STRENGTH PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE WITH 30 KG/M^3 STEEL FIBER

WONG WAI YIK

UNIVERSITI TUNKU ABDUL RAHMAN

STRENGTH PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE WITH 30 KG/M^3 STEEL FIBER

WONG WAI YIK

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

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

May 2023

DECLARATION

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

Signature : 

Name : WONG WAI YIK

ID No. : 1801633

Date : 15/5/2023

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STRENGTH PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE WITH 30 KG/M^3 STEEL FIBER"** was prepared by **WONG WAI YIK** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature : 

Supervisor : IR DR LIM SIONG KANG

Date : 17/5/2023

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, Ir. Dr. Lim Siong Kang 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 my loving parents and friends who helped and encouraged me in my final year project. Finally, thank you to all those who have guided and assisted me indirectly in the lab session and report writing.

ABSTRACT

The usage of lightweight concrete is getting increase nowadays in the construction industry. Lightweight foamed concrete (LFC) is commonly found in the construction industry as it is a suitable material for thermal and sound insulation, lighter and cost-economical. However, the strength of LFC is diminished due to the low density and pore structures. According to the research, incorporating steel fiber into concrete can recover the diminished strength of lightweight foamed concrete. Hence, this study focus on the strength properties of LFC with 30 kg/m^3 of steel fiber. Three types of LFC were prepared in this study, which was a trial mix of LFC (LFC-TM), a control mix of LFC (LFC-CTR), and LFC with the incorporation of 30 kg/m^3 steel fiber (LFC-30SF). The LFC-CTR and LFC-30SF were cast based on the obtained optimum water-to-cement ratio from the plotted performance index curve. The fresh properties of LFC-CTR and LFC-30SF were determined from the flow table test and inverted slump test. The strength properties studied for LFC-CTR and LFC-30SF were compressive strength, splitting tensile strength and flexural strength at the curing ages of 7, 28 and 56 days. From the test results obtained, the strength of LFC was improved by adding the steel fiber into the mix. Based on the performance index, the LFC-30SF had improved compressive strength at 13.14 % and splitting tensile strength at 29.9 % compared to LFC-CTR at 56 days of curing. The improvement in flexural was not noticeable, but the effect of steel fiber was proven from the failure mode in LFC-30SF. The improvement in engineering properties of LFC was mainly due to the steel fiber reinforcement. The inclusion of steel fiber was distributed randomly throughout the concrete matrix. The orientation of steel fiber in the concrete matrix was random, which allow the bridging effect to be more significant. The steel fiber helps in bridging cracks in all directions. The stability of LFC decreased after the steel fiber was added into the mix while the workability increased. In short, incorporating steel fiber can improve the strength properties of LFC, which can increase the application of LFC in the construction industry. It was recommended to consider the low density of steel fiber in the LFC mix in future studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

A	area, mm^2
d	diameter of the cylindrical concrete specimen, mm
d_1	average width of specimen, mm
d_2	average depth of prism specimen, mm
F	maximum applied load, N
f_c	compressive strength, MPa
f_t	tensile strength, MPa
f_{cf}	flexural strength, MPa
I	distance between the supporting rollers, mm
l	length of the cylindrical concrete specimen, mm
P	maximum load applied, N
T	splitting tensile strength, MPa
β-C_2S	β-dicalcium silicate
Al	aluminium
ASTM	American Society for Testing and Materials
C	carbon
Ca	calcium
CH	calcium hydroxide
C-S-H	calcium silicate hydrate
C_3S	tricalcium silicate
EDX	energy-dispersive X-ray
Fe	iron
LFC	lightweight foamed concrete
LFC-TM	trial mix of lightweight foamed concrete
LFC-CTR	control mix of lightweight foamed concrete
LFC-30SF	lightweight foamed concrete with the incorporation of 30 kg/m^3 steel fiber
LWAC	lightweight aggregate concrete
Mg	magnesium
NFC	No-fines concrete

O	oxygen
OPC	Ordinary Portland Cement
S	sulphur
SEM	scanning electron microscopic
SFRC	steel fiber reinforced concrete
SF	steel fiber
Si	silicon
W/C	water-to-cement

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Since 6500 BC, concrete has become the most basic construction material on the earth (Li, 2011). Concrete is manufactured from cement, aggregates, water and admixture. Fine aggregate and coarse aggregate are two different kinds of aggregate. Fine aggregate is small in size and can pass through a 3/8 inches sieve. Examples of fine aggregate are sand, crushed stone, cinders, etc. Coarse aggregate is bigger than fine aggregate, and the size of the coarse aggregate particle is bigger than 0.19 inches. Examples of coarse aggregate are gravels, pebbles, clinkers, brick chips, etc. The cement will combine with water and admixture to form a cementitious paste during the mixing process. The cementitious paste fills the space between aggregate particles and binds them together. The cement containing C_3S and β-C_2S will undergo a hydration process that produces calcium silicate hydrated gel (C-S-H) (Harrisson, 2017). As a result, cement paste hardens and increases strength, turning into concrete, a rock-like substance.

The behaviour of concrete depends on the mixing proportions of raw materials and the type of raw materials used. There are three types of concrete categorised by density, which are ordinary concrete, heavyweight concrete and lightweight concrete. Ordinary concrete is concrete with a density between 2240 kg/m^3 to 2400 kg/m^3 (Hedjazi, 2019). Ordinary concrete is widely used in construction as it is cheaper than other concrete. Heavyweight concrete has the greatest density among other types of concrete. The heavyweight concrete has a density value ranges 3000 kg/m^3 to 4000 kg/m^3. It is made up of cement, water and coarse aggregate. Heavyweight concrete is applied for large structures requiring solidity and strength. Lightweight concrete is low density concrete due to artificial modification on the plastic concrete. Lightweight concrete has weak mechanical performance (Alonge and Ramli, 2013). It can be produced using lightweight aggregate, artificial entrained air, or a foaming agent. The lightweight concrete has a density value ranges 300 kg/m^3 to 2000 kg/m^3 (Hedjazi, 2019). Lightweight concrete is commonly used in construction because it is thermally and acoustically insulating, lighter, and more cost-effective.

Lightweight foamed concrete (LFC) is a cellular concrete made by entraining the foam into cement mortar using a suitable foaming agent (Brady, Watts and Jones, 2001). The foam can be formed by mixing the foaming agent gently in the plastic cement mortar, or it can be formed by aerating the foaming agent before being added to the mixture (Alonge and Ramli, 2013). 20 % of foamed concrete contains entrapped air pores caused by the entrained foam in mortar slurry (Alonge and Ramli, 2013). The size of the bubbles ranges from around 0.1 to 1.5 mm. However, coalescence can result in much larger voids, especially at the top of pours (Brady, Watts and Jones, 2001).

Fiber act as an additive in concrete which can improve the performance of concrete. Concrete with reinforcement of fiber is also known as fiber reinforcement concrete. Fibers are commercially accessible and made from steel, plastic, glass, and other natural materials (Behbahani, Nematollahi and Farasatpour, 2013). Steel fibers are discrete, small steel lengths with various cross sections with a length-to-diameter ratio of 20 to 100. The added fiber in fresh concrete can improve the shear resistance and toughness and assist in crack control (Chanh, 2015). Steel fiber reinforcement concrete has wide applications, such as hydraulic structure, pavement construction, precast application, etc (Behbahani, Nematollahi and Farasatpour, 2013).

1.2 Importance of the Study

The features of LFC are low density, high workability, good sound and thermal insulation and self-compacting. But, the density and the porous nature of lightweight foamed concrete have made high-strength development challenging. Therefore, this study examines the effect of steel fiber reinforcing on the flexural, splitting tensile, and compressive strengths of LFC. Furthermore, the steel fiber reinforcement can enhance the resistance to cracks and has high durability. Hence, the steel fiber reinforcement in concrete can reduce maintenance and project costs due to its high durability. Therefore, it is suitable for application in pavements and tunnel construction.

1.3 Problem Statement

Concrete is a fundamental construction material in this modern society. Concrete comes in various varieties in the market. Nowadays, construction uses LFC extensively. Compared to ordinary concrete, lightweight foamed concrete costs economically. Besides, LFC is lighter than ordinary concrete, which reduces the total implied dead load on the structure. Hence, less reinforcement is required in the structure, and the construction costs will be lower. Although lightweight foamed concrete has a lower density, it has lower mechanical strength than normal weight concrete. The inclusion of steel fiber into lightweight foamed concrete can recover diminished strength. In addition, the lightweight foamed concrete incorporated with steel fiber has higher ductility. Silica fume as a pozzolan can improve concrete's mechanical and durability properties.

1.4 Aim and Objectives

The main aim of this study is to produce lightweight foamed concrete (LFC) and 1600 kg/m^3 lightweight foamed concrete incorporated with 30 kg/m^3 steel fiber (LFC-30SF).

The objectives of this study are:

(i) To produce 1600 kg/m^3 fresh and hardened density of lightweight foamed concrete and lightweight foamed concrete incorporated with 30 kg/m^3 steel fiber with a tolerance of ± 50 kg/m^3 and identify its optimal water to cement ratio.

(ii) To investigate the engineering properties of lightweight foamed concrete cube, prism, cylinder with incorporation of steel fiber and silica fume, regarding compressive strength, splitting tensile strength and flexural strength.

(iii) To examine the influence of steel fiber on the fresh qualities of lightweight foamed concrete, including its flowability and stability.

1.5 Scope and Limitation of the Study

This study focuses on the influence of 30 kg/m^3 steel fiber reinforcement in lightweight foamed concrete in engineering properties, including flexural, splitting tensile and compressive strength. The LFC with a 1600 kg/m^3 fresh and hardened density with the incorporation of steel fiber with a tolerance of ± 50 kg/m^3 is prepared to perform engineering properties testing in this study. The preparation of all concrete specimens and raw materials and mixing and casting procedures are performed according to ASTM standards.

The engineering properties are determined from compressive, flexural strength, and splitting tensile tests. A compression machine is required to test the concrete cube and cylinder for compressive and splitting tensile strength. A concrete prism specimen is tested with a Shimadzu Universal Testing Machine to obtain flexural strength. All of the tests are performed according to the ASTM standard and requirements.

Orang Kuat Ordinary Portland Cement, fine aggregates passing through 600 μm sieve, water, SikaAER-50/50 foaming agent, STAHLCON hooked-end type steel fiber and silica fume were used to produce different LFC. To achieve the objectives, three types of LFC were prepared, which is the trial mix of lightweight foamed concrete (LFC-TM), the control for lightweight foamed concrete mix (LFC-CTR), and lightweight foamed concrete with the incorporation of 30 kg/m^3 steel fiber (LFC-30SF). Each type of concrete was cast according to the testing method. For LFC-TM, block concrete specimens are prepared for the compressive test. For LFC-CTR and LFC-30SF, cubic, cylindrical and prism specimens were prepared for the compressive, splitting tensile, and flexural tests, respectively.

The water-to-cement (W/C) ratio for the trial mix concretes ranges from 0.52 to 0.68 with a 0.04 interval. First, the optimum W/C ratio was obtained from the control mix with the highest compressive strength at 7 days and 28 days. Then, the casting of LFC-CTR and LFC-30SF were carried out using the optimum W/C ratio. Finally, the LFC-CTR and LFC-30SF were tested for splitting tensile, compressive, and flexural strength at curing ages of 7 days, 28 days and 56 days.

The limitation in this study is the shortage of raw materials. The shortage of materials due to the delay in the supplier's delivery will cause the casting work extension. Besides, the condition of the testing machine will be the limitation throughout this study. The testing machine may malfunction, causing inaccuracy in the testing result. Besides, the testing machine operation is complex and may require assistance from the lab officers. Furthermore, the oven may share with other students, which will cause insufficient space in the oven. The schedule for the oven-dried process was delayed due to the availability of an oven rack. Besides, steel fiber is denser than cement mortar. Therefore, the steel fiber in cement mortar will tend to settle at the bottom of the mix during the hardening process. On top of that, the balling effect of steel fiber will occur during the mixing of the concrete mix. The balling effect will affect the uniformity of the concrete mix, which will further affect the performance of concrete.

1.6 Contribution of the Study

LFC is an ideal material for constructing roads, bridges and tunnels. They possess low density, which can reduce the weight of roadbeds. Due to the low mechanical strength in LFC, LFC will usually use for non-loading purposes or impose a minimum loading in buildings. Nowadays, LFC is used to manufacture panels or blocks for walls as it has a high strength-to-weight ratio. Apart from that, LFC is a good insulation material due to its low thermal conductivity, which uses in the construction of walls, floors, roofs, and other structures.

LFC also is an environmentally friendly material. Production of LFC will require less energy than traditional concrete, which can reduce carbon emissions. Next, The lightweight nature of foamed concrete reduces transportation costs as it requires less fuel to transport. This also reduces the carbon footprint of construction projects.

1.7 Outline of the Report

This report is divided into six chapters. The report begins with an abstract that summarises the objective, objectives, methodology, trial mix, results and discussion and conclusion of the study.

In chapter one, a brief introduction of concrete and the problem statement of this study are included. Then, the three aims of this study are discussed. Besides, the scope and the limitations of this study are determined and discussed.

In chapter two, literature reviews are performed based on the scope of the study. The literature review on the properties and applications of LFC, Ordinary Portland Cement, silica fume and steel fiber reinforced concrete.

Chapter three discusses a detailed methodology for preparing raw materials, mixing procedures and testing methods. The method to carry out the compressive, splitting, tensile, and flexural tests are explained.

Chapter four discusses the trial mix results for LFC-CTR and LFC-30SF. First, the compressive strength test results of each trial mix are discussed. The performance index is computed based on each compressive strength. The peak performance index determines the optimal water to cement ratio for LFC-CTR and LFC-30SF.

Chapter five discusses the strength test results of both LFC-CTR and LFC-30SF at curing ages 7, 28 and 56 days. The strength tests, namely the compressive test, splitting tensile test and flexural test, are carried out to determine the engineering properties of both concrete mixes. This chapter also discusses the result of SEM-EDX analysis.

Chapter six concludes the objectives achieved in this study. Apart from that, some recommendations and suggestions are discussed to improve future research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Lightweight Concrete

Lightweight concrete is a type of concrete that is commonly employed in buildings due to its characteristics. Lightweight concrete was invented in 3000 BC during the Mohenjo-Daro and Harappa civilisation, and its technical advancements continue to be made. A few historical buildings were constructed with lightweight concrete, such as St. Sofia Cathedral in Istanbul and the Pantheon in Rome, the best-known examples (Meena, et al., 2020). Slowly, the production of lightweight concrete has indicated the advancement of material technology in the 19th and 20th centuries (Thienel, Haller and Beuntner, 2020).

Figure 2.1: St. Sofia Cathedral in Istanbul, Turkey (Pollard, 2022).

Lightweight concrete has defined itself as having a lighter weight than ordinary concrete. Lightweight concrete generally has densities varying from 300 kg/m^3 to 1850 kg/m^3 (Alonge and Ramli, 2013). The densities of ordinary concrete range from 2200 kg/m^3 to 2600 kg/m^3 (Iffat, 2015). Hence, using lightweight concrete in construction will reduce the total dead load of the structure. Reduced heat conductivity and low shrinkage are additional benefits of lightweight concrete being low density (Chaipanich and Chindaprasirt, 2015).

Due to its higher porosity than normal concrete, the lightweight concrete has lower strength than normal concrete. The lightweight concrete contains up to 67 % of pores, which are impermeable to liquids and gases. Due to the spaces between the lightweight concrete, it has the characteristics of thermal and acoustic insulation (Kurpińska and Ferenc, 2017). However, lightweight concrete with low density and high porosity also will result in lower strength.

Lightweight concrete is categorised based on its strength. Low-density lightweight concrete has densities and strengths ranging from 300 kg/m^3 to 800 kg/m^3 and 0.7 MPa to 2.0 MPa, respectively. Moderate strength lightweight concrete with densities ranging from 800 kg/m^3 to 1350 kg/m^3 has a strength of 7 MPa to 14 MPa. Structural lightweight concrete has the highest strength compared to other lightweight concrete, which ranges from 17 MPa to 63 MPa, and its densities range from 1350 kg/m^3 to 1920 kg/m^3 (Chaipanich and Chindaprasirt, 2015).

2.2 Type of Lightweight Concrete

Due to the advancement in material technology, there are several methods to produce lightweight concrete. There are three types of lightweight concrete, which include no-fines concrete (NFC), lightweight aggregate concrete (LWAC) and aerated concrete. NFC is produced by involving coarse aggregates in the concrete mix. LWAC is produced using lightweight aggregate in the concrete mixture instead of ordinary aggregate. Foamed concrete is produced by entraining bubble voids into concrete mix to form a cellular structure (Meena, et al., 2020).

2.2.1 No-fines Concrete

No-fines concrete involves the removal of fine aggregate in the concrete mix. Since the early 1950s, NFC has been used in the building sector. The aggregate used in the manufacturing of no-fines concrete ranges in size from that which passes through a sieve of 20 mm to that which is retained on a sieve of 10 mm (Ushane, Kumar and Kavitha, 2014). The microstructure of no-fines concrete consists of the interconnected void network (Maguesvari and Narasimha, 2013). Due to the absence of fine aggregates, the drying shrinkage properties diminished in NFC.

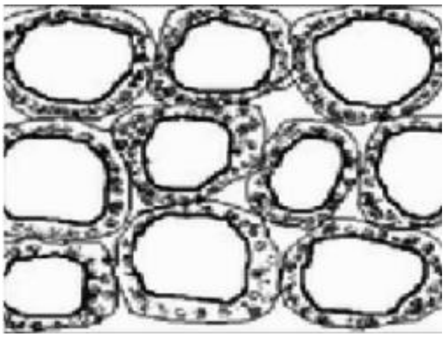


Figure 2.2: Microstructure of No-Fines Concrete (Ramadhansyah, et al., 2014).

NFC contains large voids, which result in porous structures has caused a reduction in density (Iffat, 2015). The porous structure in no-fines concrete has increased the permeability of concrete. The permeability of concrete has increased due to the no-fines concrete's porous nature. Lee et al. (2019) reported that when water enters the concrete and dries up, it changes the relative density of the concrete. Its relative density ranges from 1700 to 2015 kg/m^3.

The density reduction has reduced the weight of NFC, contributing to fewer dead loads. However, its strength is lower than conventional concrete. Its maximum compressive strength is 11.25 MPa. However, the strength is still less than the typical characteristic strength (Lee, et al., 2019).

Due to its performance and characteristics, NFC has been widely used nowadays. NFC is used for pavement construction because it has high porosity, which minimises surface runoff. The pavement surface runoff will flow through the no-fines concrete, contributing to stormwater management.

