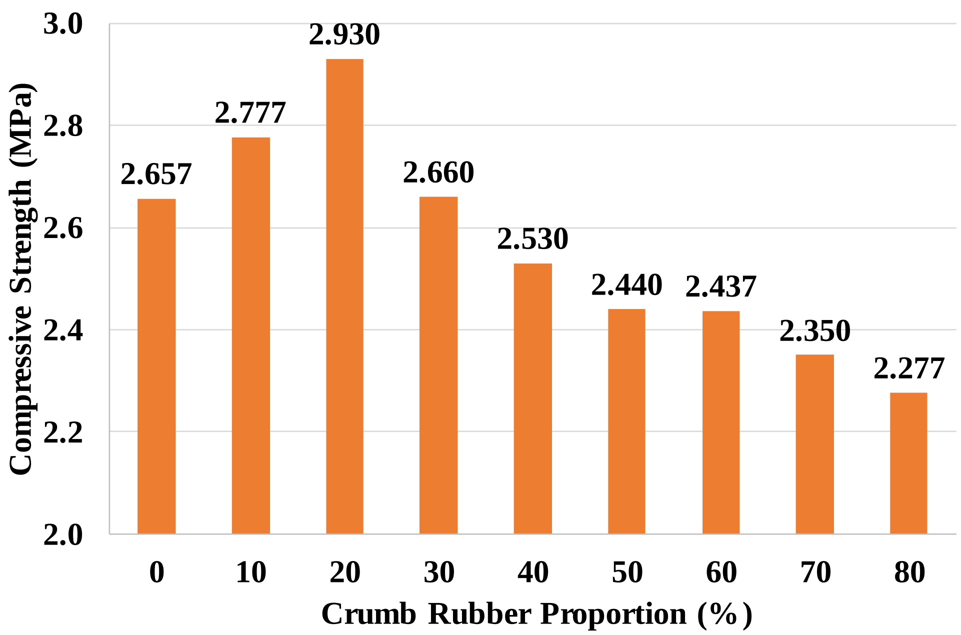

Figure 4.1: Compressive Strength versus Percentage of Granular Crumb Rubber Proportion – GCLFC.

Based on Figure 4.1, it shows that the compressive strength increases at the first 20 % of the bar chart and then decreases dramatically after that. The compressive strength of GCLFC is at its peak at 20 % of granular crumb rubber proportion with an increment of 10.27 % compared to the controlled mix, which is 2.930 MPa. After that, it falls to 2.277 MPa at 80 % of crumb rubber proportion. The reason for such decrease is due to the lack of proper bonding between cement paste and crumb rubber particles, as compared to natural aggregate (sand) and cement paste. As a result, the non-uniform distribution of stresses applied could lead to the formation of cracks (Sofi, 2018).

Table 4.2: The Result of Compressive Strength Test of PCLFC.

Specimen Designation	**Compressive Strength (MPa)**			
	A	**B**	**C**	**Avg.**
CLFC - 0	2.620	2.850	2.880	2.657
PCLFC - 10	2.890	2.930	2.730	2.783
PCLFC - 20	2.990	2.880	2.710	2.850
PCLFC - 30	2.910	2.750	2.550	2.860
PCLFC - 40	2.740	2.850	2.740	2.737
PCLFC - 50	3.380	3.510	2.990	2.740
PCLFC - 60	3.390	3.720	3.560	3.293
PCLFC - 70	3.180	4.080	3.140	**3.557**
PCLFC - 80	3.180	4.080	3.140	3.467

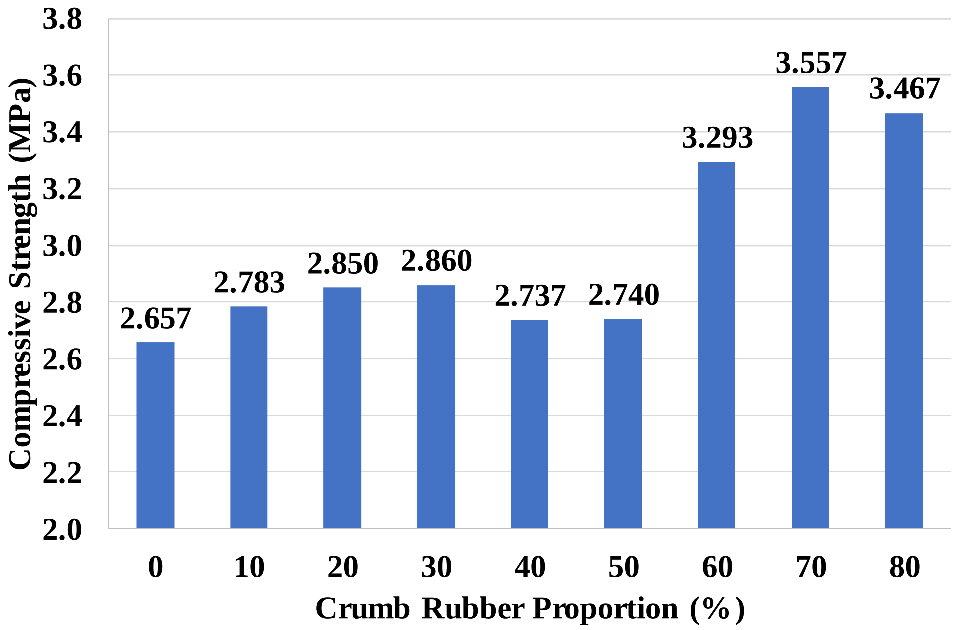

Figure 4.2 : Compressive Strength versus The Percentage of Crumb Rubber – PCLFC.

The bar chart for PCLFC depicts that the compressive strength of PCLFC fluctuated and generally rises throughout the chart. It increases at the beginning but there is a significant diminution in the strength when it hits 40 % of powdered crumb rubber proportion. This phenomenon might have happened due to the uneven distribution of foam and crumb rubber during concrete mixing, which forms an unstable mix with high voids and porosity (Johnson, 2018). Concrete with higher voids is more permeable to soluble elements and water. Hence, a slight reduction in strength and durability is expected in this kind of situation. However, it continues to rise after 50 % of crumb rubber proportion and reaches its highest compressive strength at 70 % with the compressive strength result of 3.557 MPa. Overall, the obtained results have shown that the PCLFC, which contains a portion of powdered crumb rubber particles has better compressive strength as it increases 33.87 % compared to the controlled mix, CLFC – 0.