2.2.2 Lightweight Aggregate Concrete (LWAC)

Lightweight aggregate concrete (LWAC) is produced by replacing sand and crushed stone with lightweight aggregate. According to ASTM C330 (2009), lightweight aggregate is categorised into two types based on their sources, which are natural aggregate and artificial lightweight aggregate. One of the artificial lightweight aggregates is industrial waste aggregate which is obtained during industrial processes such as cinder, light sand, fly ash ceramisite, expanded slag balls and so on (Zhang, 2011). Natural lightweight aggregates such as pumice, diatomite, scoria, volcanic cinder, sawdust, rice husk, light sand and so on are obtained from natural resources. On the other hand, expanded perlite and clay ceramisite are lightweight artificial aggregates made from local materials.

Lightweight aggregate is further characterised as coarse or fine aggregate based on aggregate diameter. The diameter of lightweight coarse aggregate is greater than 5 mm, whereas the diameter of lightweight fine aggregate is less than 5 mm. The bulk density of lightweight coarse aggregate is less than 1000 kg/m^3, and the density of lightweight fine aggregate is 1200 kg/m^3 (Zhang, 2011).

Since lightweight artificial aggregate is more environmentally friendly than natural, it is mainly used to produce lightweight aggregate concrete. Due to its high accessibility, artificial aggregates like expanded clay and shale is commercially available. These artificial lightweight aggregates are produced through the sintering process, which takes from 1000 °C to 1200 °C (Ibrahim, et al., 2016). However, the manufacturing cost of lightweight artificial aggregate is higher due to its high energy consumption. As the natural lightweight aggregate will cause depletion of natural resources, these artificial aggregates act as an alternative building material that will undoubtedly result in significant construction cost savings while also protecting the environment (Shafigh, Jumaat and Mahmud, 2010).

LWAC is weaker than normal aggregate concrete because lightweight aggregates are less rigid than normal weight aggregates. Thus, the lightweight aggregate produces concrete with a lower elastic modulus and more creep and shrinkage. However, high porosity lightweight aggregate is ideal for producing non-structural insulating concretes (Yuan, et al., 2021).

2.2.3 Foamed Concrete

Foamed concrete, often called aerated concrete, is lighter than ordinary concrete. Air is induced into the concrete, which can lower the density of concrete. Lightweight foamed concrete (LFC) is defined as cement pastes or mortars in which air voids have been intentionally confined (Shah, et al., 2021). The characteristics of LFC that are favourable in the construction industry are low self-weight, high workability, good thermal insulation etc. Thus, LFC is ideal for many building applications.

LFC almost has the same manufacturing material as normal concrete. LFC can be manufactured using pre-foaming and mixed foaming methods (Ramamurthy, Nambiar and Ranjani, 2009). The foam is artificially entrained into the plastic mortar using a suitable foaming agent (Lim, et al., 2013). LFC is considerably lighter than normal concrete. It has a plastic density ranging from 1000 to 1600 kg/m^3. LFC has lower final dry densities than normal concrete, ranging from 100 to 300 kg/m^3. Besides, it has a compressive strength ranging from 0.2 to 10 N/mm^2 and more at 28 days.

A stable LFC mix ensures the stability and consistency of fresh mixed foamed concrete. Ramamurthy, et al (2009) stated that the formation of a stable LFC mix is influenced by factors such as foaming agent selection, foam preparation method, mixture design strategies etc. Furthermore, the consistency and stability of the LFC mix are essential in maintaining its hardened properties. The hardened properties of LFC are affected by the separation of artificial air bubbles and cement mortar caused by the instability and inconsistency of LFC mix (Lim, et al., 2013). Apart from that, the instability of LFC mix also will cause the artificial air bubbles to burst in freshly mixed LFC.

2.3 Properties of Lightweight Foamed Concrete

The properties of LFC, such as fresh and hardened properties are important in determining the performance of the concrete. Different materials and proportions of LFC will result in different properties. Fresh properties of LFC included plastic density, consistency and workability. Hardened properties include compression, tensile, and flexural strengths.

2.3.1 Fresh Properties of Lightweight Foamed Concrete

The plastic foamed concrete mixture has self-compacting rheology and high flowability (Amran, Farzadnia and Ali, 2015). Thus, fresh properties such as workability, consistency and stability should be considered in foamed concrete. The fresh properties studied in this report cover the consistency, workability and plastic density.

2.3.1.1 Consistency of Lightweight Foamed Concrete

Foamed concrete consistency is the flowability of freshly mixed LFC. The degree of wetness in plastic LFC will be indicated by its consistency, which is usually determined by carrying out the flow cone and marsh tests. However, a flow table test is necessary to determine the consistency of LFC based on ASTM C1437 (2020). The slurry spread value and the spread diameter of lightweight foamed concrete were measured from the flow table test.

Some factors affect LFC's consistency. Higher water content causes foamed concrete segregation during casting. Foamed concrete segregates due to excess water content, reducing its workability(Amran, Farzadnia and Ali, 2015). The higher water-to-cement ratio in LFC will reduce the foam content, which results in higher fresh density. Higher fresh density reduces LFC consistency. Thus, plastic density is another factor affecting the lightweight foamed concrete consistency.

2.3.1.2 Workability of Lightweight Foamed Concrete

The term ‘workability’ has included fluidity, compact-ability and stability. According to ASTM C125 (2021), workability is the parameter to determine the amount of work required in placing, compacting and finishing the freshly mixed concrete with the least amount of homogeneity loss (Li, 2011). The workability test for LFC can be conducted by spreadability and flow table test. However, an inverted slump test is conducted to study the workability of LFC following ASTM C1611 (2014). The average slump value is calculated from the inverted slump test's spread diameter at four angles. The slump value can be used to regulate the consistency of fresh concrete.

2.3.1.3 Plastic Density of Lightweight Foamed Concrete

The fresh density of LFC is known as plastic density. Most foamed concrete has a plastic density of 400 kg/m^3 to 1600 kg/m^3 (Othman, et al., 2021).

2.3.2 Hardened Properties of Lightweight Foamed Concrete

The properties of hardened LFC, such as compressive strength, splitting tensile strength and flexural strength are essential in identifying the structural performance.

2.3.2.1 Compressive Strength

Concrete's compressive strength plays a significant role in determining the amount of load it can support. The air voids are entrained into the LFC mix by incorporating the stable foam into the plastic concrete. The introduction of stable foam will increase the volume of foamed concrete without adding weight. Thus, foamed concrete's density will be lower than ordinary concrete's. However, the compressive strength of LFC decreases when decreasing density (Wong, et al., 2019). As a matter of fact, the amount of foam added will directly affect the compressive strength of LFC. Excessive foam added will decrease the compressive strength of LFC. It will cause air void formation in hardened LFC. As a result, the LFC will gain porosity. The porous structure of LFC is more likely to break when loads are applied. The porous structure of LFC is shown as Figure 2.3.

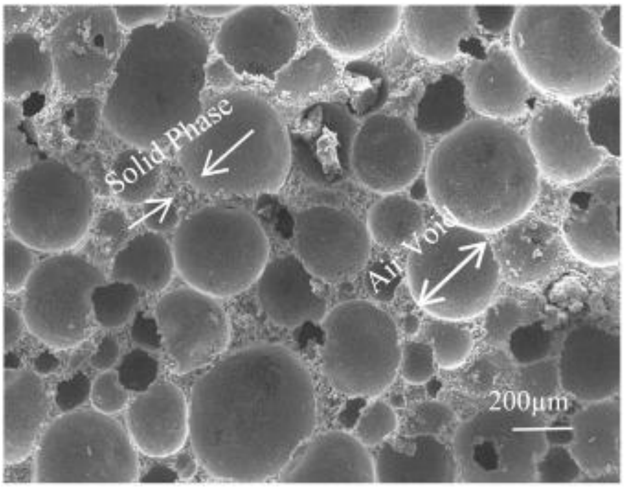


Figure 2.3: Microstructure of Lightweight Foamed Concrete (Batool, Rafi and Bindiganavile, 2018).

In short, the foam dosage affects foamed concrete's dry density and compressive strength. The foamed concrete with 20 percent foam dosage has high compressive strength at 8.8 MPa for a dry density of 1600 kg/m^3. Based on Figure 2.4, the compressive strength and dry density decrease with the foam dosage increase.

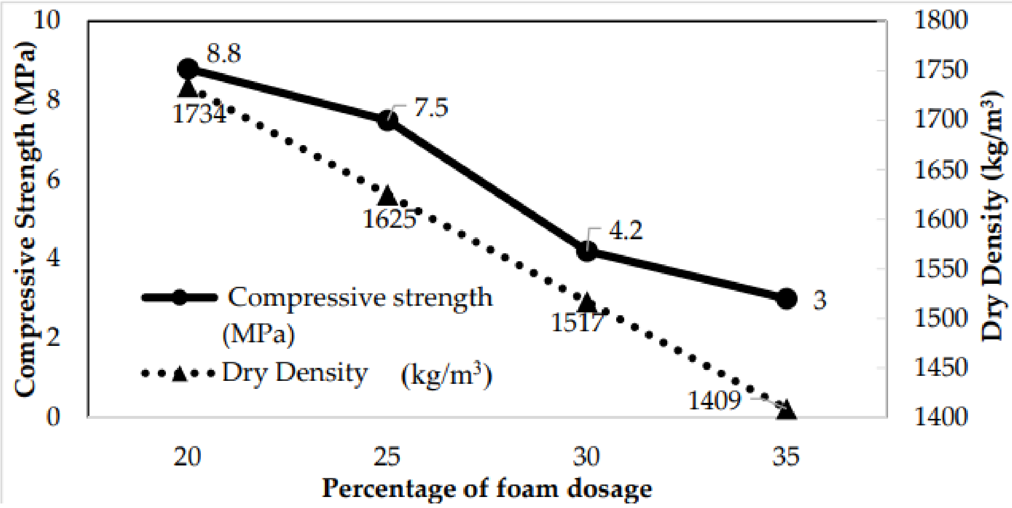


Figure 2.4: Relationship Between Compressive Strength and Dry Density of Foamed Concrete Due to Foam Dosage (Othman, et al., 2021).

Foamed concrete with 400 to 1800 kg/m^3 dry density has 28 days compressive strengths of 0.5 to 10 MPa at a 0.35 to 0.63 W/C ratio and a constant cement-to-aggregate ratio of 1.0 (Amran, Farzadnia and Ali, 2015). The compressive strength at 7 days equals to 73 percent of the 28 days (Tiong, Lim and Lim, 2017).

The cement content affects foamed concrete's compressive strength. Fly ash and silica fumes as a cement replacements will enhance the foamed concrete compressive strength (Farzadnia and Amran, 2015).

2.3.2.2 Splitting Tensile Strength

Splitting tensile strength measures how well concrete can hold up against tensile force or stress. Splitting tensile strength is essential as concrete is subjected to pure tension or a combination of tension and compression. The splitting tensile strength is tested using a cylindrical foamed concrete specimen in accordance with ASTM C496 standard (2017). Due to the lower density in LFC, the splitting tensile strength will also be lower than in ordinary concrete.

According to reports, LFC generally has a larger ratio of tensile strength to compressive strength than ordinary concrete, which is between 0.2

and 0.4. The splitting tensile to compressive strengths ratio ranged from 0.08 to 0.11 (Paknehad, et al., 2022). Thus, there is a connection between compressive strength and splitting tensile. This relationship has been proven in Table 2.1 and the tensile strength of LFC can be determined with the equations. The splitting tensile strength of LFC typically equals 15 % to 35 % of its compressive strength (Amran, et al., 2020).

Table 2.1: Empirical Model for LFC Tensile Strength Determination (Amran, et al., 2015).

Equations	Annotations
$\boldsymbol{f_t = 0.20\ (f_c)^{0.70}}$	For density between 1400 and 1800 kg/m^3
$\boldsymbol{f_t = 0.20\ (f_c)^{0.67}}$	f_c = 28 days compressive strength, N/mm2
$\boldsymbol{f_t = 1.03\ (f_c)^{0.5}}$	When W/C = 0.5 and f_c = 28 days compressive strength, N/mm^2
$\boldsymbol{f_t = 0.23\ (f_c)^{2/3}}$	f_c = compressive strength while using lightweight aggregate concrete

The compressive and splitting tensile strength are affected by the same factors. A higher W/C ratio in LFC will diminish the splitting tensile strength due to its lower density. Besides, introducing mineral admixtures and fibers will also strengthen the splitting tensile strength. This is because mineral admixtures and fibers increase the shear capacity between fine aggregates and foaming agents.

2.3.2.3 Flexural Strength

Tensile strength includes flexural strength. Flexural strength is a concrete beam or slab's ability to keep from breaking when bent. Typically, the flexural strength of LFC is 15 to 35 percent of its compressive strength. (Amran, et al., 2020). The flexural to compressive strength ratio is nearly zero for LFC with a density of less than 300 kg/m^3.

Similar to splitting tensile strength, both the W/C ratio and the type of additive influence the flexural strength of LFC. The high W/C ratio will diminish the flexural strength due to the drop in concrete density. Due to its low density and poor splitting tensile strength, LFC can be strengthened using concrete additives. The inclusion of suitable fibers in LFC can increase the tensile strength to reduce cracking at early ages (Raj, et al., 2019).

2.4 Advantages and Disadvantages of Foamed Concrete

The application of LFC is commonly found in the construction industry. Therefore, LFC is useful in the construction industry as it brings many benefits.

LFC is lighter than ordinary concrete (Swati, 2020). Artificially incorporating foam into plastic mortar reduces concrete density. The density has decreased because the amount of concrete has increased. The LFC is a highly porous microstructure (Elrahman, et al., 2021). This microstructure has caused the LFC to be lightweight, so the adjacent sub-structure is not subjected to much vertical stress.

LFC has lower heat conductivity than ordinary concrete. This is due to microscopic air voids inside having low thermal conductivity. Hence, LFC can reduce the heat conducted through it and lower the temperature of a building. The LFC also has better fire resistance. LFC also has good sound insulation compared to normal cement. Sound waves cannot pass through a void medium. Consequently, sound wave energy may become trapped within voids or empty areas (Lim, et al., 2021).

LFC has water retention properties. The LFC contains multiple air bubbles, which cause a high percentage of porosity. LFC also has a low permeability coefficient. Next, LFC has high resistance to freezing and thawing. The microscopic air bubbles have caused void structures in hardened concrete. The concrete's internal stress is reduced during the freezing and thawing. As a result, the cracking of concrete will not occur easily. LFC is more economical than normal concrete. The cost of manufacturing LFC is lower because the foam entrained into plastic mortar will increase the volume of concrete. Besides, the construction cost will decrease as the material used is decreased. On top of that, the LFC is easier to transport and handle than normal concrete. Hence, the transportation fees will be economical.

LFC also brings disadvantages to the user. However, lightweight foamed concrete has also brought some advantages. The reduction in the density of LFC is due to the introduction of voids throughout the sample caused by the foam (Iffat, 2015). The porosity of the LFC will increase, and the permeability will increase. Hence, the LFC's compressive strength will be lower compared to normal concrete. Besides, it is expensive because it contains more cement than regular concrete. Next, the LFC shrinks more than regular concrete because of the high paste concentration and lack of coarse particles. Lastly, LFC requires much more time to mix.

2.5 Application of Lightweight Foamed Concrete

LFC is commonly found in the construction industry nowadays. Due to the properties of LFC, such as density reduction, low thermal conductivity, high workability, simplicity of production and low cost, it is widely used in the construction of various buildings and buildings.

LFC has the properties of low density, which is suitable for cavity filling and insulation. Thus, LFC is an ideal material for fire insulation and thermal and acoustic insulation. In addition, LFC is also used as a road sub-base and shock absorption barrier for airports and regular traffic. Furthermore, as the LFC has water retention properties, it is suitable for constructing storage tanks, old sewers, basements and ducts, etc.

Different densities of LFC have their uses in different applications (Sari and Sani, 2017). The normal density of LFC, ranging from 1000 to 1500 kg/m^3 is usually used for cast-in-place walls, load-bearing or non-load-bearing constructions, and housing applications. LFC is also involved in foundation construction, infrastructure, drainage, etc. Table 2.2 lists the application of LFC according to different densities ranging from 300 to 1800 kg/m^3.

Table 2.2: Summary of LFC Applications Based on Density (Sari and Sani, 2017).

Density (kg/m^3)	Application
300-600	-Used to replace existing soil, helps to stabilise soil and builds rafts.
500-600	-Used to stabilises geotechnical restoration and soil settlement. -Road construction
600-800	-Alternative to granular fill for void filling. -Used in filling of old sewerage pipes, wells, basement and subways.
800-900	-Used to manufacture blocks, balcony railings, partitions, parapets, etc.
1100-1400	-Used in prefabrication and cast-in place wall, either load bearing or non-load bearing and floor screeds.
1100-1500	-Used in residential construction.
1600-1800	-For slabs and other load-bearing building elements requiring higher strength.

2.6 Ordinary Portland Cement

Ordinary portland cement (OPC) is a fundamental material in concrete production. It acts as a binding material and holds aggregate together to form a cement paste with water. OPC is a fine powder made of raw materials such as limestone (Calcium Oxide), clay, shale, iron oxide and silica sand (Singh, 2020). These raw materials are ground and mixed in rawmill. The raw mix forms clinkers during the burning process in a cement kiln. The clinker is then ground to become cement.

According to ASTM C150/ C150M-22 (2022), Portland cement is categorized into eight types: type I to type V and type IA, IIA and IIIA. In the standard specifications of portland cement, these Portland cement is only produced from cement clinker, water, calcium sulfate, and limestone. The Portland cement contain chemical composition as shown in Table 2.3.

Table 2.3: Average Composition of Ordinary Portland Cement (Patnaikuni, et al., 2018).

Component	Percentage range by mass
CaO	60-69
SiO_2	17-25
Al_2O_3	3-8
Fe_2O_3	2-4
MgO	1-5
SO_3	1-3
$Na_2O + K_2O$	0.3-1.5

The content of cement will affect the properties of ordinary concrete and LFC. Some supplementary materials can replace cement to meet up the desired concrete properties. Fly ash, silica fume and incinerator bottom ash can replace 25 % to 100 % of cement binder (Amran, Farzadnia and Ali, 2015). It can enhance the consistency of fresh concrete mix and increase later strength (Reiterman, et al., 2019).

2.7 Aggregate

Aggregate is a required component in the production of concrete. Aggregates are inert, granular materials that are either coarse or fine. Different types of aggregate used in concrete will directly affect the fresh and hardened properties of concrete. The fine aggregate size is smaller than 4.75 mm, which can pass through No. 4 sieve. On the other hand, the size of the coarse aggregate is bigger than 4.75 mm, which is retained on a No. 4 sieve (Aginam, Chidolue and Nwakire, 2013).