Figure 4.3 illustrates the comparison of the average compressive strength between both GCLFC and PCLFC with different percentages of crumb rubber proportion. The inclusion of crumb rubber that acts as a filler or an additive in lightweight foamed concrete had shown a partial improvement in the compressive strength for both concretes.

By comparing the graphs from Figure 4.3, it is apparent that both graphs consist of an upward trend on the compressive strength development but for the GCLFC, it declines right after it reaches its peak at 20 % (2.930 MPa) of crumb rubber proportion, earlier than the PCLFC which continues to increase until 70 % with a peak value of 3.557 MPa.

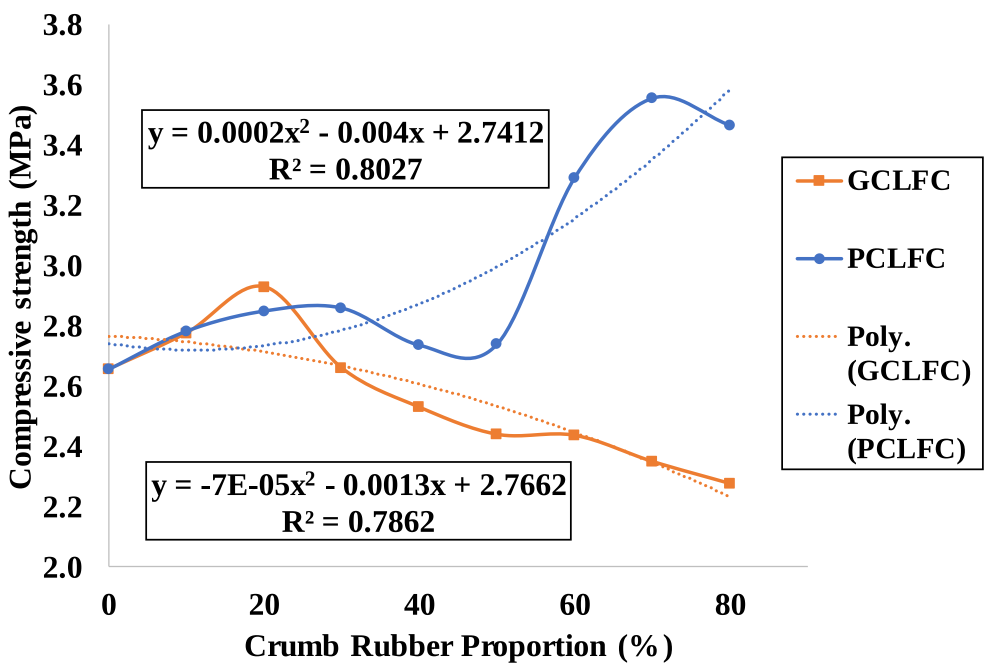

Figure 4.3 : The Relationship between The Compressive Strength of GCLFC and PCLFC.

Besides that, the PCLFC with the particle size of 40 mesh has bigger effects in the increment of the compressive strength compared to the GCLFC with the particle size of 1 to 40 mm. This could be explained by looking at the compressive strength of PCLFC, which has further improved by 33.87 % at 70 % of crumb rubber proportion. Cement mortar consists of different sizes of pores inside and the finer size of crumb rubber particles may fill the pores and improve the density of concrete which caused the compressive strength to increase.

For GCLFC, the compressive strength has improved by 4.52 % to 10.28 % during the first 10 and 20 % of crumb rubber proportion. However, beyond the crumb rubber proportion of 20 %, the strength started reducing tremendously to 2.277 MPa, a reduction percentage of 14.3 %. This observation can be explained by the excessive amount of crumb rubber with a hydrophobic property which in turn creates the additional number of voids into the concrete causing a poor bonding between the crumb rubber particles and the cement paste (Yong, 2016). Besides, rubber particles generally contain relatively low strength and as the proportion of crumb rubber increases, the properties of rubber would eventually dominate the properties of concrete which results in the loss of strength (Pelisser, et al., 2011). Moreover, the development of micro-crack attributed by the high content of crumb rubber particles will affect the compressive strength of the GCLFC (Abdullah, et al., 2017).

4.2.2 Splitting Tensile Strength

The splitting tensile strength is one of the most useful and fundamental properties which could determine the performance and size of cracking in a concrete structure. Concrete is weak in tension due to its brittle nature and it cannot resist tension directly. Moreover, cracks will develop when tensile forces applied exceed the tensile strength of concrete. A total of 51 concrete cylindrical samples with dimension (H = 200mm, d = 100mm) were cast in this study for splitting tensile strength test. These cylindrical samples consist of different percentages of crumb rubber replacement for both granular and powdered crumb rubbers. Table 4.3 shows the result of the splitting tensile strength test of GCLFC and the average splitting tensile strength for GCLFC with different percentages of granular crumb rubber replacement is illustrated in Figure 4.4.

Table 4.3: The Result of Splitting Tensile Strength Test of GCLFC.

Specimen Designation	Splitting Tensile Strength (MPa)			
	A	**B**	**C**	**Avg.**
CLFC - 0	0.353	0.331	0.299	0.328
GCLFC - 10	0.344	0.360	0.321	0.342
GCLFC - 20	0.341	0.401	0.455	**0.399**
GCLFC - 30	0.398	0.376	0.369	0.381
GCLFC - 40	0.315	0.306	0.442	0.354
GCLFC - 50	0.321	0.325	0.293	0.313
GCLFC - 60	0.341	0.344	0.248	0.311
GCLFC - 70	0.280	0.245	0.245	0.257
GCLFC - 80	0.226	0.251	0.226	0.234