2.8 Foam

Foam is air bubbles entrapped in concrete mortar to create voids and spaces. Then, it is mechanically entrained into the fresh concrete mix to form LFC. Foam can be produced using a foam generator with different foaming agents. The commonly used foaming agents in the construction industry are synthetic and protein-based foaming agents.

The synthetic foaming agent is a chemical reagent that dissolves in water quickly due to its hydrophilic properties to form air bubbles (Kumar, et al., 2018). The protein-based foaming agent, derived from animal blood gum, will produce a more robust bubble structure. It produced air bubbles by breaking the peptide linkage between protein molecules, resulting in protein degradation. The degradation process has formed hydrogen bonds between molecular groups, resulting in the formation of stable foam air bubbles (Kumar, et al., 2018). Protein-based foaming agents provide a closed-cell bubble structure that can entrap more air in bubbles (Farzadnia and Amran, 2015). The closed-cell bubble structure will enhance the stability of air void network, resulting in stable foam bubbles.

Some factors from the foaming agent will affect the fresh and hardened properties of LFC. The excess volume of foam will affect the flow of LFC. Besides, the prolonged duration of mixing concrete with foam will cause the foam to break and become unstable. The hardened properties of foamed concrete, such as the compressive strength, are greatly affected by the type of foaming agent used. The protein-based foaming agent will produce foamed concrete with higher compressive strength than the synthetic foaming agent (Hashim and Tantray, 2021). The stability of foam significantly impacts the properties of LFC. The stability of foam is essential as it will affect the inclusion of air bubbles in the concrete, affecting the stiffness and compressive strength of LFC.

2.9 Introduction to Fiber

The usage of fiber as an additive to concrete is increasing nowadays. Fiber reinforcement concrete is utilised extensively in construction due to its characteristics and application. The inclusion of fiber in concrete has brought advantages to its properties. Fiber-reinforced concrete has more crack and shrinkage resistance than conventional concrete. As a matter of fact, the fibers in concrete are distributed throughout the concrete at relatively small spacings, which provide uniform resistance in all directions (Rao and Rao, 2014). On top of that, fiber-reinforced concrete will have higher ductility due to the uniform distribution of fiber in concrete (Yao, Li and Wu, 2003). Besides, some fibers also increases the mechanical strength of concrete.

Many types of fiber that can be founded on the market. Each type of fiber has different characteristics in fiber-reinforced concrete. The fibers are steel, glass, synthetic, and natural (Ragavendra, et al., 2017). On top of that, each fiber has distinct shapes and dimensions. The typical size of fiber ranged from 0.5 in. to 3.0 in (Bagala, Fraser and May, 2018). Different lengths of fiber will result in different performances of fiber-reinforced concrete. For example, the shorter fiber will assist in bridging micro-cracks while the longer fiber will assist in macro cracks (Behera, et al., 2020).

2.10 Steel Fiber Reinforced Lightweight Foamed Concrete

Steel fiber is one type of fiber that is widely used in the production of fiber reinforced concrete. In the manufacturing of fiber-reinforced concrete, steel fiber is a common type of fiber. There are a few types of steel fiber, such as corrugated steel fiber, twisted steel fiber, hooked-end steel fiber and straight fiber, as shown in Figure 2.5 (Larsen and Thorstensen, 2020). Steel fibers are available in various shapes and sizes, with lengths ranging from 0.25 to 2.5 in. (0.6 to 6.4 cm) and diameters ranging from 0.02 to 0.04 in. (0.05 to 1.0 cm).

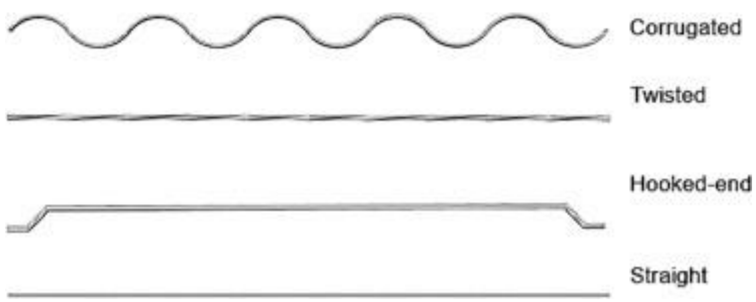


Figure 2.5: Types of Steel Fibers (Larsen and Thorstensen, 2020).

In producing steel fiber-reinforced concrete (SFRC), the amount of fiber used is often expressed as a percentage or volume fraction. The different volume fractions of steel fiber will produce different behaviour in SFRC. A low proportion of steel fiber is utilized to remove the plastic shrinkage (Tabassum, et al., 2018). SFRC is usually used as pavement reinforcement (Behbahani, 2011). A moderate proportion of steel fiber is utilized to improve mechanical properties. Concrete reinforced with a high proportion of steel fiber is typically used for impact and explosion resistance structures.

This study investigates the influence of LFC reinforced with steel fibers on mechanical strength. LFC is well known for its low density but has lower strength than ordinary concrete. The effect of steel fiber in concrete is to strengthen its mechanical properties. The compressive strength of SFRC ranges between 60 to 100 MPa (Velayutham and Cheah, 2014). Similar to LFC, the inclusion of steel fiber in LFC can improve strength and durability properties (Mydin, et al., 2015). Among all types of steel fibers in Figure 2.5, the hooked-end steel fiber can produce the highest performance of steel reinforced (Mustaffa, et al., 2011). As a matter of fact, the hooked-end steel fiber can hold the concrete by using the hook and prevent it from seperating into two parts (Sahu, et al., 2011).

2.11 Mechanical Strength of Steel Fiber Reinforced Lightweight Foamed Concrete

The inclusion of steel fiber into LFC will influence the mechanical strengths, namely compressive strength, flexural strength and splitting tensile strength.

With the inclusion of steel fiber, the compressive strength will slightly gain in steel fiber reinforced LFC (Amran, et al., 2020). In research by Awang and Ahmad, the LFC without steel fibers has a lower compressive strength than LFC with steel fibers. The research also proves that a higher volume fraction of steel fiber will produce higher compressive strength of steel fiber-reinforced LFC. Apart from the factor of volume fraction, the type of steel fiber used also influences the strength of LFC.

The significant improvement of flexural strength is more evident in steel fiber reinforced LFC. In research by Mydin et al. (2015), among the control mix of foamed concrete and the content of 0.2 % and 0.4 % fraction of steel fiber in foamed concrete, the 0.4 % steel fiber result had the higher flexural strength at 28 days (Mydin, et al., 2015). In research by Awang and Ahmad, among the normal LFC and LFC with a steel fiber content of 0.25 % and 0.4 %, the foamed concrete with 0.4 % of steel fiber has the highest flexural strength at 28 days (Awang and Ahmad, 2012). The result proved that including steel fiber in foamed concrete can improve flexural strength. The results show that steel fiber content affects steel fiber reinforced foamed concrete's flexural strength.

Similar to flexural strength, splitting tensile improves more than compressive strength in SFRC. In research by Ahmad and Awang, the overall splitting tensile strength in steel fiber reinforced concrete had improved by 92.1 % compared to normal foamed concrete (Awang and Ahmad, 2012). The significant improvement in flexural strength is due to the high workability of steel fiber. From the research by Mydin, et al. (2015), the research show that the tensile strength of steel fiber reinforced foamed concrete varies for different proportions of steel fiber.

2.12 Silica Fume As Alternate Pozzolanic Material in Concrete

Silica fume is a pozzolanic material produced from alloy production. Silica fume is a tiny white- or gray-colored spherical-shaped particle with less than 1 micron diameter. It is 100 times finer than average cement particles. The specific surface area of silica fume consists of 20000 kg/m^2. It is a by-product of the alloy production process. Different alloys produced will affect the content of silica. In the manufacturing of ferrosilicon, only 50 % silicon is used, which has a substantially lower silica concentration and is less pozzolanic (Panesar, 2019). The quartz reduction process generates silicon dioxide vapour (SiO_2), which is oxidised and condensed to produce tiny non-crystalline silica particles (Chahal and Siddique, 2011).

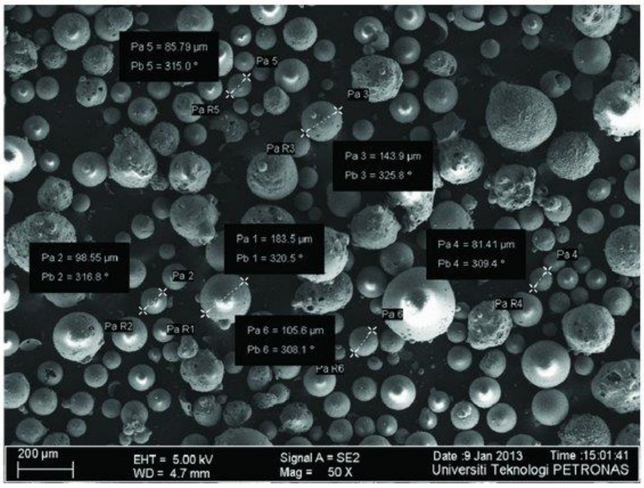


Figure 2.6: Microstructure of Silica Fume Through Field Emission Scanning Electron Microscope (FESEM) (Khan, et al., 2014).

Nowadays, structural concrete is utilised extensively in the construction industry. The high strength requirement in structural concrete causes the proportion of cement to increase to enhance the binder properties. This will lead to high cost and non-environmental friendly. Silica fume as a pozzolan is used to replace cement content partially to strengthen the concrete properties. The silica fume will react with free calcium hydroxide and generate more calcium-silicate-hydrate (C-S-H) during hydration process. Silica fume in concrete can develop early strength of concrete. Besides, adding it to concrete improves its workability (Rasol, 2015). Due to the low permeability of concrete, the durability will increase and prevent harmful ions from diffusing into concrete (Katpady, et al., 2018). Consequently, the corrosion of reinforced steel bars in concrete can be avoided. As part of the cement is being replaced with silica fume, the content of carbon hydroxide will reduce, which can avoid the sulphate attack. The addition of silica fume will increase the workability of silica fume concrete (Srivastava, et al., 2015).

The incorporation of different proportions of silica fume into the concrete will affect the strength properties and durability. At 7 and 28 days, 10 % to 15 % silica fume replacement produced the optimum compressive and flexural strengths (Pradhan and Dutta, 2013). From the research by Bhanja and Sengupta (2005), using 5 % to 25 % silica fume increases compressive strength by 6.25 % to 29.85 % for W/C ratios between 0.26 and 0.42. The increase in compressive strength is due to the binding properties and improvement in the aggregate-paste bond.

The addition of silica fume also affects concrete tensile strength. From the research by Bhanja and Sengupta (2005), the splitting tensile strength at 28 days increased significantly until the silica fume content of 15 %. However, the silica fume content of more than 15 % will not affect the splitting tensile strength much. With 15 % silica fume replacement and a water to binder ratio of 0.26, the highest splitting tensile strength was measured at 6.65 MPa. The lowest value was 3.82 MPa with a 15 % silica fume replacement and water to binder ratio of 0.42.

Liew, Xiong and Lai (2021) show that the flexural strength of silica fume concrete was improved as the silica fume can fill up the void between particles. According to the research by Biswal and Sadangi (2010), using silica fume to replace cement up to 15 % increases the flexural strength of concrete. From the research by Bhanja and Sengupta (2005), the flexural strength increase by adding silica fume. The highest flexural strength of 15 % silica fume replacement concrete is 11.87 MPa at the water-to-cement ratio of 0.26.

2.13 Summary

LFC is a lightweight concrete produced by entraining bubble voids into the concrete mix to form a cellular structure. Pre-foaming or mixed foaming method can manufacture LFC. The bubble voids are produced by using a foaming agent with a foam generator. A stable foam is required to maintain the properties of LFC. Production of a stable LFC mix depends on foaming agent selection, foam preparation method, mixture design strategies, etc. LFC has advantages in low self-weight, low permeability, good thermal, sound insulation and better freez-thaw resistance. Compared to ordinary concrete, LFC has lower compressive, splitting tensile and flexural strength. However, the strength of the LFC can be enhanced by using cement replacements, mineral admixtures and concrete additives.

The inclusion of fibers in concrete is also known as fiber reinforcement concrete. Using fibers in concrete will enhance the mechanical strength, ductility, cracking resistance and shrinkage resistance. Different types of fibers will produce different properties of fiber-reinforced concrete. There are four types of steel fiber. For example, corrugated, twisted, hooked-end and straight steel fiber. Different content of steel fiber in concrete will have different applications. Incorporating steel fiber in LFC can enhance compressive strength, durability, flexural strength and splitting tensile strength.

Silica fume as a pozzolan is added to replace the cement content partially. Silica fume can increase the binder properties in concrete. Besides, silica fume can improve the workability of concrete, compressive, splitting tensile and flexural strength at different content. Hence, silica fume concrete is necessary for structural concrete.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter will begin by illustrating the work plan in a flow chart. Then, the work plan will describe the flow of the case study. After that, a detailed methodology for producing LFC-TM, LFC-CTR and LFC-30SF will be discussed. The methodology included preparing raw materials, mixing procedures, testing of fresh properties, casting procedures, curing and demoulding procedures and testing hardened properties.

3.2 Flow Chart of the Study

The design flow chart for the study of strength properties of 1600 kg/m^3 lightweight foamed concrete (LFC-CTR) and 1600 kg/m^3 lightweight foamed concrete incorporated with 30 kg/m^3 of steel fiber (LFC-30SF) are shown in Figure 3.1.

Firstly, the raw materials prepared for the trial mixes of LFC-TM and LFC-30SF were the Orang Kuat Ordinary Portland Cement CEM I 52 N, the fine aggregates, water, STAHLCON hooked-end steel fiber, silica fume and Sika Foaming agent. Each materials were prepared according to the standard requirements. The range of WC ratios for both type of trial mixes were set from 0.52 to 0.68 with an incremental interval of 0.04. Before casting, the fresh properties tests were carried out, namely fresh density, flow table and inverted slump tests. Then, the trial mix specimens were casted in cube shape with dimension 100 mm × 100 mm × 100 mm. The hardened trial mix specimens were undergo curing process in water tank for 7 and 28 days. After reached the curing age, the compressive strength test was carried out to determine which WC ratio will produce the LFC-TM with highest performance index. The highest performance index indicated the optimum WC ratio.

The LFC-CTR and LFC-30SF were casted with the optimum WC ratio. Before casting, the fresh cement mortar was undergo the fresh properties tests, namely fresh density, flow table and inverted slump tests. After that, the LFC-CTR and LFC-30SF were casted in cube, prism and cylindrical moulds. The curing ages for the LFC-CTR and LFC-30SF were 7, 28 and 56 days. After reached desired curing age, the hardened properties tests were carried out, namely compressive, splitting tensile and flexural tests. All results were obtained and tabulated with the average results from three samples.

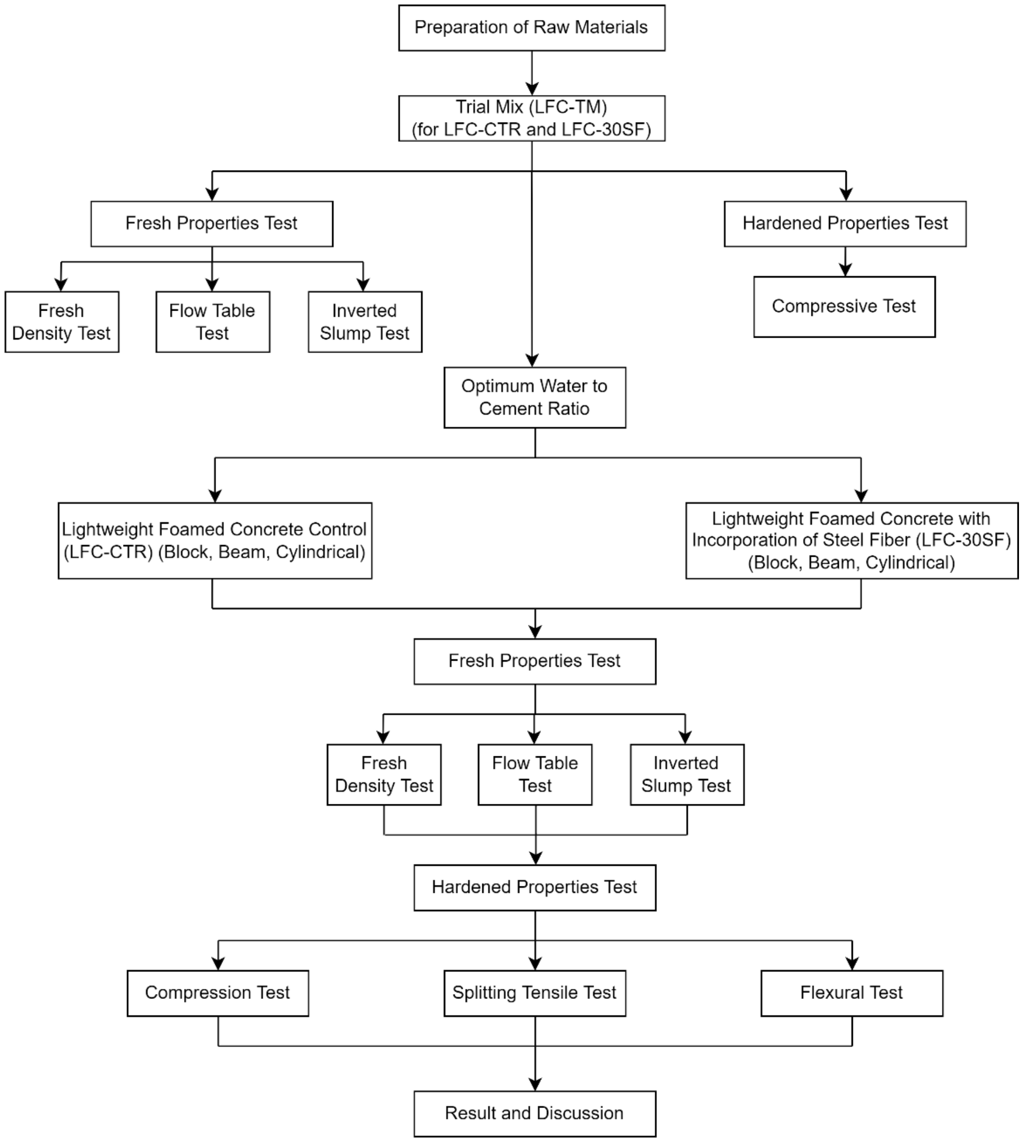


Figure 3.1: Design Flow Chart.

3.3 Preparation of Raw Materials

The raw materials for producing lightweight foamed concrete with the incorporation of steel fiber were Ordinary Portland Cement, water, fine aggregate, foaming agent, steel fiber and silica fume.