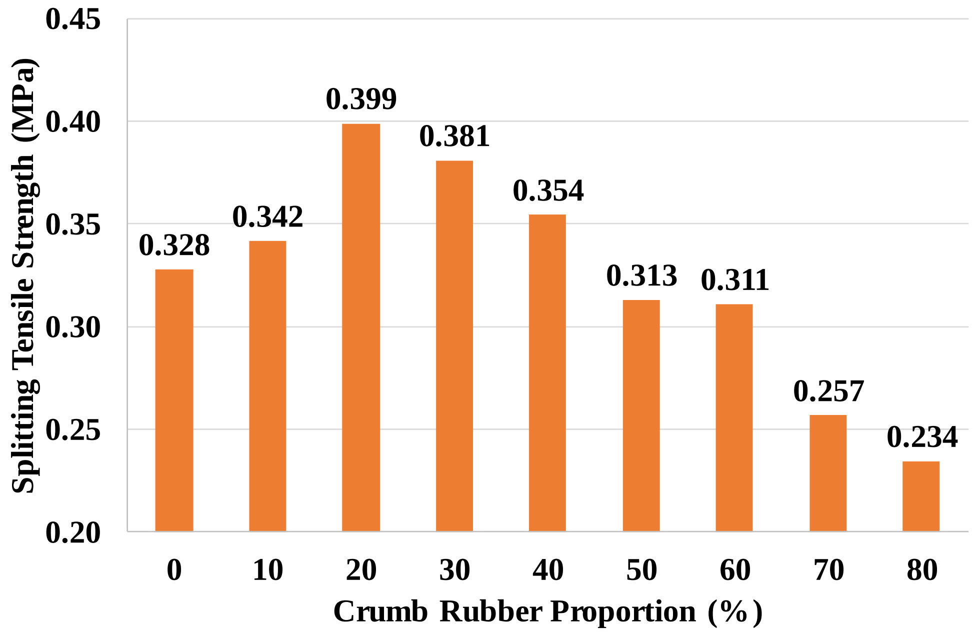

Figure 4.4: Splitting Tensile Strength versus The Percentage of Crumb Rubber – GCLFC.

Similar to the trend observed in compressive strength of GCLFC, the bar chart of splitting tensile strength increases at the first 20 % of crumb rubber replacement and then declines vigorously after that. The reason behind this increase is inflicted by the improvement of adhesion between crumb rubber particles with cement paste compared to the adhesion of normal aggregate (sand) with the cement matrix. The irregular shape and rough surface of crumb rubber particles with uncountable voids have the ability to effectively absorb the tensile stresses and hence increasing the splitting tensile strength (Grinys, et al., 2012).

However, a significant drop in splitting tensile strength would occur once the crumb rubber particles exceed its maximum amount of replacement, which is from 30 % onwards. The splitting tensile strength of GCLFC is at its peak during 20 % of granular crumb rubber replacement, with a result of 0.399 MPa and it falls to 0.234 MPa at 80 %.

On the other hand, Figure 4.5 shows the average splitting tensile strength of PCLFC with different percentages of powdered crumb rubber replacement. The splitting tensile strength for PCLFC has shown a rather steady strength growth starting from 20 % to 70 % of crumb rubber proportion. As the percentage of powdered crumb rubber proportion increases, the splitting tensile strength increases. The highest reading for the splitting tensile strength for PCLFC is 0.533 MPa at 70 % of crumb rubber proportion, with a total increment of 62.5 %. Although the trend is similar to the compressive strength of PCLFC, the previous graph has a slight dip at 40 % of crumb rubber proportion. Overall, the results have implied that the powdered crumb rubber particles are effective in improving the splitting tensile strength of lightweight foamed concrete compared to the controlled mix, CLFC – 0 with only 0.328 MPa in splitting tensile strength. The result of the splitting tensile strength test for PCLFC is reported in Table 4.4.

Table 4.4: The Result of Splitting Tensile Strength Test of PCLFC.

Specimen Designation	Splitting Tensile Strength (MPa)			
	A	B	C	Avg.
CLFC - 0	0.353	0.331	0.299	0.328
PCLFC - 10	0.360	0.315	0.334	0.336
PCLFC - 20	0.293	0.334	0.296	0.308
PCLFC - 30	0.321	0.360	0.331	0.337
PCLFC - 40	0.388	0.411	0.407	0.402
PCLFC - 50	0.385	0.388	0.474	0.416
PCLFC - 60	0.487	0.503	0.411	0.467
PCLFC - 70	0.493	0.567	0.538	**0.533**
PCLFC - 80	0.465	0.417	0.430	0.437

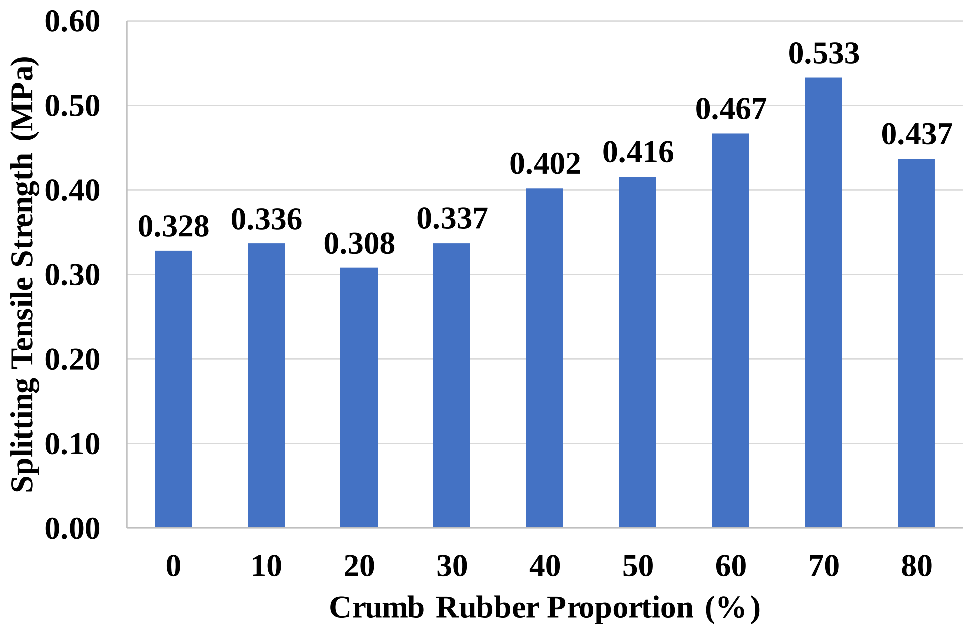

Figure 4.5: Splitting Tensile Strength versus The Percentage of Crumb Rubber -PCLFC.

Figure 4.6 compares the splitting tensile strength of the GCLFC and PCLFC. The presence of crumb rubber in lightweight foamed concrete has a different outcome in both GCLFC and PCLFC. The particle size of crumb rubber matters in terms of splitting tensile strength. GCLFC shows a declining curve while PCLFC shows a steady increase in the splitting tensile strength. For GCLFC, the results reduce ranging from 4.57 % to 28.70 % as compared to the CLFC – 0, whereas for PCLFC, it shows a continuous increment of 2.44 % to 62.50 %.

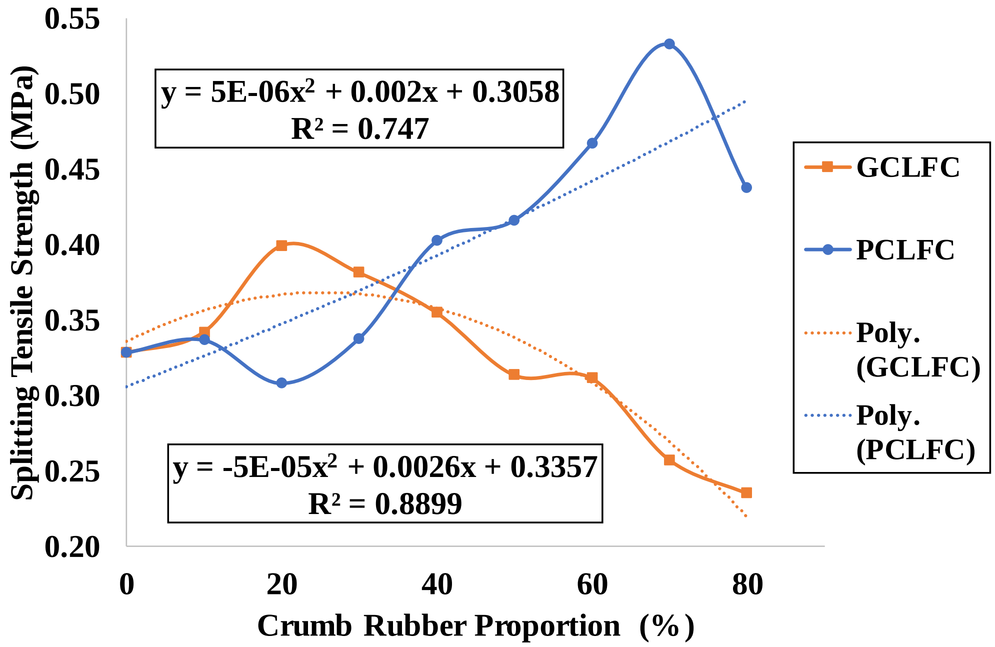

Figure 4.6: The Relationship between The Splitting Tensile Strength of GCLFC and PCLFC.

Crumb rubber is a soft material where it could act as a barrier to prevent concrete from crack growth (Sofi, 2018). Hence, the lightweight foamed concrete containing crumb rubber particles should have higher tensile strength compared to the controlled mix, CLFC – 0. However, for GCLFC, the results show an opposite hypothesis. This behaviour could be due to the weak bonding of the interface zone between the cement paste and crumb rubber particles which accelerates the breakdown of the concrete (Taha, et al., 2008).

Compared to the previous compressive strength graph, this graph shows a more consistent result. One notable finding is that during the testing stage, the size and number of cracks appeared on the GCLFC was larger than the ones on PCLFC. This is due to the bonding between the crumb rubber particles and the cement paste of GCLFC, which is not as strong as the bonding of powdered crumb rubber particles and the cement paste. Figure 4.7 and 4.8 shows the concrete failure of GCLFC and PCLFC for splitting tensile test.

Figure 4.7: Concrete Failure of GCLFC.

Figure 4.8: Concrete Failure of PCLFC.

To generalise the results of the crumb rubber lightweight foamed concrete for splitting tensile strength, it may be noted that there is a slight increase in the splitting tensile strength for GCLFC when a small amount of crumb rubber particles are introduced (Eltayeb, et al., 2020). Finer (powdered) crumb rubber particles are better with the ability of void filling. With a larger surface area of the fine (powdered) crumb rubber particles, the overall surface area of the concrete paste was able to increase. Therefore, a more evenly mixture was produced, resulting in a higher splitting tensile strength. Moreover, finer crumb rubber generates more effective packing structures especially in the zone of interfacial of the lightweight foamed concrete, making it more homogenous hence increases the tensile strength of the concrete (Abdullah, et al., 2017).

4.2.3 Flexural Strength

The flexural strength of concrete can be defined as the maximum bending stress that concrete can sustain before yielding. It can be obtained by using a technique called three-point flexural test. When a three-point load is applied to the centre of a concrete prism, it will experience tension at the bottom and compression at the top simultaneously. The elongation action caused by the bending would result in the failure (break) of the prism when it cannot sustain the tension forces. Hence, cracks would occur at the bottom. A total of 51 concrete prism samples with dimension (40mm x 40mm x 160mm) were cast in this study for the flexural strength test. The flexural strength of GCLFC and PCLFC are averaged and reported in Figure 4.9 and 4.10, respectively.

Table 4.5: The Result of Flexural Strength Test of GCLFC.

Specimen Designation	Flexural Strength (MPa)			
	A	**B**	**C**	**Avg.**
CLFC - 0	2.221	2.191	2.138	2.183
GCLFC - 10	2.130	2.367	-	**2.248**
GCLFC - 20	1.760	1.755	1.617	1.710
GCLFC - 30	1.714	1.766	2.029	1.837
GCLFC - 40	0.911	0.822	1.214	0.982
GCLFC - 50	0.875	1.237	1.493	1.202
GCLFC - 60	1.318	1.164	1.033	1.172
GCLFC - 70	1.003	1.020	1.397	1.140
GCLFC - 80	1.079	0.981	0.861	0.974

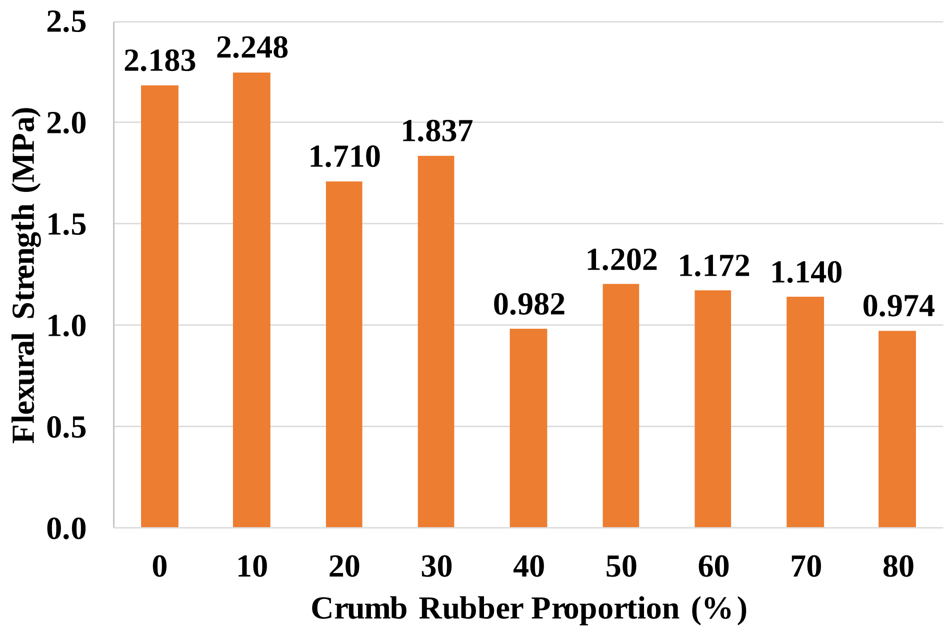

Figure 4.9: Flexural Strength versus The Percentage of Crumb Rubber – GCLFC.