3.3.1 Ordinary Portland Cement

The Ordinary Portland Cement (OPC) used in this study was Orang Kuat Ordinary Portland Cement CEM I 52 N, manufactured by YTL Cement Sdn. Bhd. Figure 3.2 shows the Orang Kuat OPC from YTL Cement Sdn. Bhd. It is certified by MS ISO 9001, MS ISO 14001, OHSAS 18001 and MS EN 197-

1:2014. The chemical composition and physical properties of Orang Kuat OPC are shown in Table 3.1. The oxide composition of OPC is shown in Table 3.2

Figure 3.2: Orang Kuat Ordinary Portland Cement by YTL Cement Sdn. Bhd.

Table 3.1: Chemical Composition and Physical Properties of Orang Kuat Ordinary Portland Cement (YTL Cement, 2022).

Tests		Units	Specification MS EN 197-1: 2014 CEM I 42.5N	Test Results
			Chemical Composition	
Insoluble Residue		%	≤ 5.0	0.4
Loss On Ignition (LOI)		%	≤ 5.0	3.2
Sulfate Content (SO_3)		%	≤ 3.5	2.7
Chloride (Cl^-)		%	≤ 0.10	0.02
			Physical Properties	
Setting Time (Initial)		Mins	≥ 60	130
Soundness		Mm	≤ 10	1.2
Compressive Strength	**: 2 days**	MPa	≥ 10	29.7
(Mortar Prism) (1:3:0.5)	**: 28days**	MPa	≥ 42.5; ≥ 62.5	48.9

Table 3.2: Oxide Composition of 52.5 N OPC (Mo, et al., 2014).

Oxide Composition	OPC
Silicon dioxide (SiO_2)	19.8
Ferric oxide (Fe_2O_3)	3.10
Calcium oxide (CaO)	63.4
Sodium oxide (Na_2O)	0.19
Magnesium oxide (MgO)	2.50
Aluminium oxide (Al_2O_3)	5.10
Sulphur trioxide (SO_3)	2.40
Potassium oxide (K_2O)	1.00
LOI	1.80

The production of LFC should not involve using hydrated cement clinker. Hence, the Orang Kuat Ordinary Portland Cement was sieved through a 300 μm sieve to avoid hydrated cement clinker. After sieving the Ordinary Portland cement, the sieved cement was stored in an air-tight container to avoid dampness.

Figure 3.3: Sieved Cement Stored in Air-Tight Container.

3.3.2 Fine Aggregate

In this study, sand was used as a fine aggregate. It was provided by the university. The sand was collected and dried in an oven at 100 °C for 1 day to remove moisture from the sand particles. The moisture content in aggregate will influence the accuracy of the W/C ratio in concrete. According to the ASTM C33 (2007), the particle size of fine aggregate must be within 75 μm (No. 200 sieve) and able to pass through 4.5 mm (No.4 Mesh). The sand used in this study was 100 % passing through a 600 μm sieve. The grading of the sand was determined by carrying out a sieve analysis. Through a sieve analysis, the size distribution of fine aggregates was identified in term of passing rate. The fine aggregates were sieved through 600 μm, 300 μm, 150 μm, and 63 μm. The sieve analysis result is recorded and illustrated in Appendix A-1. The result of the sieve analysis was presented in the graph of cumulative passing rate against sieve size as shown in Figure 3.4. The fineness modulus of the sand used was 2.89. After 24 hours of oven-dried process, the sand was sieved through a 600 μm sieve, as shown in Figure 3.5, Figure 3.6 and Figure 3.7, respectively. The sieving of fine aggregate ensured the foam added into the concrete mix would not burst and impair the foam's effectiveness. Lastly, the sieved fine aggregates was stored in an air-tight container as shown in Figure 3.8.

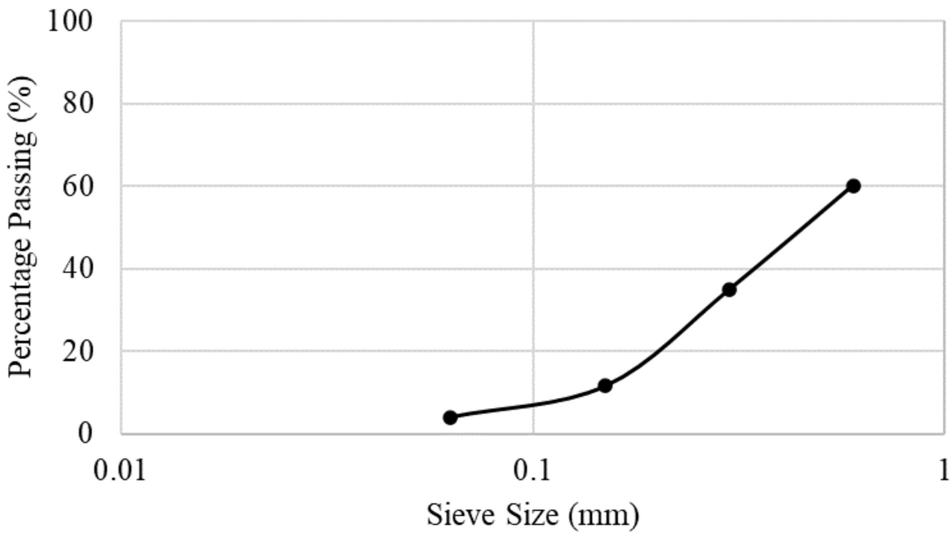


Figure 3.4: Graph of Percentage Passing Versus Sieve Size.

Figure 3.5: The Sand Was Oven-Dried in Oven for 24 Hours.

Figure 3.6: 600 μm Sieve.

Figure 3.7: The Oven Dried Sand Was Sieved Through a 600 μm Sieve.

Figure 3.8: The Retained Sieved Fine Aggregate Was Stored in Air-Tight Container.

3.3.1 Water

According to ASTM C1602 (2022), water is the main lubricant in the concrete mix. The long-term durability of the concrete will be directly impacted by removing any hazardous impurities that could hinder the hydration process. In this study, all lightweight foamed concretes were cast using tap water as the mixing water.

Besides, water was utilised during the curing of concrete. The water in the curing tank prevents excessive moisture loss during the hydration process. The water temperature in the curing tank was kept at room temperature of 25 ºC.

3.3.2 Foam

Foam is an essential material in producing foamed concrete. Consequently, the quantity of foam added will affect the density of LFC. The density of LFC-CTR and LFC-30SF were maintained at 1600 kg/m^3 with a tolerance limit of $\pm$ 50 kg/m^3 in this study.

Foam was produced using water, foaming chemicals, and compressed air in a foam generator as shown in Figure 3.9. The foaming agent used in this study was SikaAER-50/50 in compliance with ASTM C796-97 standard as shown in

Figure 3.10. The foaming agent produced stable foam which has the density of 45 kg/m^3 with a tolerance limit of $\pm$ 5 kg/m^3.

Before the foam generator is used, the foam generator was cleaned with water. Then, the foaming agent and water were poured into the foam generator at the ratio of a foaming agent to the water of 1:20. Then, the foam generator was pressurized to 5 kg/cm^3. Unstable foam will impact the density of the lightweight concrete. Therefore, the first batch of foam was rejected from concrete mixing.

Figure 3.9: Foam Generator.

Figure 3.10: SikaAER-50/50.

3.3.3 Steel Fiber

Steel fiber is a fiber that is added into LFC to produce steel fiber reinforced LFC. In this study, the hooked-end steel fiber was used with branded STAHLCON, as shown in Figure 3.11 and Figure 3.12.

Figure 3.11: STAHLCON Steel Fiber.

Figure 3.12: Hooked-End Type Steel Fiber.

The tensile strength of steel fiber is important because it provides additional reinforcement to the concrete. The steel fiber in the concrete must withstand the stress before they deform or break. Hence, steel fiber with high tensile strength is required to produce steel fiber reinforced concrete with high strength. Therefore, a tensile strength test was carried out to identify the tensile strength of steel fiber.

The tensile strength test was carried out by using the Shimadzu Universal testing machine as shown in Figure 3.13. Firstly, the Shimadzu computer software was launched and the test was set to tensile type. The diameter and the length of the steel fiber were key into the test setting. Next, the grip head was set to the joint in the machine. Then, the loading rate was set to 1 millimeter per minute. After that, the steel fiber was gripped into the grip head and locked in position as shown in Figure 3.14. The test was start after the set up was done. The test was stopped after the steel fiber failed and broke into two parts.

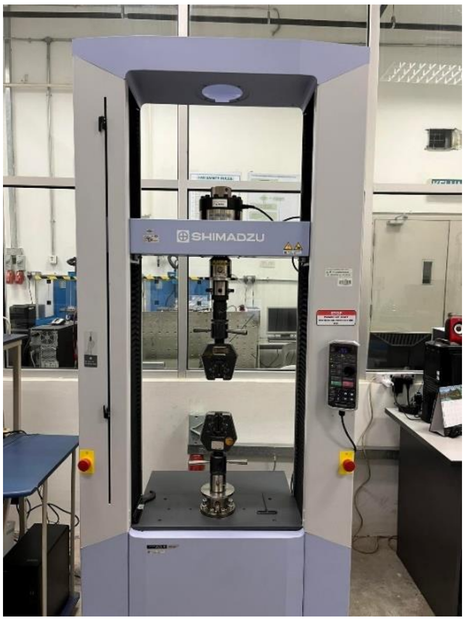


Figure 3.13: Shimadzu Universal Testing Machine.

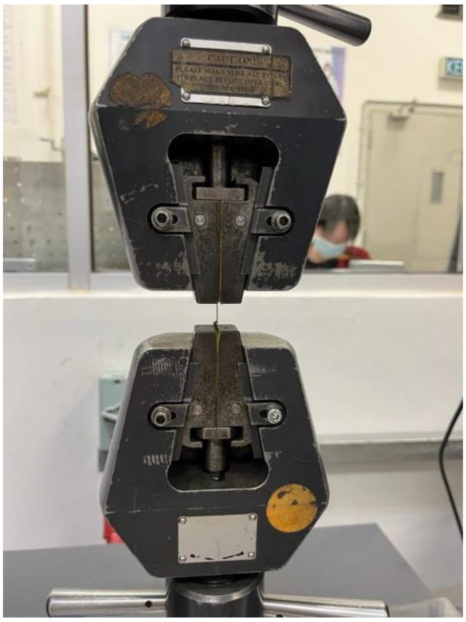


Figure 3.14: Steel Fiber Gripped To Grip Head.

3.3.4 Silica Fume

Silica fume as a pozzolana was added to enhance the strength properties of LFC. According to ASTM C1240-05 (2005), the silica fume should contain the minimum silica dioxide (SiO_2) of 85 %, maximum moisture content and loss on ignition of 3 % and 6 % respectively.

Figure 3.15: Silica Fume.

3.4 Preparation of Apparatus

3.4.1 Concrete Mould

In this study, different shapes of the concrete specimen were used to carry out the strength tests respectively. This study prepares three types of concrete moulds: cubic mould, prism mould and cylindrical mould. The dimension of cubic mould is 100 mm × 100 mm × 100 mm as shown in Figure 3.16. The cylindrical mould has a diameter of 100 mm and a height of 200 mm as shown in Figure 3.17. The dimension of the prism mould is 40 mm × 40 mm × 160 mm as shown in Figure 3.18. All of these moulds are prepared in accordance with ASTM C31/C31M-19 standard (ASTM, 2019).

Figure 3.16: Cubic Mould.

Figure 3.17: Cylindrical Mould.

Figure 3.18: Prism Mould.

Before casting, each mould was unscrewed, and every surface was cleaned with a scrapper and air blower. Then, the dimension of each mould was measured and recorded after the screws were tightened to avoid inaccurate casting volume of concrete specimens. Next, the mould interior was oiled to smoothen the de-moulding process, as shown in Figure 3.19. After that, the fresh concrete was poured into the moulds.

Figure 3.19: The Surface of Cubic Mould Was Applied with Oil.

3.5 Mixing Procedures

The mixing procedures for LFC-TM, LFC-CTR and LFC-30SF are discussed in this sub-chapter. The mixing procedures are important in obtaining accurate results from the strength tests. First, LFC-TM was cast to determine the W/C ratio of LFC-CTR and LFC-30SF. Then, the casting of LFC-CTR and LFC-30SF were conducted with the same mixing procedures using the optimum water to cement ratio. LFC-30SF was then added with 30 kg/m^3 of steel fiber.

3.5.1 Trial Mix (LFC-TM)

In this study, the trial mixes are necessary to determine the optimal water-to-cement ratio for casting LFC-CTR and LFC-30SF. Hence, two types of trial mix were required, which were lightweight foamed concrete with 10 % silica fume replacement at a density of 1600 kg/m^3 and lightweight foamed concrete with 10 % silica fume replacement and 30 kg/m^3 of steel fiber. The range of density of the trial mix was set from 0.52 to 0.68 with an interval of 0.04. Next, the cubic specimens were cast with the W/C ratios of 0.52, 0.56, 0.60, 0.64 and 0.68. The casted cubic specimens were then undergo a compressive strength test. The result was presented by plotting a compressive strength versus water to cement ratio graph. From the graph, the highest point the graph indicates the optimum water to cement ratio.

Firstly, the raw materials were prepared in accordance with the proportions of the designed mix. The proportion of cement and fine aggregate was set at 1:1. The amount of water required for the trial mixes were prepared according to the desired W/C ratio, which were 0.52, 0.56, 0.60, 0.64 and 0.68. After the preparation of raw materials were completed, the cement, fine aggregates and silica fume were added to the mixing bowl. The added materials were then mixed thoroughly by hand without adding water. This process, also known as dry mixing as shown in Figure 3.20. The dry mixing is to ensure the materials are mixed uniformly. After the dry mix was mixed uniformly, water was added to the dry mix. The dry mix was mixed thoroughly by hand until a homogeneous mix was produced. Figure 3.21 shows the mixing of dry mix with water.

Figure 3.20: Mixing of Dry Mix Manually.

Figure 3.21: Mixing of Dry Mix with Water.

After the concrete mix was mixed homogenously, the fresh density test was conducted to determine the density of freshly mixed concrete in compliance to ASTM C796. A detailed procedure of the fresh density test will be discussed in the subchapter 3.6.1. Then, the desired amount of foaming agent and water were poured into the foam generator to produce foam. The first batch of foam produced was rejected due to its instability, which would influence the density of the lightweight concrete. After that, the generated foam was weighed and recorded. The generated foam was then added to the concrete mix. Then, the remaining generated foam was weighed again to determine the amount of foam added to the concrete mix. Following that, the fresh density of foam-added concrete was then tested. The steps were repeated until the density of foamed concrete has reached 1600 kg/m^3. Figure 3.22 shows the production of stable foam. Figure 3.23 shows the weight of generated foam before added into the concrete mix. Figure 3.24 shows the mixing of generated foam with concrete.

Figure 3.22: Stable Foam Was Used for Production of Foamed Concrete.

Figure 3.23: The Weight of Generated Foam Was Taken Before Added Into the Concrete Mix.

Figure 3.24: Generated Stable Foamed Concrete Was Added and Mixed in Concrete Mix.

After the lightweight foamed concrete has reach density 1600 kg/m^3 with $\pm$ 50 kg/m^3 tolerance, an inverted slump test was carried out in compliance with ASTM C1611 (2014). In line with ASTM C1437-01, a flow table test was conducted. A detailed procedure of the inverted slump test and flow table test will be discussed in the subchapter 3.6.2. After the fresh properties tests were performed, a fresh density test was repeated to ensure that the fresh foamed concrete mix maintains the desired density.

The fresh foamed concrete was poured into an oiled cubic mould. The excessive foamed concrete was then strucked off to enable an even and flat surface of the concrete in the mould. Figure 3.25 shows the pouring of foamed concrete mix into the cubic mould. Then, each of the concrete mould filled with foamed concrete mix were labelled by using paper. After that, the freshly mix foamed concrete was allowed to set and harden for 24 hours.

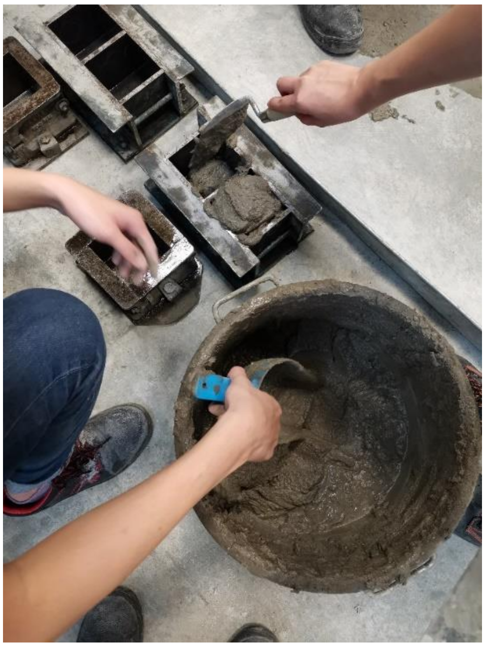


Figure 3.25: Fresh Foamed Concrete Was Poured Into Concrete Mould.

After 24 hours of the setting and hardening process, the demoulding process was carried out. First, the hardened lightweight foamed concrete was demoulded, and its hardened density was taken. After the specimens were demoulded, the surface of the specimens was labeled accordingly by using a marker. Then, water curing was carried out by incubating the concrete specimen in the water tank. It must be cured at 16 ºC to 27 ºC in the curing tank and completely immersed in water. The curing ages for the trial mix (LFC-TM) were 7 days and 28 days. The specimens were taken from the curing tanks at 7 and 28 days, respectively, and oven-dried 24 hours before the testing day. Figure 3.26 shows the demoulding the concrete specimens while Figure 3.27 shows the curing process of foamed concrete in water curing tank.

Figure 3.26: Specimens Demould Process.

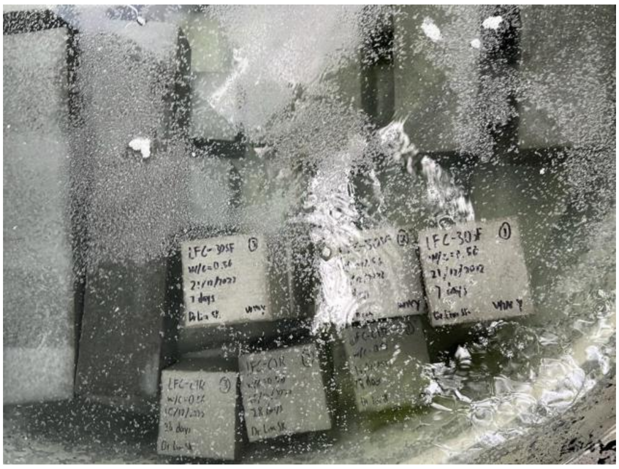


Figure 3.27: Curing Foamed Concrete Specimens in Water Tank.

The mixing procedures for the trial mix of LFC with 10 % silica fume replacement and 30 kg/m^3 of steel fiber is similar as the LFC with 10 % silica fume replacement but without silica fume. However, for the trial mix of LFC with 10 % silica fume replacement, 30 kg/m^3 of the hooked-end steel fiber was added after the density of LFC reaches 1600 kg/m^3. Then, the fresh density test was repeated to evaluate the fresh density of after the addition of 30 kg/m^3 steel fiber.

3.5.2 LFC-CTR

The control mix (LFC-CTR) mixing procedures are almost similar to the trial mix (LFC-TM). However, the LFC-CTR were cast in cubic, cylindrical, and prism specimens. In addition, the curing ages for all LFC-CTR specimens were 7 days, 28 days and 56 days.

3.5.3 LFC-30SF

The mixing procedures of LFC-30SF are almost similar to the control mix (LFC-CTR). However, the LFC-30SF were cast in cubic, cylindrical, and prism specimens. In addition, the curing ages for all LFC-30SF specimens are 7 days, 28 days and 56 days.

3.6 Fresh Properties Testing

The properties of freshly mix foamed concrete and foamed concrete reinforced with steel fiber were determined by carrying out the fresh properties tests. The fresh properties tests covered in this study are the fresh density, flow table, and inverted slump tests.

3.6.1 Fresh Density Test (ASTM C796)

In this study, the ASTM C796 (2004) standard was adopted when performing the fresh density test. Fresh density test calculates the weight of bulk or compacted aggregates per cubic meter. The materials required to perform the test was a container with one liter capacity and a weighing machine. First, the empty container was tarred to zero at the weighing machine. Then, the fresh lightweight foamed concrete was filled into the container, and the excess foamed concrete was struck off. After that, the container was hit and shaked to ensure that the air inside is escaped and there is no void presence. Afterward, the weighing machine weighed the container containing lightweight foam concrete to assess its fresh density. The addition of foam was required until the desired concrete density was reached. Figure 3.28 shows the fresh density test of lightweight foamed concrete.

Figure 3.28: Determination of Density of Foamed Concrete at Fresh State.

3.6.2 Flow Table Test (ASTM C230)

In line with ASTM C230, the consistency of LFC-TM, LFC-CTR, and LFC-30SF was tested using a flow table test. The apparatus involved in flow table test was a flow table and mould. Firstly, the surface of flow table was cleaned and the mould was put on the centre of flow table as shown in Figure 3.29. Then, the freshly mixed foamed concrete was poured into the mould until the mould was filled. Next, the excessive concrete was removed to ensure a flat top surface. The mould was lifted slowly and raised, and dropped on the flow table a maximum of 25 times. The amount of drop in the flow table was recorded, and the slump spread diameter was measured.

Figure 3.29: The Mould Positioned in the Middle of Flow Table.

3.6.3 Inverted Slump Test (ASTM C1611)

After the desired density of LFC-TM, LFC-CTR and LFC-30SF were obtained, an inverted slump test was performed to study the workability of concrete in compliance with ASTM C1611 (2014). The result of the inverted slump test was obtained by measuring the spread diameters of the fresh concrete. A slump cone and a base plate were required to perform the test. Firstly, the slump cone was placed inversely on the centre of the base plate. Then, hold the slump cone tightly on the base plate to avoid leaking concrete mix from the bottom. Next, the freshly mixed LFC was poured into the inverted slump cone until it was full-filled. The excess concrete was removed to provide a flat top surface. Lastly, the slump cone was raised vertically and slowly at about 1 feet. The slump spread diameter was measured and recorded. Figure 3.30 shows the inverted slump cone was fully filled with lightweight foamed concrete while Figure 3.31 demonstrates the measurement of slump spread diameter.

Figure 3.30: The Inverted Slump Cone Was Fully Filled With LFC.

Figure 3.31: Measurement of Slump Spread Diameter.

3.7 Hardened Properties Testing

The hardened properties of the LFC-TM, LFC-CTR and LFC-30SF were tested using destructive tests. There were three types of destructive tests, which were compressive, splitting tensile and flexural strength tests were performed.

3.7.1 Compressive Strength Test (BS EN 12390-3)

In line with BS EN 12390-3 (2019), the compressive strength test was conducted on LFC-TM, LFC-CTR, and LFC-30SF. For the compressive strength test, a concrete compression machine as shown in Figure 3.32, was required. The maximum load that can sustain by the concrete specimen without failure can be determined from the test. Then, the compressive strength of the concrete was determined by dividing the peak load applied by the cross-sectional area of concrete specimens. Equation 3.1 illustrates the calculation of the compressive strength. Cubic specimens (100 mm × 100mm × 100mm) of LFC-TM, LFC-CTR and LFC-30SF were used to performed the compressive strength test at 7 days, 28 days and 56 days.

$$f_c = \mathrm{P/A} \tag{3.1}$$

where

f_c = compressive strength, MPa

P = Maximum load sustained by the concrete specimen, N

A = Cross-sectional area of the concrete specimen where load is applied, mm^2

Figure 3.32: Concrete Compression Machine.

Before conducting the test, the dimension of the cubic concrete specimen was measured. Then, the cubic concrete specimen and the platform of the compression machine were cleaned to ensure no debris on the surface. Next, the cubic concrete specimen was positioned at the centre of the compression machine. The parameters of the compression machine were set before the test started. The pace rate was set to 0.5 kN/s, and the dimension of the cubic specimen was set. The test was then started, and the cubic concrete specimen was loaded at the specified loading rate until it failed and cracks appeared on its surface. The maximum load indicated by the machine was recorded to calculate the compressive strength.

3.7.2 Splitting Tensile Strength Test (ASTM C496)

The splitting tensile strength test was carried out for LFC-CTR and LFC-30SF in accordance to ASTM C496 (2004). A concrete compression machine as shown in Figure 3.33, was used to conduct the splitting tensile strength test. Cylindrical specimens of LFC-CTR and LFC-30SF were required to perform the splitting tensile strength test for 7 days, 28 days and 56 days. Firstly, the surface of the cylindrical specimen and the platform of the concrete compression machine were cleaned to ensure no debris on it. Next, the cylindrical specimen was then positioned in a steel mould. The bearing strips were placed at the upper and bottom of concrete specimen to distribute the load uniformly along the cylindrical specimen's surface. Followed by placing the steel mould with the cylindrical specimen at the centre of the compression machine. The parameters of the compression machine were set before the test was started. The pace rate was set to 0.5 kN/s, and the dimension of the cylindrical specimen 100 mm in diameter and 200 mm in height was set. The splitting tensile strength test was then started. The specimen was loaded at the predefined loading rate until it failed and cracked appear on its surface. The maximum load that the specimen could withstand was determined and applied to calculate splitting tensile strength by using Equation 3.2.

$$T = \frac{2P}{\pi l d} \tag{3.2}$$

where

T = spitting tensile strength, MPa

P = Maximum load sustained by the cylindrical concrete specimen, N

l = length of the cylindrical concrete specimen, mm

d = diameter of the cylindrical concrete specimen, mm

Figure 3.33: Concrete Compression Machine for Splitting Tensile Strength Test Was Set Up.

3.7.3 Flexural Strength Test (BS EN 12390-5)

According to ASTM C78/C78M (2019), the flexural strength also defined as modulus of rupture. The flexural strength test was carried out for LFC-CTR and LFC-30SF at 7 days, 28 days and 56 days. The prism specimens of LFC-CTR and LFC-30SF were required to conduct the flexural strength test. The dimension of the prism specimen is 40 mm × 40 mm × 160 mm. In this study, a Shimadzu Universal Testing Machine was used to conduct the flexural strength test in accordance with BS EN 12390-5 standard. This machine can apply loading up to 50 kN with load speeds ranging from 0.05 to 1000 mm/min. In addition, this machine can record data from a test at a frequency of 800 Hz. Figure 3.34 shows the Shimadzu Universal Testing Machine.

Figure 3.34: Shimadzu Universal Testing Machine.

Firstly, the prism specimens for testing were cleaned, and the loading lines were marked on the surface of the prism specimens. Then, launched the TRAPEZIUMX software on the computer and keyed in the information of the testing method. The test mode, test types, force polarity, force direction, the material of specimen, dimension of the specimen and the type of data required to process. The loading speed of the machine was set to 0.2 mm/min. Then, the prism specimen was put on the flexural strength test fixture according to the marked loading lines. The flexural strength test was then started, and the prism concrete specimen was loaded at the specified loading rate until it failed and cracked appear on its surface. The maximum load the specimen could withstand was obtained and applied to compute flexural strength.

This study used a three-point flexural test to conduct the flexural strength test of LFC-CTR and LFC-30SF. The loading speed was set to 0.2 mm/min. The calculation of flexural strength was performed in Equation 3.3.

$$f_{\mathrm{cf}} = \frac{3 \times F \times I}{2 \times d_1 \times {d_2}^2} \tag{3.3}$$

where

f_{cf} = flexural strength, MPa

F = maximum applied load indicated by the testing machine, N

I = distance between the supporting rollers, mm

d_1 = average width of prism specimen, mm

d_2 = average depth of prism specimen, mm

3.8 Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray Analysis (EDX)

Scanning electron microscope, also known as SEM, utilised a focused electron beam to produce high resolution images of a sample's surface. An electron beam scanned the sample's surface and the image was created by collecting the scattered or emitted electrons from the sample. The interaction between the electrons and the sample's atoms can result in an image containing details on the sample's surface topography, morphology, and composition.

Before the SEM analysis, the concrete specimens were prepared in small sizes. Both the diameter and height of the specimens must be within 15mm. The small size of specimens was to ensure it can mount on the pin stubs, as shown in Figure 3.35. Before SEM analysis, the specimens were coated with a layer of gold and palladium using the EMITECH Sputter Coater machine, as shown in Figure 3.36. The pin stubs with the coated samples were then screwed on the specimen multiholder. The specimen multihoder with coated samples was then place inside the Hitachi S-3400N SEM machine, as shown in Figure 3.37, to conduct samples analysis. In this study, the images of specimens were captured under the magnifications of 50×, 100×, 200×, 500× and 1000×.

Figure 3.35: Concrete Specimen Mounted on the Pin Stubs.

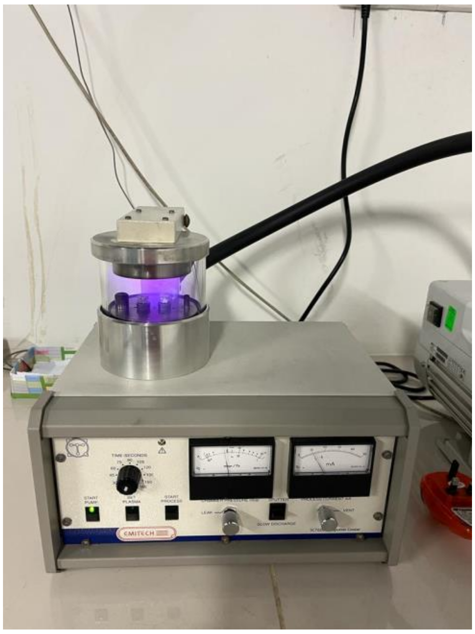


Figure 3.36: Specimens Coating with EMITECH Sputter Coater.

Figure 3.37: Hitachi S-3600N SEM.

After the SEM analysis, the energy dispersive x-ray spectroscopy was carried out. Energy dispersive X-Ray (EDX) is used to identify the elemental composition of a material by analysing the distinctive X-rays emitted when a material was bombarded with high-energy electrons or X-rays. The specimens were subjected to a beam of X-Rays to allow the atoms in the specimens to emit X-Rays. These X-Rays were collected and the energies of the X-Rays were measured to determine the presence of the specified elements in the specimens.

3.9 Summary

In this chapter, the preparation of raw materials, the mixing procedures and the fresh and hardened properties test used are discussed. All of the LFC was produced at the fresh and hardened density of 1600 kg/m^3 with a tolerance limit of ± 50 kg/m^3. The LFC-30SF was produced by adding 30 kg/m^3 of steel fiber into the lightweight foamed concrete mix. In this study, LFC-TM, LFC-CTR and LFC-30SF were prepared.

The optimum W/C ratio of the control mix of LFC and LFC incorporated with steel fiber was determined from the trial mixes. A total of thirty cubic specimens (100 mm × 100 mm × 100 mm) were cast at the W/C ratio of 0.52 to 0.68 with an interval of 0.04. Fifteen cubic specimens of LFC-

TM were required in 7 day compressive strength test, while the other fifteen cubic specimens of LFC-TM were required in 28 days compressive strength test. LFC-CTR was the control mix of lightweight foamed concrete without the reinforcement of steel fiber. A total of twenty-seven specimens were needed for the LFC-CTR. From the twenty-seven specimens, nine cubic specimens were needed in the compressive strength tests, nine cylindrical specimens were needed in the splitting tensile strength test, and nine beam specimens were needed in flexural strength tests. Each strength test was performed for 7 days, 28 days and 56 days. The number of LFC-30SF specimens required is the same as the LFC-CTR.

SEM-EDX analysis were conducted to observed the microstructure of LFC-CTR and LFC-30SF. The element composition in both concrete mixed were determined through the EDX analysis.

CHAPTER 4

TRIAL MIX

4.1 Introduction

Chapter 4 discusses the mix proportions and fresh and hardened properties of the trial mixes of the lightweight foamed concrete with 30 kg/m^3 of steel fiber (LFC-TM). The curing age of the LFC-TM is 7 and 28 days before the strength test. The trial mixes in this study are required to determine the optimal water-to-cement (W/C) ratio for casting the control of lightweight foamed concrete (LFC-CTR) and the mixes of lightweight foamed concrete with 30kg/m^3 of steel fiber (LFC-30SF). Besides, this chapter also discusses the tensile test result for the STAHLCON hooked-end steel fiber.

4.2 Tensile Test for Steel Fiber

The steel fiber used in this study is the STAHLCON hooked-end steel fiber. The diameter and length of steel fiber are 0.55 mm and 35 mm, respectively. The steel fiber was added into LFC-30SF as a reinforcement to LFC. The tensile strength of steel fiber ensures the ability to bridge the cracks in the concrete. The tensile test of steel fiber was carried out with the Shimadzu Universal Testing machine. The results of the tensile strength of steel fiber are presented in Table 4.1 and Figure 4.1.

Table 4.1: Tensile Test Result for Steel Fiber.

Avg. Maximum Stress (MPa)	**Strain at Maximum Stress (%)**	**Avg. Load at Maximum Tensile Stress (N)**	**Avg. Tensile Stress at Yield Offset 0.2% (MPa)**
1423.19	11.15	338.13	33.45

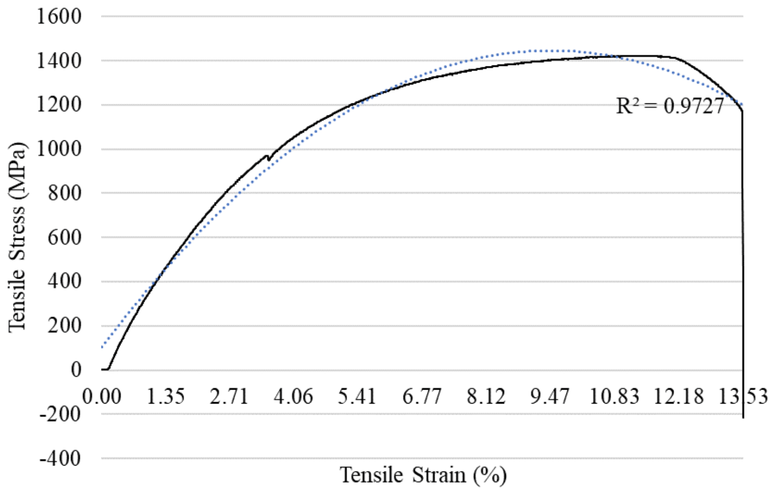


Figure 4.1: Graph of Tensile Stress Versus Tensile Strain.

4.3 Control Mix

Control mix is the lightweight foamed concrete without reinforcing steel fiber. The W/C ratio of the trial mix proportions for LFC-CTR is set from 0.52 to 0.68 with an incremental interval of 0.04. Table 4.2 summarises the trial mix proportions data of control mix.

Table 4.2: Trial Mix Proportions for LFC-CTR.

Sample	W/C	Material (kg/m³)						Percentage (%)
		Cement	Sand	Water	SF	Silica Fume	Foam	
[3]LFC-TM 0.52	0.52	571.5	635	330.2	0	63.5	8.96	0.71
LFC-TM 0.56	0.56	562.5	625	350	0	62.5	8.45	0.68
LFC-TM 0.60	0.60	553.5	615	369	0	61.5	7.97	0.65
LFC-TM 0.64	0.64	544.5	605	387.2	0	60.5	7.52	0.62
LFC-TM 0.68	0.68	535.5	595	404.6	0	59.5	7.11	0.60

Note:

Percentage = Percentage of foam based on the sum of dry material weight (Cement, Sand)

4.3.1 Fresh Properties of Trial Mix for LFC-CTR

The fresh properties test included flow table test, inverted slump test and fresh density test. The fresh properties tests are conducted to maintain the consistency of cement mortar. Table 4.3 illustrates the fresh properties of the trial mix for LFC-CTR with the W/C ratio ranging from 0.52 to 0.68 with an incremental interval of 0.04.

Table 4.3: Fresh Properties of Trial Mix for LFC-CTR.

W/C	**Fresh Density (kg/m^3)**	**Flow Table Spread, (number of drop)**	**Average Inverted Slump Diameter (mm)**	**Consistency**	**Stability**
0.52	1561.2	37	342.5	0.976	0.984
0.56	1570	34	407.5	0.981	0.967
0.60	1579	25	412.5	0.987	0.964
0.64	1598	20	562.5	0.999	0.987
0.68	1571.8	17	672.5	0.982	0.961

Note:

Fresh Density = The density of fresh foamed concrete before casting

From Table 4.3, the average inverted slump values are increasing with the W/C ratio. Besides, the flow table values decreased when the W/C ratio increased. The results proved that the higher the W/C ratio, the higher the workability of concrete. As a result, the number of drops required to allow the cement mortar to reach the edge of the flow table is less. Furthermore, all of the LFC possessed high stability as the stabilities of all LFC are nearly one. High stability indicated that the air bubbles in the LFC were stable. Besides, high stability will cause high consistency of concrete. As a result, the hardened densities of all LFC were well-maintained and within the density range of 1600 ± 50 kg/m^3.

4.3.2 Hardened Properties of Trial Mix for LFC-CTR

The tests for hardened properties of Trial Mix for LFC-CTR are the hardened densities test and the compressive strength test. The sample required for the compressive strength test is the cube sample with the dimension of 100 mm × 100 mm × 100 mm. The required curing ages for the trial mix samples are 7 and 28 days. Table 4.4 presents the hardened properties of the trial mix for LFC-CTR at 7 and 28 days of curing. All average hardened densities for all W/C ratios were within the acceptable density range of 1600 ± 50 kg/m^3.