The gradual reduction in the flexural strength can be explicitly seen from Figure 4.9 as the percentage of crumb rubber replacement increases. At 10 % of crumb rubber proportion records the highest flexural strength (2.248 MPa) of GCFLC, and beyond that, it starts reducing to 0.974 MPa at 80 %. The greatest reduction in flexural strength occurs at 40 % of crumb rubber replacement, with a 55 % strength reduction compared to the controlled mix, CLFC – 0 (0.982 MPa).

During the flexural test, the specimens without the crumb rubber particles (CLFC – 0) split into two pieces shortly after cracking and it exhibited brittle failure. However, for the specimens containing crumb rubber particles showed deformation and it did not disintegrate completely.

Furthermore, the bar chart for PCLFC is rather unusual as there are two peaks. The first peak falls at 40 % (2.329 MPa) while the second peak is at 80 % (2.829 MPa) of crumb rubber proportion. At the beginning of the bar chart (0 % to 40 %), the flexural strength of PCLFC decreases remarkably, but at 40 % of crumb rubber replacement, unexpectedly, the flexural strength soars to 2.329 MPa and further reduces over to 1.762 MPa at 50 %. It should be noted that the smaller the size of the crumb rubber particles used in concrete, the lesser the loss of strength (Su, et al., 2015). This could be explained due to the increased compactness of concrete by the filler effect of the finer crumb rubber particles, which leads to the reduction of the stress singularity at the internal voids. As a result, the likelihood of concrete fracture would be reduced.

Table 4.6: The Result of Flexural Strength Test of PCLFC.

Specimen / Designation	Flexural Strength (MPa)			
	A	**B**	**C**	**Avg.**
CLFC - 0	2.221	2.191	2.138	2.183
PCLFC - 10	2.049	2.310	2.127	2.162
PCLFC - 20	2.104	1.874	1.988	1.989
PCLFC - 30	1.938	1.835	1.554	1.776
PCLFC - 40	2.521	2.012	2.455	2.329
PCLFC - 50	1.876	1.714	1.695	1.762
PCLFC - 60	1.928	1.811	1.522	1.754
PCLFC - 70	1.752	1.793	1.969	1.838
PCLFC - 80	3.058	3.111	2.317	**2.829**

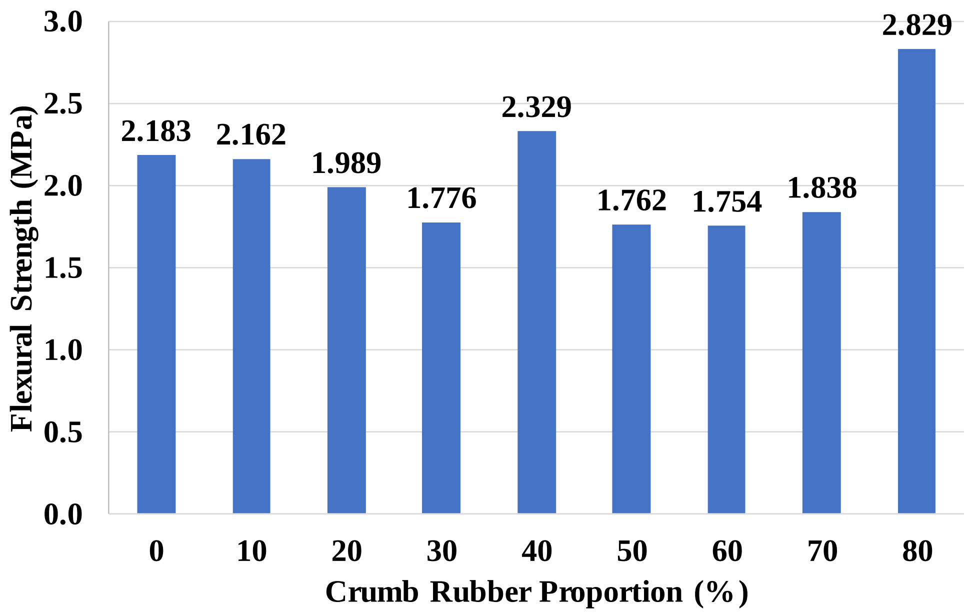

Figure 4.10: Flexural Strength versus The Percentage of Crumb Rubber – PCLFC.

Figure 4.11 illustrates the relationship between the flexural strength of both GCLFC and PCLFC at 0% to 80% of crumb rubber proportion. Based on the graph, PCLFC shows an overall higher flexural strength compared to GCLFC. PCLFC has achieved a maximum flexural strength of 2.829 MPa, an increment of 29.6 % compared to the controlled mix, CLFC – 0. Besides, as expected, the trend for PCLFC is an upward curve while GCLFC exhibits a downward curve.

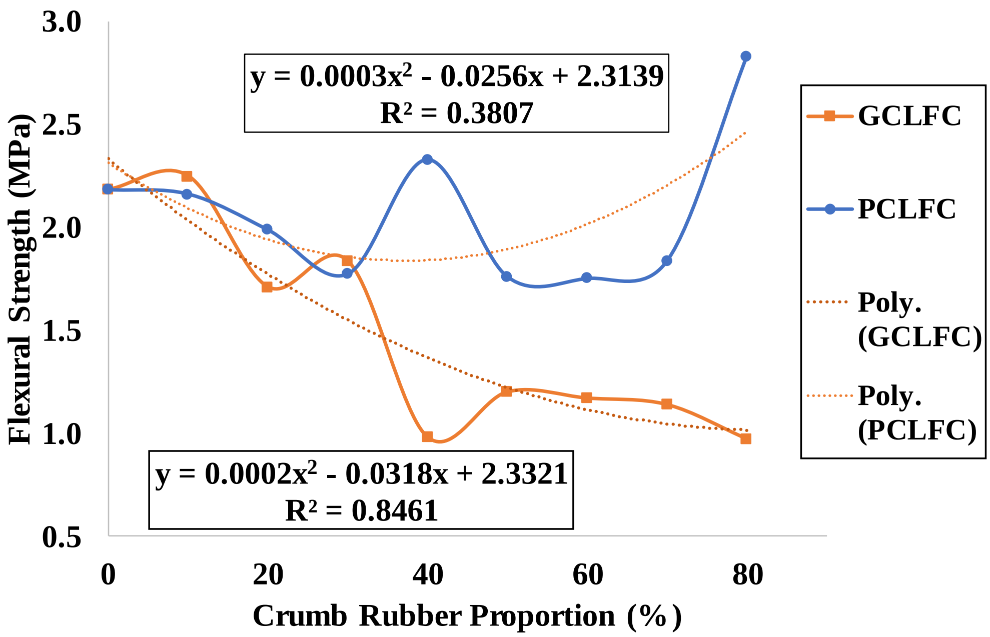

Figure 4.11: The Relationship between The Flexural Strength of GCLFC and PCLFC.

For the GCLFC, the justification for the decreasing flexural strength is primarily due to the bonding between the granular crumb rubber particles and the cement paste which is simply inadequate (Lim, et al., 2019). Moreover, the diminution of flexural strength is also mainly inflicted by the shape and size of the crumb rubber particles (Gupta, et al., 2014). During the loading phase, the cracks propagation will be accelerated by the smooth texture of crumb rubber particles; hence the reduction of the overall resistance against the applied force will occur.

On the other hand, the increasing flexural strength of PCLFC could be explained by the effective packing structures produced by the powdered crumb rubber especially in the zone of interfacial as well as the strong bonding between the cement paste and the crumb rubbers that helped in the bridging of cracks and delayed the failure of the PCLFC (Grinys, et al., 2012).

4.3 Summary

To summarise, the results obtained from the mechanical tests were analysed, tabulated and discussed. It was concluded that the presence of crumb rubber in lightweight foamed concrete is not necessarily detrimental. The results of this study indicate that using both granular and powdered crumb rubber in lightweight foamed concrete has a potential improvement in the mechanical strength except that both have different optimum crumb rubber proportion. Overall, the results have shown a similar trend for both GCLFC and PCLFC in all 3 tests.

The mechanical strength of PCLFC increases as the crumb rubber proportion increases and the ideal percentage of powdered crumb rubber proportion is at 70 - 80 %. This is because finer (powdered) crumb rubber particles are good with the ability of void filling and generate more effective packing structures, especially in the zone of interfacial of the lightweight foamed concrete. However, for GCLFC, the mechanical strength only rises at 10 – 20 % of crumb rubber proportion. Beyond 20 %, the GCLFC will undergo a reduction in mechanical strength due to the lack of proper bonding between cement paste and crumb rubber particles.

Figure 4.12 shows the correlation of the combined mechanical strength test results between both GCLFC and PCLFC. The maximum compressive strength is 2.930 MPa (GCLFC) and 3.557 MPa (PCLFC), maximum flexural strength is 2.248 MPa (GCLFC) and 2.829 MPa (PCLFC) while the maximum splitting tensile strength is only 0.399 MPa (GCLFC) and 0.533 MPa (PCLFC). Table 4.7 summarises the increment percentage of the mechanical strength between the controlled mix, CLFC – 0 and both types of crumb rubber lightweight foamed concrete.

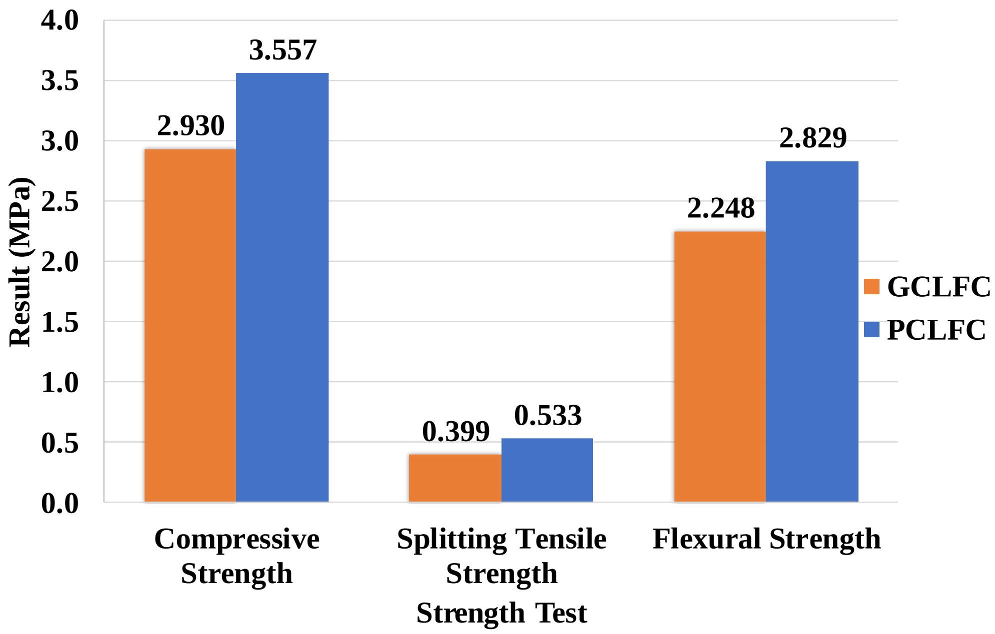

Figure 4.12: Comparison of The Mechanical Strength Results for GCLFC and PCLFC.

Table 4.7: The Percentage Increment of The Mechanical Strength between The Controlled Mix, GCLFC and PCLFC.

Strength Increment / Mechanical Strength	Increment Percentage of GCLFC (%)	Optimal Percentage of Crumb Rubber Proportion	Increment Percentage of PCLFC (%)	Optimal Percentage of Crumb Rubber Proportion
Compressive Strength	10.27	20 %	33.87	70 %
Splitting Tensile Strength	21.65	20 %	62.50	70 %
Flexural Strength	2.97	10 %	29.59	80 %

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the analysis of results and laboratory testing, several conclusions can be drawn.