Table 4.4: Hardened Properties of Trial Mix for LFC-CTR.

Sample	**Average Hardened Density (kg/m^3)**		**Average Compressive Strength (MPa)**	
	7 days	**28 days**	**7 days**	**28 days**
LFC-CTR 0.52	1574.27	1599.13	9.68	14.84
LFC-CTR 0.56	1623.53	1623.47	11.00	16.40
LFC-CTR 0.60	1644.33	1631.47	10.57	15.13
LFC-CTR 0.64	1617.87	1619.33	10.09	14.60
LFC-CTR 0.68	1630.73	1639.47	9.92	14.34

Note:

Average Hardened Density = The average value of density from three demoulded concrete samples

From Figure 4.2, the compressive strength of LFC was increased from the W/C ratio of 0.52 to 0.56. However, the compressive strength dropped from the W/C ratio of 0.56 to 0.68. The changes in the compressive strength within the W/C ratio of 0.52 and 0.68 have indicated a peak compressive strength at the W/C ratio of 0.56. The highest compressive strength of LFC-CTR at 7 days and 28 days are 11.00 MPa and 16.40 MPa, respectively.

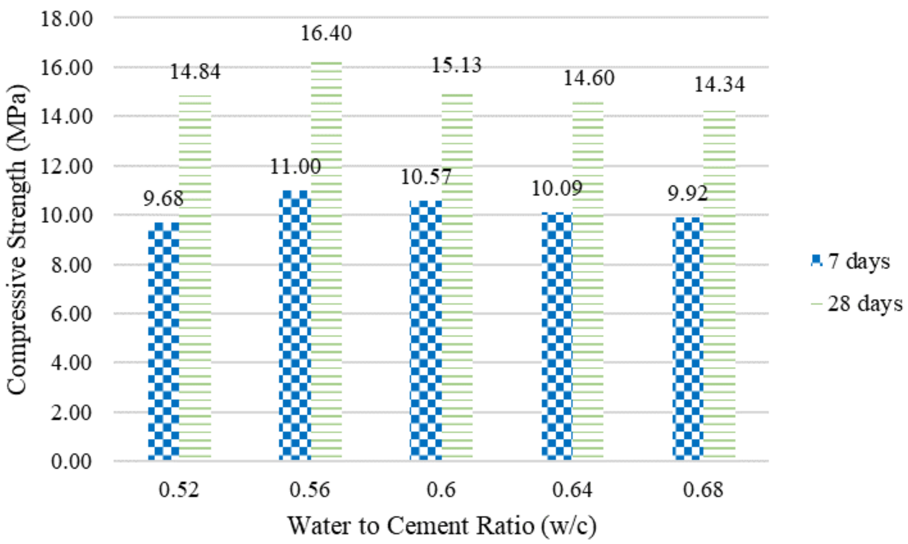


Figure 4.2: Graph of Compressive Strength (MPa) Versus Water to Cement Ratio (W/C).

4.3.3 Performance Index

A performance index is essential to evaluate the strength performance of concrete. Although the target density is 1600 kg/m^3, it was difficult to maintain the density at exactly 1600 kg/m^3. All of the LFC will have varying densities. The high density of the LFC will lead to high strength, so it was unreliable to determine the highest strength based on the strength graph. Hence, the performance index was calculated as the strength per 1000 kg/m^3. The results of compressive strength test and performance index is summarised in Appendix A-2. From Figure 4.3, the highest performance index was observed at the W/C ratio of 0.56 for 7 and 28 days. Thus, the optimum W/C ratio for LFC-CTR was 0.56.

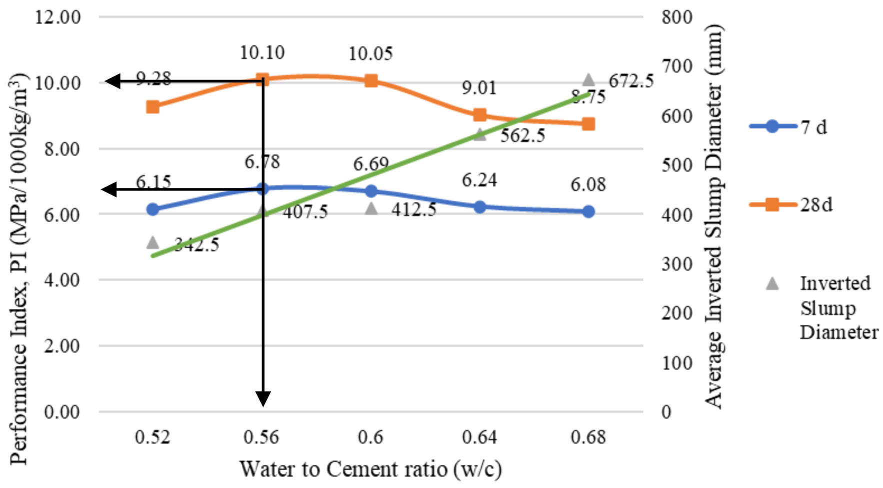


Figure 4.3: Performance Index of Trial Mix for LFC-CTR.

4.4 LFC-30SF

The trial mix of LFC-30SF is a mix of LFC with 30 kg/m^3 of steel fiber. Similar to the control mixes, the W/C ratio of the trial mix proportions for LFC-30SF is set from 0.52 to 0.68 with an incremental interval of 0.04.

4.4.1 Trial Mix Proportions for LFC-30SF

Table 4.5 summarises the trial mix proportions data of the LFC-30SF.

Table 4.5: Trial Mix Proportions for LFC-30SF.

Sample	W/C	Material (kg/m^3)						Percentage
		Cement	Sand	Water	SF	Silica Fume	Foam	(%)
LFC-30SF 0.52	0.52	558	620	322.4	30	62	9.69	0.76
LFC-30SF 0.56	0.56	549	610	341.6	30	61	9.21	0.74
LFC-30SF 0.60	0.60	540	600	360	30	60	8.75	0.71
LFC-30SF 0.64	0.64	535.5	595	380.8	30	59.5	8.06	0.66
LFC-30SF 0.68	0.68	526.5	585	397.8	30	58.5	7.66	0.64

The trial mix proportions were calculated using the absolute volume method. Table 4.5 shows that the volume of foam required decreased when the W/C ratio increased. Next, the silica fume is used as the replacement of 10% of the total volume of cement.

4.4.2 Fresh Properties of Trial Mix for LFC-30SF

Table 4.6 summarises the result of fresh properties of trial mix for the LFC-30SF.

Table 4.6: Fresh Properties of Trial Mix for LFC-30SF.

W/C	**Fresh Density (kg/m^3)**	**Flow Table Spread, (number of drop)**	**Average Inverted Slump Diameter (mm)**	**Consistency**	**Stability**
0.52	1561	30	38.25	0.976	0.984
0.56	1580.4	25	43	0.988	0.969
0.60	1557	21	56.5	0.973	0.950
0.64	1552	15	59.5	0.970	0.950
0.68	1553	7	77.5	0.971	0.960

The fresh densities of LFC-30SF were maintained within the density range of 1600 ± 50 kg/m^3. The number of drops in the flow table test decreased when the water to cement ratio increased. This was because the high water content would result high workability in concrete. Thus, the slump values increased when the water to cement ratio increased. Besides, the consistency and stability of all LFC-30SF were nearly one, which indicated the air bubbles were stable in the concrete mix. Hence, fewer air bubbles in the mix were burst. The LFC-30SF only experienced minor changes in hardened density compared to the fresh density.

4.4.3 Hardened Properties of Trial Mix for LFC-30SF

The tests for hardened properties of Trial Mix for LFC-30SF are the hardened density test and the compressive strength test. The required curing age for the trial mix samples is 7 days and 28 days. Table 4.7 shows the hardened properties of the trial mix for LFC-30SF with 7 and 28 days curing ages, respectively. The hardened density of the LFC-30SF is essential for comparison with the LFC-CTR. The hardened density is maintained at 1600 ± 50 kg/m^3.

Table 4.7: Hardened Properties of Trial Mix for LFC-30SF.

Sample	**Average Hardened Density (kg/m^3)**		**Average Compressive Strength (MPa)**	
	7 days	**28 days**	**7 days**	**28 days**
LFC-30SF 0.52	1567.33	1604.73	9.39	15.59
LFC-30SF 0.56	1635.87	1626.4	11.84	17.19
LFC-30SF 0.60	1636.8	1639.53	9.09	15.54
LFC-30SF 0.64	1639.5	1628.83	8.50	12.92
LFC-30SF 0.68	1614.83	1619.17	8.20	12.18

Figure 4.4 demonstrates the results of the compressive strength of LFC-30SF from W/C ratio of 0.52 to 0.68. Initially, the compressive strength of LFC-30SF was increased from the water to cement ratio of 0.52 to 0.56. From the water to cement ratio of 0.56 to 0.68, the compressive strength at 7 and 28 days reduced. Hence, the highest compressive strength of LFC-30SF is at the water to cement ratio of 0.56, which is 11.84 MPa at 7 days of curing age and 17.19 MPa at 28 days of curing age. According to the compressive strength result, the optimal water to cement ratio is 0.56 without considering the factor of hardened density.

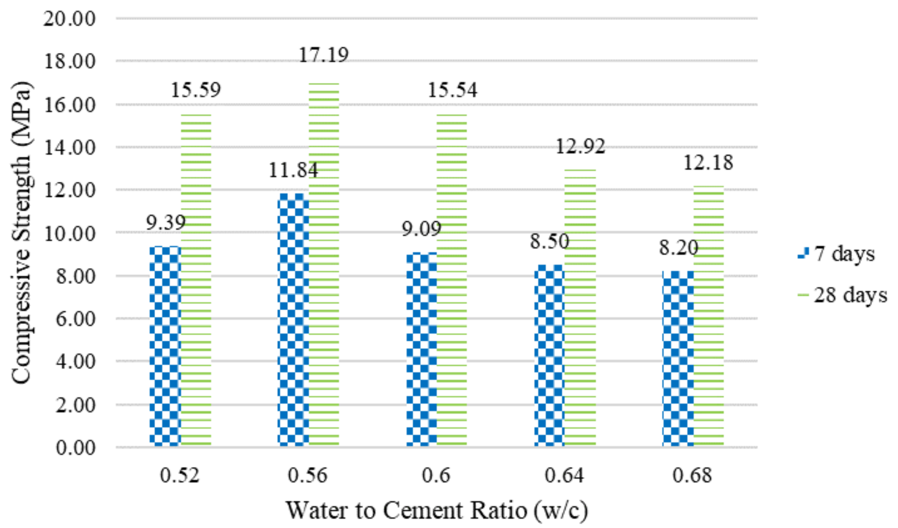


Figure 4.4: Graph of Compressive Strength (MPa) Versus Water to Cement Ratio (W/C).

4.4.4 Performance Index

Figure 4.5 summarises the performance index of the trial mix for LFC-30SF from the W/C ratio of 0.52 to 0.68 with an incremental interval of 0.04.

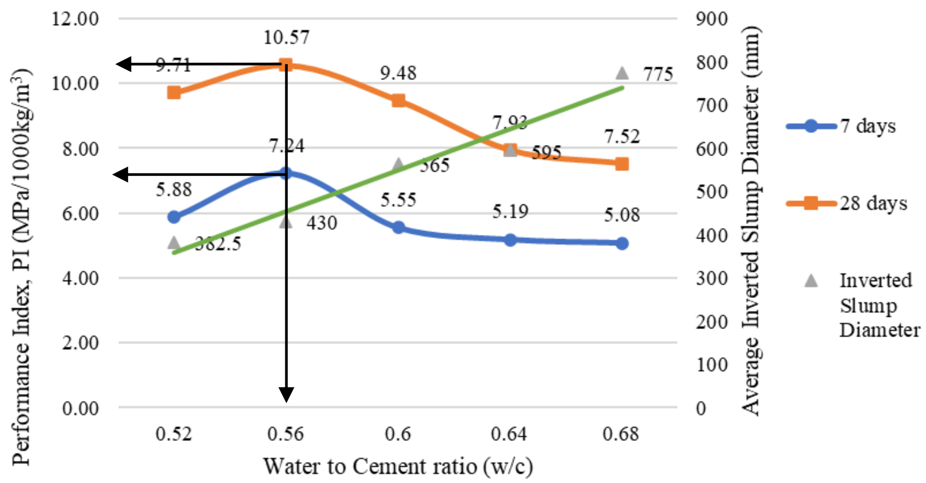


Figure 4.5: Performance Index of Trial Mix for LFC-30SF.

The performance index graph is important in determining the optimal W/C ratio of LFC-30SF with consideration of hardened density. The performance index (PI) is calculated using the compressive strength divided by the density over 1000 kg/m^3. The results of compressive strength test and performance index are summarised in Appendix A-3. From Figure 4.5, the highest performance index at 7 days and 28 days is 7.24 MPa per 1000 kg/m^3 and 10.57 MPa per 1000 kg/m^3, respectively. Hence, the optimal W/C ratio of LFC-30SF is 0.56.

4.5 Summary

In short, compressive strength test were carried out to determine the highest compressive strength from the six sets of trial mix. The result of trial mixes were analysed in terms of the performance index. However, the compressive strength and performance index for LFC-CTR and LFC-30SF showed the same trend of results at 7 and 28 days of curing. The highest compressive strength and performance index for LFC-CTR and LFC-30SF were observed at the W/C ratio of 0.56. Thus, the optimum W/C ratio for LFC-CTR and LFC-30SF were 0.56.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

This chapter discusses the engineering properties of lightweight foamed concrete (LFC-CTR) and lightweight foamed concrete with 30 kg/m^3 steel fiber (LFC-30SF). The optimal W/C ratio obtained from trial mix, is used in casting LFC-CTR and LFC-30SF. The effect of steel fiber on the fresh properties of LFC also discussed in this chapter. The curing ages required prior to the strength tests are 7, 28 and 56 days. The results of the strength tests included compressive strength test, splitting tensile strength test and flexural strength test were discussed in chapter five with each of the performance index respectively. Apart from that, the Scanning Electron Microscopic (SEM) with Energy-Dispersive X-Ray (EDX) are carried out and discussed in this chapter.

5.2 Mix Proportion

Table 5.1 shows the mix proportions of LFC-CTR and LFC-30SF.

Table 5.1: Mix Proportions of LFC-CTR and LFC-30SF.

Specimen	W/C	Material (kg/m^3)						Percentage (%)
		Cement	Sand	Water	Foam	SF	Silica Fume	
LFC-CTR	0.56	562.5	625	350	8.45	0	62.5	0.68
LFC-30SF	0.56	549	610	341.6	9.21	30	61	0.74

The mix proportions of both LFC-CTR and LFC-30SF were calculated by using absolute volume method. The cement to sand ratio was 1:1. The silica fume was the replacement of 10 % of the cement.

5.3 Fresh Properties

Table 5.2 shows the fresh properties of LFC-CTR and LFC-30SF. Fresh properties tests such as fresh density test, flow table test and inverted slump test were carried in this study.

Table 5.2: Fresh Properties of LFC-CTR and LFC-30SF.

Sample	Fresh Density (kg/m^3)	Flow Table Spread, (number of drop)	Average Inverted Slump Diameter (mm)	Consistency	Stability
LFC-CTR	1556.00	27	405.00	0.973	0.972
LFC-30SF	1566.07	23	436.75	0.979	0.968

The fresh density test is essential in maintaining density at 1600 ± 50 kg/m^3. From Table 5.2, the fresh density of LFC-CTR and LFC-30SF were maintained at the acceptable range. The LFC-CTR and LFC-30SF were cast near the acceptable density lower range because some unstable air bubbles will burst during the hardening process. The hardened density of the LFC will increase as the air bubbles burst. Based on the result obtained from the flow table test and inverted slump test, the flowability and workability of LFC-30SF were higher than LFC-CTR.

5.4 Compressive Strength

Figure 5.1 shows the graph of compressive strength of LFC-CTR and LFC-30SF at 7, 28 and 56 days curing ages.

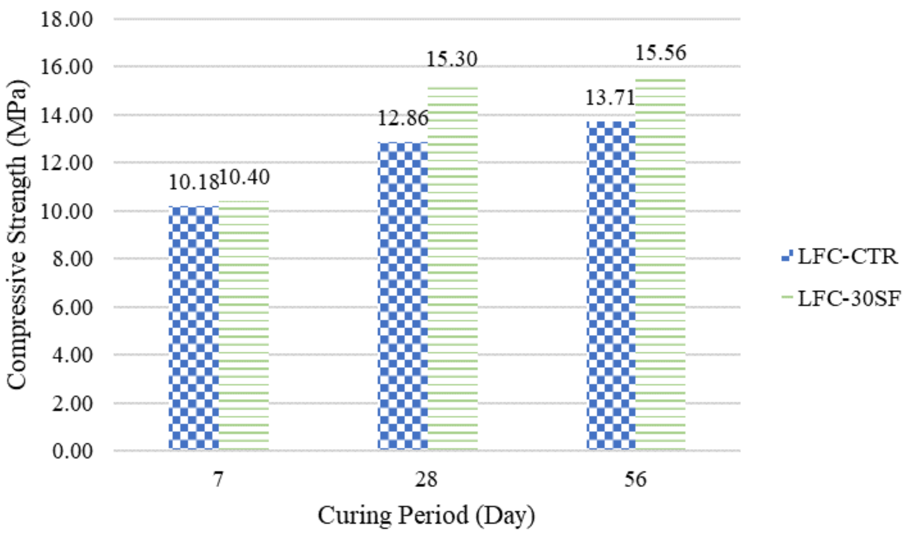


Figure 5.1: Compresive Strength of LFC-CTR and LFC-30SF at 7, 28 and 56 Days Curing Period.

From Figure 5.1, the overall compressive strength of both types of LFC increased from 7 to 56 days of curing. However, the changes in compressive strength from 28 days to 56 days was not significant. This is because the most of the strength gain will occur at the first 28 days of curing. At the first 28 days of curing, the hydration process of cementitious materials takes place. Calcium silicate hydrate (C-S-H) gel and calcium hydroxide (CH) are formed when cement particles react with water. The C-S-H gel contributed the most strength to the concrete. The hydration process will become slower after 28 days due to the depletion of the available water and unreacted cementitious material. As a result, strength gains were significant during the first 28 days but slower after that. The compressive strength of LFC-CTR were 10.18 MPa, 12.86 MPa and 13.71 MPa at 7, 28 and 56 days of curing, respectively. The compressive strength of LFC-30SF are 10.40 MPa, 15.30 MPa and 15.56 MPa at 7, 28 and 56 days of curing, respectively. From the results, the compressive strength of LFC-30SF at 7, 28 and 56 days of curing were higher than LFC-CTR.