The utilization of either granular or powdered crumb rubber in lightweight foamed concrete could affect the mechanical properties. By replacing a partial mass of sand with granular crumb rubber, there is a potential improvement in the mechanical strength, but it will also lead to the reduction of mechanical strength as the percentage of rubber increases. From the previous chapter, the compressive strength for GCLFC was reported, which rises till 20 % of crumb rubber proportion with a value of 2.930 MPa, an increment of 10.27 % compared to the controlled mix, CLFC - 0. However, beyond 20 %, the compressive strength of GCLFC starts reducing and reduced by 4.8 % to 14.3 %. Same goes to the splitting tensile strength for GCLFC, the optimum percentage of the crumb rubber proportion is at 20 % (0.399 MPa), with a strength increment of 21.65 %. After that, it starts decreasing by 4.57 % to 28.7 % at 30 % to 80 % of crumb rubber proportion. As for the flexural strength for GCLFC, the optimum crumb rubber proportion falls at 10 % (2.248 MPa). Compared to the CLFC – 0, there is only 2.97 % in the increment of flexural strength. Then, the strength continues diminishing till 80 % of crumb rubber proportion by 15.85 % to 55.4 %.

On the other hand, by replacing a part of sand with powdered crumb rubber leads to the enhancement of strength as the percentage of rubber increases. The PCLFC has shown that the compressive strength could increase by 3.01 % to 33.87 % compared to the CLFC - 0. The optimum crumb rubber proportion percentage is at 70 % by achieving a maximum value of 3.557 MPa. The trend of splitting tensile strength is also similar to the compressive strength of PCLFC. The maximum splitting tensile strength is 0.533 MPa, which is at 70 % of crumb rubber proportion. An increment by 2.44 % to 62.5 % of splitting tensile strength has been archived by PCLFC. Lastly, the optimum crumb rubber percentage for PCLFC flexural strength is at 80 %. It has increased by 6.7 % to 29.59 % compared to the CLFC – 0 with a maximum value of 2.829.

In a nutshell, by comparing both granular and powdered crumb rubber lightweight foamed concrete, a higher mechanical strength could be achieved by the finer size (powdered) of the crumb rubber in lightweight foamed concrete. As mentioned above, the increment of the mechanical strength for PCLFC is higher compared to the GCLFC. The compressive strength of PCLFC increased by 33.87 % while GCLFC only increased by 10.37 %. In addition, the splitting tensile strength of PCLFC rose by 62.50 % while GCLFC only rose by 21.65 %. Finally, the flexural strength of PCLFC had an increment of 29.59 % while GCLFC had only 2.97 % of increment. The objectives have been achieved.

5.2 Recommendations for Future Work

Several recommendations and suggestions below could be taken into consideration in order to improve and achieve more reliable and accurate results for future study:

I. Study the effects of different percentages of crumb rubber on other engineering properties such as sound insulation, thermal conductivity, impact and water absorption instead of mechanical properties.

II. Investigate the long-term effects of the strength and workability of lightweight foamed concrete, by including the use of chemical admixture such as superplasticizer in the mix proportion for future study.

III. Adopt a broader range of crumb rubber sizes and shape on the mechanical properties of lightweight foamed concrete instead of comparing only two sizes.

IV. Study the effects on the mechanical properties of crumb rubber lightweight foamed concrete by considering different proportions of silica fume.

REFERENCES

Abdullah, S. R., Riwayat, A. I., Awal, A. A. and Hossain, M. Z., 2017. Effect of Rubber Powdered Particle on the Strength of Foamed Concrete. *International Journal of GEOMATE,* 13(38), pp. 129-134.

Aiello, M. and Leuzzi, F., 2010. Waste tyre rubberized concrete: Properties at fresh and hardened state. *Waste Management,* 30(8-9), pp. 1696-1704.

ASTM C 496/C 496M – 04, 2011 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, *Annual Book of ASTM Standards Volume 04.02*, pp. 1–5.

ASTM C1611: Standard test method for slump flow of self-consolidating concrete. American Society of Testing and Materials.

ASTM C78/C78M, 2002. ASTM C78/C78M - 02 - Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), *ASTM International*, pp. 1–3. (Oon, Ooi, and Pot, 2020)

Atahan, A. O., and Yücel, A. Ö., 2012. Crumb rubber in concrete: Static and dynamic evaluation. *Construction and Building Materials,36*, pp. 617-622.

Batayneh, M., Marie, I. and Asi, I., 2008. Promoting the use of crumb rubber concrete in developing countries. *Waste Management,* 28(11), pp. 2171-2176.

Benazzouk, A., Douzane, O., Mezreb, K., Laidoudi, B., and Quéneudec, M., 2008. Thermal conductivity of cement composites containing rubber waste particles: Experimental study and modelling. *Construction and Building Materials,22*(4), pp. 573-579.

Bing, C., Zhen, W. and Ning, L., 2012. Experimental Research on Properties of High-Strength Foamed Concrete. *Journal of Materials in Civil Engineering,* 24(1).

Bravo, M. and Brito, J. d., 2012. Concrete made with used tyre aggregate: durability-related performance. *Journal of Cleaner Production,* Volume 25, pp. 42-50.

British Standards Institution, 2002. Testing hardened concrete–Part 3: Compressive strength of test specimens. *London: BS EN 12390-3:2002*.

BS EN 206, 2013. BSI Standards Publication Concrete — Specification, performance, production and conformity, *British Standard*, (May), pp. 30.

BS1881,1983. Testing Concete (Part 116) - Method for determination of compresive strength of concrete cubes, *Bsi*, (December), p. 11.

Eltayeb, E., Ma, X., Youssf, O. and Mills, J. E., 2020. Influence of rubber particles on the properties of foam concrete. *Journal of Building Engineering,* Volume 19, pp. 2352-2367.

Fattuhi, N. I. and Clark, L. A., 1996. Cement-based materials containing shredded scrap truck tyre rubber. *Construction and Building Materials,* 10(4), pp. 229-236.

Gafoori, N. and Diawara, H., 2007. Strength and Wear Resistance of Sand - Replaced Silica Fume Concrete. *ACI Materials Journal*, 104(2), pp.206-214.

Ganjian, E., Khorami, M. and Maghsoudi, A. A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and Building Materials,* 23(5), pp. 1828-1836.

Grinys, A., Sivilevicius, H. and Dauksys, M., 2012. Tyre Rubber Additive Effect on Concrete Mixture. *Journal of Civil Engineering and Management,* Volume 18, pp. 393-401.

Hilal , A. A., 2011. Effect of Crumb Tyres Rubber on Some Properties of Foamed Concrete. *Anbar Journal for Engineering Sciences* , 4(2).

Issa, C. A. and Salem, G., 2013. Utilization of recycled crumb rubber as fine aggregates in concrete mix design. *Construction and Building Materials,* Volume 42, pp. 48-52.

Kaloush, K. E., Way, G. B. and Zhu, H., 2005. Properties of Crumb Rubber Concrete. *Transportation Research Record: Journal of the Transportation Research Board,* Volume 1914, pp. 8-14.

Khaloo, A., Dehestani, M. and Rahmatabadi, P., 2008. Mechanical properties of concrete containing a high volume of tyre–rubber particles. *Waste Management*, 28(12), pp.2472-2482.

Kumar, S., 2006. Waste Tyre Management in Malaysia. Retrieved from http://psasir.upm.edu.my/id/eprint/145/

Lv, J., Zhou, T., Du, Q., and Wu, H., 2015. Effects of rubber particles on mechanical properties of lightweight aggregate concrete. *Construction and Building Materials, 91*, pp. 145-149.

Mehta, P. K., 1986. *Concrete, Structure, properties and Materials.* Englewood Cliffs: Science Engineering Medicine.

Md Noor, N., Yamamoto, D., Hamada, H. and Sagawa, Y., 2016. Crumb rubber Concrete Durability Against Abrasion. *MATEC Web of Conferences*, 47, pp.01006.

Mugahed Amran, Y. H., Farzadnia, N. and Abang Ali, A. A., 2015. Properties and applications of foamed concrete; a review. *Construction and Building Materials,* Volume 101, pp. 990-1005.

Neville, A. M. and Brooks, J. J., 1987. *Concrete Technology.* Second ed. London: Pearson.

Paine, K. A., and Dhir, R. K., 2010. Research on new applications for granulated rubber in concrete. *Proceedings of the Institution of Civil Engineers - Construction Materials,163*(1), pp. 7-17.

Pelisser, F., Zavarise, N., Longo, T. A. and Bernardin, A. M., 2011. Concrete made with recycled tire rubber: Effect of alkaline activation and silica. *Journal of Cleaner Production,* Volume 19, pp. 757-763.

Pierce, C. E. and Blackwell, M. C., 2003. Potential of scrap tire rubber as lightweight aggregate in flowable fill. *Waste Management,* 23(3), pp. 197-208.

Rashaad, A. M., 2015. A comprehensive overview about recycling rubber as fine aggregate replacement in traditional cementitious materials. *International Journal of Sustainable Built Environment,* 5(1), pp. 46-82.

Shetty, M. S., 2008. *Concrete Technology Theory and Practice.* Revised ed. New Delhi: S. CHAND and COMPANY PVT. LTD..

Siddique, R, and Khan, M,I (2011). Supplementary Cementing Materials, Silica fume. XVI Publishers, 288 P, ISBN:978- 3-642-17865-8.

Siddique, R., and Naik, T. R., 2004. Properties of concrete containing scrap-tyre rubber – an overview. *Waste Management,24*(6),pp. 563-569.

Sivakumar, M., Poorani, M., Sudha, S. J. and Deepa, S., 2016. Influence of Silica Fume on Mechanical Properties of Crumb Rubber Aggregate Concrete. *International Journal of Engineering Research and Technology (IJERT),* 5(12).

Skripkiūnas, G., Grinys, A. and Cernius, B., 2007. Deformation properties of concrete with rubber waste additives. *Materials Science (Medžiagotyra),* Volume 13, pp. 219-223.

Sofi, A., 2018. Effect of waste tyre rubber on mechanical and durability properties of concrete. *Ain Shams Engineering Journal,* Volume 9, pp. 2691-2700.

Su, H. et al., 2015. Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes. *Journal of Cleaner Production,* Volume 91, pp. 288-296.

Sukontasukul, P., 2009. Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel. *Construction and Building Materials,* Volume 23, pp. 1084-1092.

Sukontasukkul, P., and Chaikaew, C., 2006. Properties of concrete pedestrian block mixed with crumb rubber. *Construction and Building Materials,20*(7), pp. 450-457.

Sunthonpagasit, N. and Duffey, M. R., 2004. Scrap tires to crumb rubber: feasibility analysis for processing facilities. *Resources, Conservation and Recycling,* 40(4), pp. 281-299.

Taha, R., El-Dieb, A. S., Abd El-Wahab, M. A. and Abdel-Hameed, M. E., 2008. Mechanical, Fracture, and Microstructural Investigations of Rubber Concrete. *Journal of Materials in Civil Engineering,* Volume 20, pp. 640-649.

Thomas, B., Gupta, R., Mehra, P. and Kumar, S., 2015. Performance of high strength rubberized concrete in aggressive environment. *Construction and Building Materials,* Volume 83, pp. 320-326.

Topçu, L. B., and Avcular, N., 1997. Analysis of crumb rubber concrete as a composite material. *Cement and Concrete Research,27*(8), pp. 1135-1139.

Topçu, I., and Avcular, N., 1997. Collision behaviours of crumb rubber concrete. *Cement and Concrete Research,27*(12), pp. 1893-1898.

Topçu, I. B., and Bilir, T. 2009. Experimental investigation of some fresh and hardened properties of crumb rubber self-compacting concrete. *Materials and Design,30*(8), pp. 3056-3065.

Turatsinze, A., Bonnet, S. and Granju, J.-L., 2005. Mechanical characterisation of cement-based mortar incorporating. *Building and Environment,* Volume 40, pp. 221-226.

Wang, H., Chen, B., and Wu, Y., 2013. A study of the fresh properties of controlled low strength rubber lightweight aggregate concrete (CLSRLC). *Construction and Building Materials,41*, pp. 526-531.

Yilmaz, A. and Degirmenci, N., 2009. Possibility of using waste tire rubber and fly ash with Portland cement as construction materials. *Waste Management,* 29(5), pp. 1541-1546.

Youssf, O., ElGawady, M. A., Mills, J. E. and Ma, X., 2014. An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes. *Construction and Building Materials,* Volume 53, pp. 522-532.

Zhang, H. et al., 2017. Green material selection for sustainability: A hybrid MCDM approach, *PLoS ONE*, 12(5), pp. 1–26.