The results had proven that steel fiber can enhance the compressive strength of LFC. The inclusion of steel fiber in the porous structure of LFC will act as reinforcement that able to holds the structure (Awang and Ahmad, 2012). Besides, the steel fiber inside the LFC can distribute the stress when the concrete is being loaded. Steel fiber also has the ability in bridging the cracks within the concrete matrix. The inclusion of steel fibers can significantly improved the compressive strength of LFC.

5.5 Splitting Tensile Strength

Figure 5.2 shows the splitting tensile strength of LFC-CTR and LFC-30SF at 7, 28 and 56 days of curing. The cylindrical LFC specimens with 100 mm diameter and 200 mm height are required to carry out the splitting tensile strength test. Prior to testing, the specimens at 7 days of curing were ovendried for 4 hours while 24 hours for 28 and 56 days of curing.

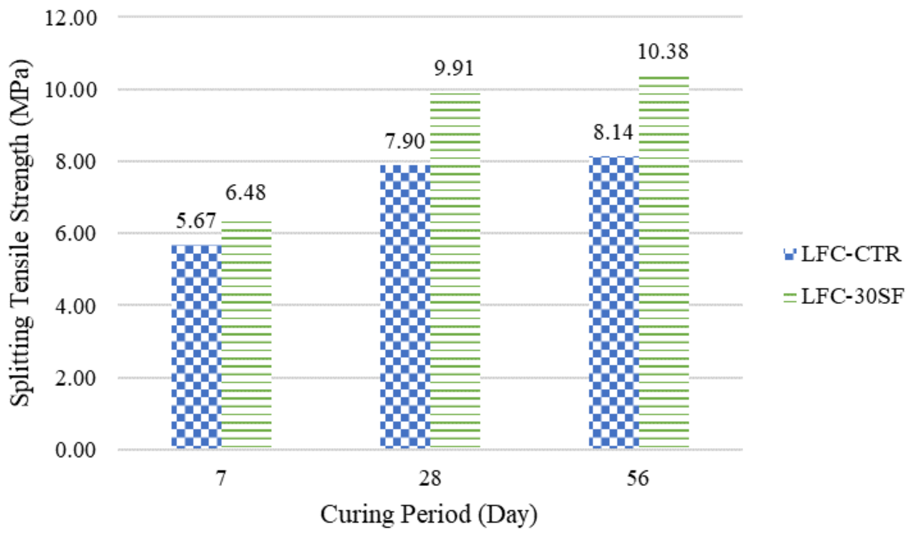


Figure 5.2: Splitting Tensile Strength of LFC-CTR and LFC-30SF at 7, 28 and 56 Days Curing Period.

The splitting tensile strength of LFC-CTR and LFC-30SF increased with the curing ages, as shown in Figure 5.2. The splitting tensile strength of LFC-CTR was 5.67 MPa at 7 days of curing and increased to 7.90 MPa at 28 days of curing. The splitting tensile strength of LFC-CTR developed slowly after 28 days, which was 8.14 MPa at 56 days. From 7 to 28 days of curing, the splitting tensile strength of LFC-CTR developed by 39.33 %, and from 28 to 56 days of curing, it increased by 3.04 %. This is due to the rate of strength development in concrete is higher at the first 28 days of curing. Similar to

LFC-30SF, the splitting tensile strength was 6.48 MPa, 9.91 MPa and 10.38 MPa at 7, 28 and 56 days of curing, respectively.

By comparing the results between LFC-CTR and LFC-30SF, the LFC-30SF had higher splitting tensile strength than LFC-CTR. This is because the steel fiber produced bridging effect which helped to distributed the loads and stress evenly to all part of concrete. As a result, less stress will concentrate at the crack area and the width of the cracks can be controlled. Moreover, the inclusion of steel fiber were distributed randomly throughout the concrete matrix. The orientation of steel fiber in concrete matrix was random, which allow the bridging effect more significant. The steel fiber helps in bridging cracks in all directions. Thus, the addition of steel fiber enhanced the resistance of the concrete to crack propagation and increases its splitting tensile strength.

5.6 Flexural Strength

Figure 5.3 shows the flexural strength of LFC-CTR and LFC-30SF at 7, 28 and 56 days of curing. The prism specimen with dimension 40 mm (width) × 40 mm (height) × 160 mm (length), is required in flexural strength test.

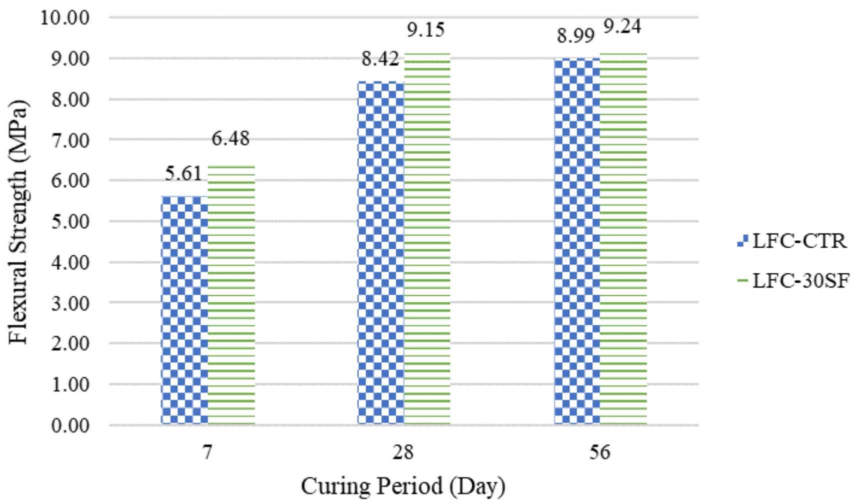


Figure 5.3: Flexural Strength of LFC-CTR and LFC-30SF at 7, 28 and 56 Days Curing Period.

Flexural strength is essential in construction to ensure that the concrete can resist the applied forces and stresses over time. The flexural strength is the ability to resist the bending or cracking when loading. From Figure 5.3, the flexural strength of LFC-CTR were 5.61 MPa, 8.42 MPa and 8.99 MPa at 7, 28 and 56 days of curing, respectively. For the LFC-30SF the flexural strength at 7, 28 and 56 days of curing were 6.48 MPa, 9.15 MPa and 9.24 MPa, respectively. The trend of the strength gain during the first 28 days of curing were almost similar compared to the compressive strength and splitting tensile strength. For LFC-CTR, the strength at 28 days has gain 50.1 percent from 7 to 28 days of curing. The LFC-30SF reached the highest flexural strength at 56 days of curing, which is 9.24 MPa. Meanwhile, the highest flexural strength of the LFC-CTR was slightly lower than LFC-30SF, which is 9.15 MPa.

The addition of steel fiber had little effect on the flexural strength of LFC. The overall flexural strength was only slightly increased. As discussed, the role of the steel fiber is to provide the bridging effect. Thus, the bridging effect on LFC-30SF was more significant based on the failure mode as shown in Figure 5.4. Figure 5.4 presents the difference in failure mode between LFC-CTR and LFC-30SF. The crack width of LFC-CTR was bigger than LFC-30SF because the steel fiber holds the LFC from separate apart.

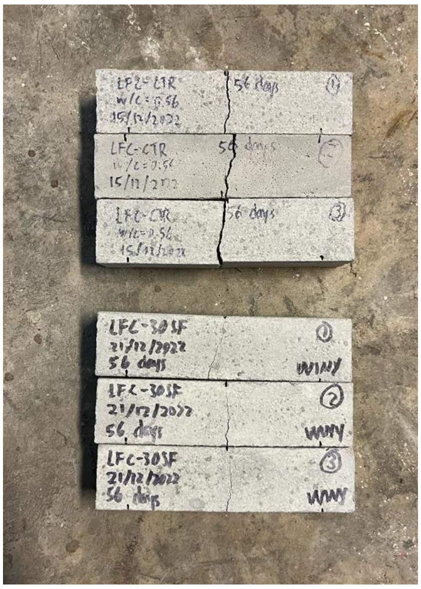


Figure 5.4: Failure Mode of LFC-CTR and LFC-30SF.

5.7 Performance Index

The performance index of concrete measures the quality and durability of concrete. The performance index can be used to evaluate the concrete's various properties, including strength, workability, durability and density. This study requires a performance index to analyse the strength performance of the LFC-CTR and LFC-30SF. Theoretically, the strength of concrete varies depending on its density. The higher the density, the greater the strength of concrete. However, the densities of all LFC samples are unable to maintain at exactly 1600 kg/m^3. Thus, the performance index in this study is the average strength of the LFC per 1000 kg/m^3. The result of performance index for compressive, splitting tensile and flexural are summarised in Appendix A-4, Appendix A-5 and Appendix A-6, respectively.

5.7.1 Performance Index for Compressive Strength

Figure 5.5 illustrates the result of average performance index of compressive strength for LFC-CTR and LFC-30SF at 7, 28 and 56 days of curing.

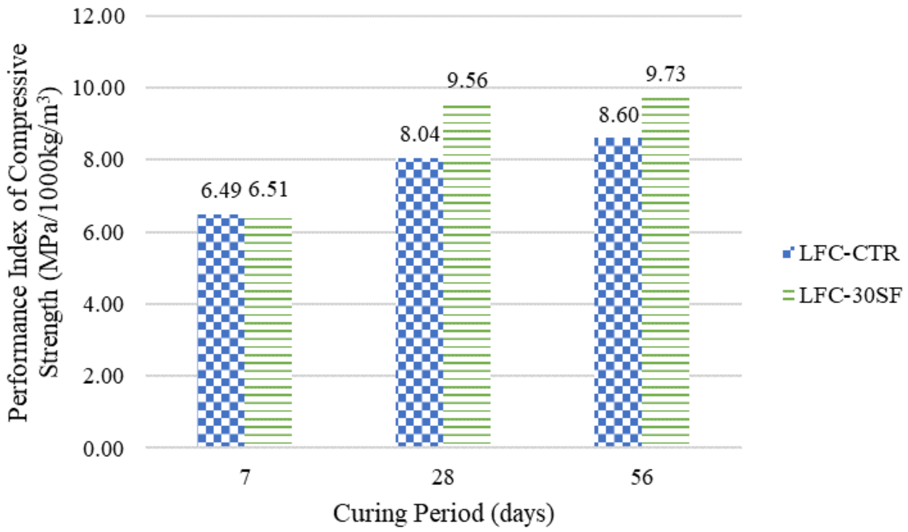


Figure 5.5: Average Performance Index of Compressive Strength of LFC-CTR and LFC-30SF at 7, 28 and 56 Days Curing Period.

From Figure 5.5, the performance index of LFC-30SF was higher than LFC-CTR. The highest performance index of LFC-30SF at 56 days of curing was 9.73 MPa per 1000 kg/m^3 while LFC-CTR only have 8.60 MPa per

1000 kg/m^3 at 56 days of curing. The trend of the strength gain by LFC-CTR and LFC-30SF were almost similar with the compressive strength graph. The compressive strength of LFC-CTR and LFC-30SF were gain 23.9 % and 46.9 %, respectively, from 7 to 28 days of curing. According to Table 5.3, the performance index of compressive strength of LFC-30SF was higher than LFC-CTR by 11.3 % at 56 days of curing. As both the LFC-CTR and LFC-30SF had high consistency and stability, the result in terms of performance index was not have much fluctuation compared to the result demonstrated in Figure 5.1.

Table 5.3: Effect of Steel Fiber on LFC in Terms of Compressive Strength.

Curing Period (Day)	**Specimen**	**Percentage of Strength of LFC-30SF Correspond to LFC-CTR (%)**
56	LFC-CTR	100.00
	LFC-30SF	113.14

5.7.2 Performance Index for Splitting Tensile Strength

Figure 5.6 demonstrates the result of splitting tensile strength of LFC-CTR and LFC-30SF at the 7, 28 and 56 days of curing in performance index form.

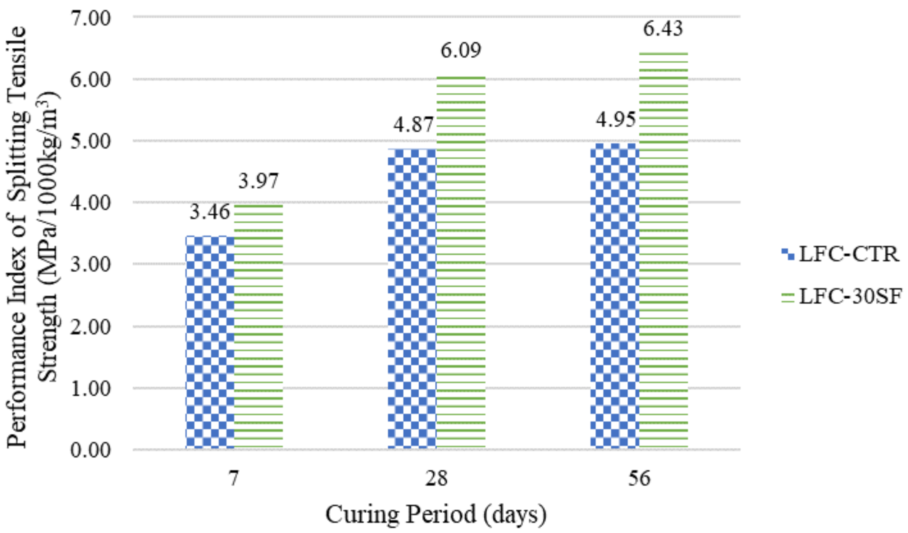


Figure 5.6: Average Performance Index of Splitting Tensile Strength of LFC-CTR and LFC-30SF at 7, 28 and 56 Days Curing Period.

According to Figure 5.6, the strength development in LFC-CTR and LFC-30SF increased tremendously in the first 28 days of curing. From 7 to 28 days of curing, the performance index for splitting tensile strength of LFC-CTR and LFC-30SF increased by 40.8 % and 53.4 %, respectively. However, the strength development of both LFC-CTR and LFC-30SF has been slowed down after 28 days of curing. Next, the performance index of both LFC-CTR and LFC-30SF was increased from 7 to 56 days of curing. According to Table 5.4, the performance index for splitting tensile strength of LFC-30SF was higher than LFC-CTR by 29.9 % at 56 days of curing. The highest performance index of LFC-30SF at 56 days of curing was 6.43 MPa per 1000 kg/m^3, while LFC-CTR only had 4.95 MPa per 1000 kg/m^3 at 56 days of curing.

Table 5.4: Effect of Steel Fiber on LFC in Terms of Splitting Tensile Strength.

Curing Period (Day)	**Specimen**	**Percentage of Strength of LFC-30SF Correspond to LFC-CTR (%)**
56	LFC-CTR	100.00
	LFC-30SF	129.90

5.7.3 Performance Index for Flexural Strength

Figure 5.7 illustrates the performance index of flexural strength of LFC-CTR and LFC-30SF at the curing age of 7, 28 and 56 days.

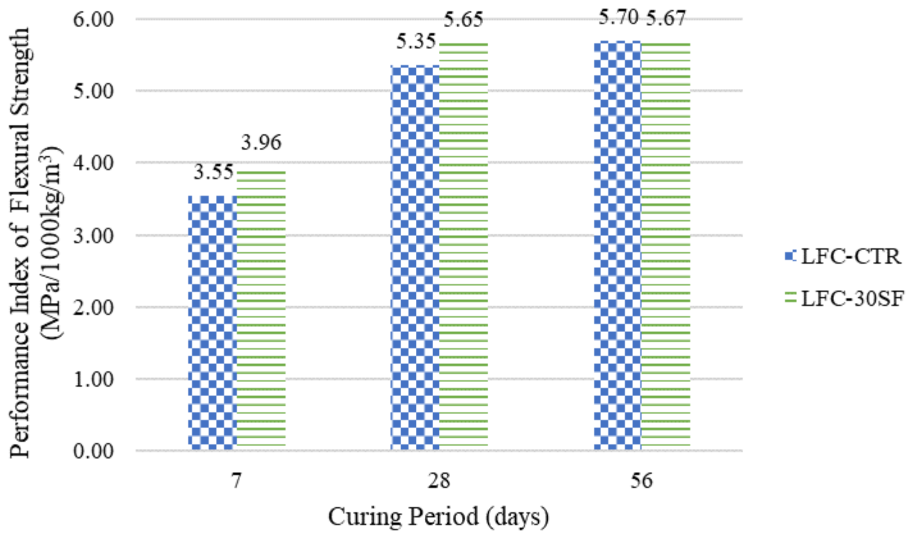


Figure 5.7: Average Performance Index of Flexural Strength of LFC-CTR and LFC-30SF at 7, 28 and 56 Days Curing Period.

From Figure 5.7, the trend of the flexural strength from 7 to 56 days curing age was almost similar with compressive strength and splitting tensile strength. However, the different in performance index of flexural strength between LFC-CTR and LFC-30SF was small. At 56 days of curing, the performance index of LFC-CTR was slightly higher than LFC-30SF. According to Table 5.5, the performance index for flexural strength of LFC-CTR was higher than LFC-30SF by 0.53 % at 56 days of curing.

Table 5.5: Effect of Steel Fiber on LFC in Terms of Flexural Strength.

Curing Period (Day)	Specimen	Percentage of Strength of LFC-30SF Correspond to LFC-CTR (%)
56	LFC-CTR	100.00
	LFC-30SF	99.47

5.8 Scanning Electron Microscopic (SEM) with Energy-Dispersive X-Ray (EDX) Analysis

A focused electron beam is utilized in the powerful imaging technique known as scanning electron microscopy (SEM) to capture high-resolution images of a sample's surface. For LFC, SEM can provide detailed information about the microstructure of the material, which can be important for understanding its properties and behavior. In this study, the specimens of LFC-CTR and LFC-30SF were prepared and analysed with SEM and EDX.

Figure 5.8 presents the SEM analysis result of LFC-CTR at 28 days of curing with magnification of 50×. Void structures were observed on the surface of LFC-CTR. The void structures were caused by the entrained air and foamed bubbles after hardening process. Besides, the size of the pores was non-uniform in the LFC-CTR mix. From the observation, the amount of pores smaller than 1.0 mm were more than the pores larger than 1.0 mm. The porous structure in LFC-CTR has proved that low strength development in LFC compared to ordinary concrete.

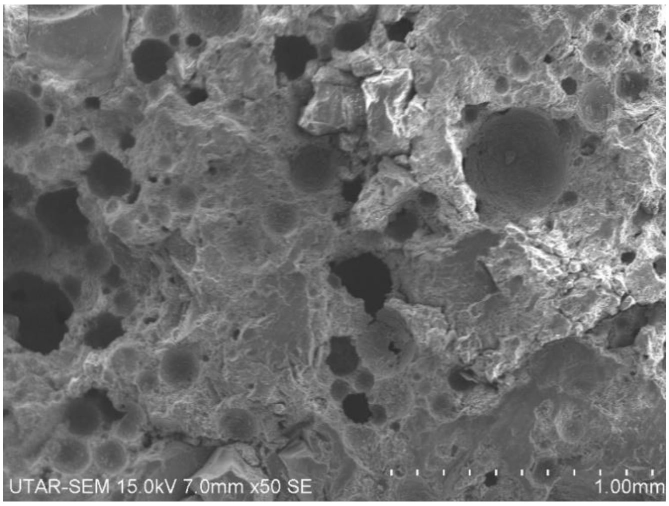
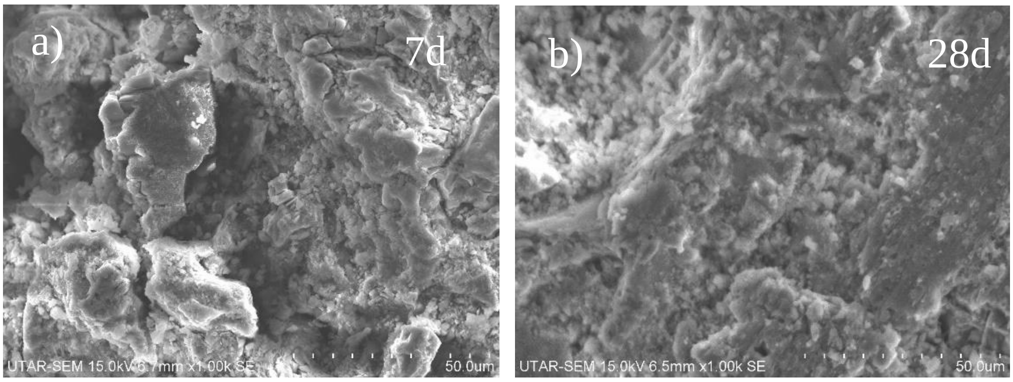


Figure 5.8: SEM Image of LFC-CTR at 28 Days of Curing.

Figure 5.9 presents the SEM analysis results of LFC-CTR at 7 and 28 days of curing with magnification of 1000×. From the observation on the microstructure of LFC-CTR at 7 days of curing, the formation of flower-like crystal has indicated the tendency to develop denser structures by the interweaving of nano-rod-like crystals. Therefore, a denser structure was observed in LFC-CTR at 28 days of curing. The needle rod-like crystals has developed to formed a compact and denser structure of concrete at 28 days of curing. A denser concrete structure that observed at 28 days of curing typically will have higher strength compared to 7 days of curing.



a) b)

Figure 5.9: SEM Images of LFC-CTR at Different Curing Age: a) 7 days; b) 28 days.

Figure 5.10 presents the SEM image of LFC-30SF at 7 days of curing. From the observation, the reinforced steel fiber had good bonding with cement composites. The good bonding between steel fiber and cement composites will result in better compression and tensile strength. Besides, a microcracks was observed in Figure 5.10.

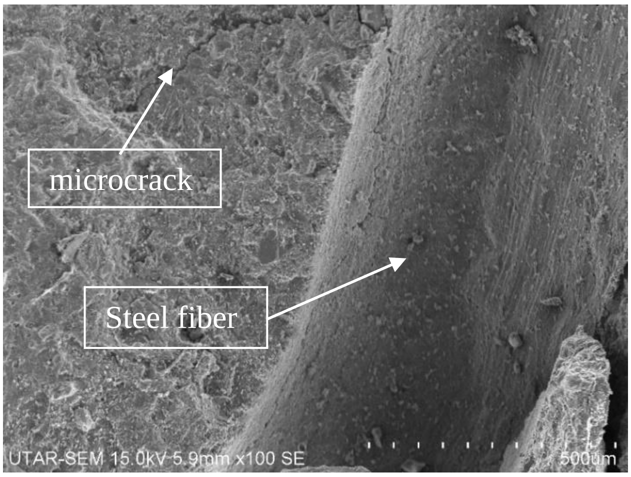


Figure 5.10: SEM Image of LFC-30SF at 7 Days of Curing.

The Energy-Dispersive X-Ray (EDX) analysis was carried out after the SEM analysis. There are eight elements required to be observed from the concrete sample, which are carbon (C), oxygen (O), magnesium (Mg), aluminium (Al), silicon (Si), sulphur (S), calcium (Ca) and iron (Fe). Table 5.6 shows the results of EDX with the element composition percentage content in the LFC-30SF at 28 days of curing. Figure 5.11 demonstrates the EDX spectrum analysis result.

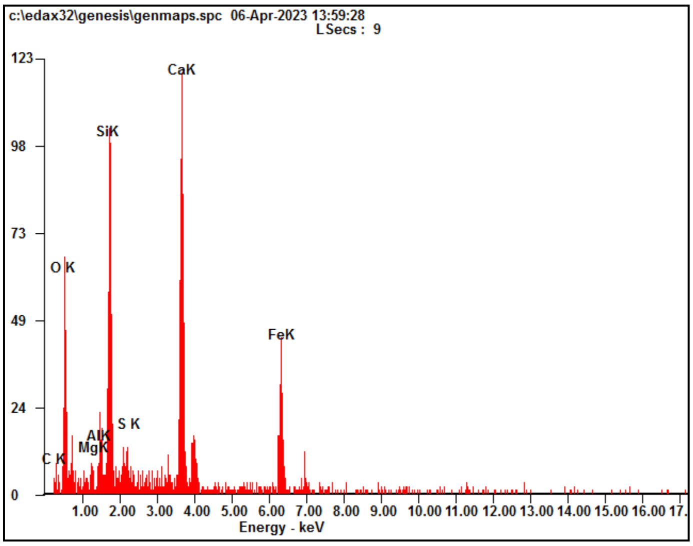


Figure 5.11: EDX Spectrum.

Table 5.6: EDX Analysis Result for LFC-30SF at 28 Days of Curing.

Element	Wt (%)	At (%)
C	3.61	7.83
O	28.03	45.63
Mg	00.72	0.77
Al	3.47	3.35
Si	16.10	14.93
S	1.17	0.95
Ca	25.48	16.56
Fe	21.42	9.99
Matrix	Correction	ZAF

The EDX result proved the presence of steel fiber in the LFC-30SF mix. There was 21.42 % iron detected on the surface of LFC-30SF. The highest element composition in the LFC-30SF mix is oxygen, which covered 28.03 % of the mix. The oxygen, silicon and calcium content were high in the LFC- 30SF mix. Besides, the high silicon content was mainly due to the inclusion of silica fume in the concrete mix to enhance the strength and workability of the concrete.

The EDX analysis was also carried out for the LFC-CTR at 7 and 28 days. Table 5.7 shows the analysis result of the composition element in both samples.

Table 5.7: EDX Analysis Result For LFC-CTR at 7 and 28 Days of Curing.

Element	**Wt (%)**		**At (%)**	
	7 days	**28 days**	**7 days**	**28 days**
C	4.12	3.36	7.54	6.36
O	41.36	37.94	56.86	53.92
Mg	0.77	1.24	0.70	1.16
Al	3.87	4.95	3.16	4.17
Si	17.93	18.26	14.04	14.78
S	1.29	1.22	0.89	0.86
Ca	30.66	33.04	16.82	18.74
Matrix	Correction		ZAF	

From the Table 5.7, the calcium content in LFC-CTR at 28 days of curing is higher than 7 days. This is because the formation of calcium silicate hydrate (C-S-H) during the hydration process at 28 days of curing is more than 7 days. Therefore, the calcium content will be higher as the curing ages increase. On top of that, the calcium content in concrete has further explained the relationship between the curing ages and the strength development in concrete. As the role of C-S-H contributes to the strength development, the more the calcium content, the higher the strength of the concrete.

5.9 Summary

The addition of steel fiber has greatly influenced the engineering properties of LFC. However, the effect of steel fiber is insignificant on the fresh properties of the steel fiber reinforced concrete. To further explain the trend of strength gain and the bonding of steel fiber in LFC, the SEM-EDX analysis was carried out.

The compressive strength of the LFC-CTR at 56 days of curing was 13.71 MPa with a performance index of 8.60. However, the compressive strength of LFC-30SF at 56 days was higher than the LFC-CTR, which was 15.56 MPa with a performance index of 9.73. This is because steel fiber in the porous structure of LFC will act as reinforcement that can hold the structure.

Apart from that, the LFC-30SF had a higher splitting tensile strength than the LFC-CTR at all curing ages. At 56 days of curing, the splitting tensile strength of LFC-30SF was 10.38 MPa, while 8.14 MPa for the LFC-CTR. For flexural strength, the LFC-30SF has slightly higher flexural strength than LFC-CTR. The flexural strength of LFC-30 SF at 56 days of curing was 9.24 MPa, while 8.99 MPa for LFC-CTR. Although the comparison of the reading result between both samples was insignificant, the failure mode has shown the effect of the steel fiber in the LFC.

Through the SEM-EDX analysis, the microstructure of LFC has been analysed. The porous structure in LFC has been observed. The difference in microstructure of LFC at 7 and 28 days of curing was also discussed. As the curing ages increase, the formation of denser concrete structures has resulted in rigid and strong concrete structures. Hence, the strength of concrete grows with the curing ages. Besides, the bonding of steel fiber with LFC has been proven. The steel fiber is bonded tightly with the LFC, which results in high compressive strength compared to the control mix. With EDX analysis, the presence of steel fiber has been proven with the 21.49 % iron content in LFC-30SF. Apart from that, the percentage of calcium elements higher in 28 days compared to 7 days was mainly due to the formation of calcium silicate hydrate during the hydration process.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

As LFC has low mechanical strength, this study investigates the effect of the inclusion of 30 kg/m^3 of steel fiber in LFC. The aim and objectives of this study were met after fresh and hardened properties testing had been carried out.

Lightweight foamed concrete (LFC-CTR) and lightweight foamed concrete incorporated with 30 kg/m^3 steel fiber (LFC-30SF) were produced at 1600 ± 50 kg/m^3 of fresh and hardened density. At the same time, the optimal W/C ratio for LFC-CTR and LFC-30SF were determined through the trial mixes. The trial mixes for both LFC-CTR and LFC-30SF were prepared with W/C ratios ranging from 0.52 to 0.68 with an incremental interval of 0.04. The optimal W/C ratio for both the LFC-CTR and LFC-30SF are the same, which is 0.56. Thus, the first objective in this study was achieved.

The second objective was achieved as the engineering properties of LFC-CTR and LFC-30SF were studied. These engineering properties namely compressive strength, splitting tensile strength and flexural strength. From the result obtained, LFC-30SF has higher compressive strength than LFC-CTR. Next, LFC-30SF has higher splitting tensile strength than LFC-CTR. According to the results obtained in flexural strength test, the flexural strength of LFC-30SF is slightly higher than LFC-CTR. In short, the engineering properties of LFC-CTR can be improved by adding the steel fiber. Thus, the second objective in this study was achieved.

The influence of 30 kg/m^3 steel fiber reinforcement on the fresh properties of LFC was studied. The fresh properties tests namely flow table test, inverted slump test and fresh density test. The flowability of LFC were enhanced after adding the steel fiber. However, the stability of LFC reduced after adding the steel fiber. Therefore, the third objective in this study was achieved.

In short, incorporating steel fiber can improve the strength properties of LFC, which can increase the application of LFC in the construction industry.

6.2 Recommendations for Future Work

The properties of LFC can be enhanced by adding steel fiber into cement mortar. However, some aspects of this study need to improve to facilitate future research. There are some recommendations and suggestions to be considered for future work. First, a low density of the steel fiber can be considered because the steel fiber is denser than the cement mortar, which will cause the steel fiber to settle at the bottom during the hardening process. Next, the steel fiber can be added into the cement mortar gradually instead of in one lump sum to avoid the balling effect. Besides, the incremental interval of W/C ratio in trial mixes can reduce to 0.02 to obtain the more optimal result. Apart from that, non-destructive tests can be carried out instead of destructive tests in identifying the properties of LFC-CTR and LFC-30SF. The non-destructive test results can be compared with the destructive test result, improving the accuracy of the result obtained.

REFERENCES

Aginam, C. H., Chidolue, C. A. and Nwakire, C., 2013. Investigating the Effects of Coarse Aggregate Types on The Compressive Strength Of Concrete. *International Journal of Engineering Research and Applications (IJERA),* 3(4), pp.1140-1144.

Alonge., O. R. and Ramli, M., 2013. Experimental production of sustainable lightweight foamed concrete. *British Journal of Applied Science & Technology*, [e-journal] 3(4), pp.994. https://doi.org/10.9734/BJAST/2013/4242.

Amran, M. et al., 2020. Fibre-Reinforced Foamed Concretes: A Review. *Materials (Basel),* [e-journal] 13(19). https://doi.org/10.3390/ma13194323.

Amran, Y. M., Farzadnia, N. and Ali, A. A., 2015. Properties and applications of foamed concrete; a review. *Construction and Building Materials,* [e-journal] 101, pp.990-1005. https://doi.org/10.1016/j.conbuildmat.2015.10.112.

ASTM, 2019. *Standard Practice for Making and Curing Concrete Test Specimens in the Field.* West Conshohocken: ASTM International.

Awang, H. and Ahmad, M. H., 2012. The effect of steel fibre inclusion on the mechanical properties and durability of lightweight foam concrete. *Advanced Engineering Informatics,* 48, pp.9348-9351.

Bagala, R., Fraser, L. and May, R., 2018. *Exploring the Properties of Fiber Reinforced Concrete,* Worcester: WPI.

Batool, F., Rafi, M. M. and Bindiganavile, V., 2018. Microstructure and thermal conductivity of cement-based foam:A review. *Journal of Building Engineering*, 20, pp.696-704.

Behbahani, H., Nematollahi, B. and Farasatpour, M., 2013. *Steel fiber reinforced concrete : A Review.* Kandy, University of Moratuwa.

Behbahani, H. P., 2011. *Flexural Behavior of Steel Fiber Reinforced Concrete,* Selangor: Universiti Technologi Malaysia. https://doi.org/10.1061/(ASCE)0899-1561(1998)10:2(86).

Behera, G. C., Panda, S. and Kanda, P., 2020. Effect of Length of Fibers on Mechanical Properties of Normal Strength Concrete. *Materials Science and Engineering,* [e-journal] 970(1-8). https://doi.org/10.1088/1757-899X/970/1/012020.

Brady, K. C., Watts, G. R. A. and Jones, M. R., 2001. *Specification for foamed concrete,* Berkshire: TRL Limited.

Chahal, N. and Siddique, R., 2011. Use of silicon and ferrosilicon industry by-products (silica fume) in cement paste and mortar. *Resources Conservation and Recycling,* [e-journal] 55(8), pp.739-744. https://doi.org/10.1016/j.resconrec.2011.03.004.

Chaipanich, A. and Chindaprasirt, P., 2015. *The properties and durability of autoclaved aerated concrete masonry blocks.* 1 ed. Swaston: Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-305-8.00009-7.

Chanh, N. V., 2015. Steel Fiber Reinforced Concrete, Ho Chi Minh: Ho Chi Minh City University of Technology.

Elrahman, M. A., Sikora, P., Stephan, D. and Chung, S.-Y., 2021. The performance of ultra-lightweight foamed concrete incorporating nanosilica. *Archives of Civil and Mechanical Engineering*, 29 April. https://doi.org/10.1007/s43452-021-00234-2.

Farzadnia, N. and Amran, M., 2015. Properties and applications of foamed concrete; a review. *Construction and Building Materials,* [e-journal] 101, pp. 990-1005. https://doi.org/10.1016/j.conbuildmat.2015.10.112.

Harrisson, A. M., 2017. Constitution and Specification of Portland Cement. *Lea 's Chemistry of Cement and Concrete (Fifth Edition)*, pp.87-155.

Hashim, M. and Tantray, M., 2021. Comparative study on the performance of protein and synthetic-based foaming agents used in foamed concrete. *Case Studies in Construction Materials,* [e-journal] 14, p.1. https://doi.org/10.1016/j.cscm.2021.e00524.

Hedjazi, S., 2019. *Compressive Strength of Lightweight Concrete.* London: IntechOpen. https://doi.org/10.5772/intechopen.88057.

Ibrahim, N. et al., 2016. *Study on Characteristics of Lightweight Aggregate Concrete Made From Foam and Ordinary Portland Cement.* s.l., EDP Sciences. https://doi.org/10.1051/matecconf/20167801105.

Iffat, S., 2015. Relation Between Density and Compressive Strength of Hardened Concrete. *Concrete Research Letter*, 6(4), pp.182-189.

Katpady, D. N. et al., 2018. Durability Assessment of Blended Concrete by Air Permeability. *International Journal of Concrete Structures and Materials*, [e-journal] 12(30). https://doi.org/10.1186/s40069-018-0260-9.

Khan, S. U., Nuruddin, M. F., Ayub, T. and Shafiq, N., 2014. Effects of Different Mineral Admixtures on the Properties of Fresh Concrete. *The Scientific World Journal*, [e-journal] 4. https://doi.org/10.1155/2014/986567.

Kumar, N., C. and Senthil, S., 2018. Experimental Study on Mechanical and Thermal Behavior of Foamed Concrete. *Materials Today: Proceedings*, [e-journal] 5(2), pp.8753-8760. https://doi.org/10.1016/j.matpr.2017.12.302.

Kurpińska, M. and Ferenc, T., 2017. *Effect of porosity on physical properties of lightweight*, Gdańsk: Gdansk University of Technology. https://doi.org/10.1051/itmconf/20171506005.

Larsen, I. L. and Thorstensen, R. T., 2020. Construction and Building Materials. *Construction and Building Materials,* [e-journal] 256. https://doi.org/10.1016/j.conbuildmat.2020.119459.

Lee, J., Lian, F., Hejazi, F. and Mohd Nasir, N., 2019. Study of properties and strength of no-fines concrete. *IOP Conference Series: Earth and Environmental Science*, [e-journal] 357, p.2. https://doi.org/10.1088/1755-1315/357/1/012009.

Liew, R. J. Y., Xiong, M. X. and Lai, B., 2021. Special considerations for high strength materials. In: R. J. Y. Liew, M. X. Xiong and B. Lai, eds. *Design of Steel-Concrete Composite Structures Using High-Strength Materials*. s.l.:Woodhead Publishing, pp.125-142. https://doi.org/10.1016/B978-0-12-823396-2.00011-3

Lim, S. K. et al., 2021. Acoustic Properties of Lightweight Foamed Concrete with Eggshell Waste as Partial Cement Replacement Material. *Sains Malaysiana*, [e-journal] 50(2), pp.537-547. https://doi.org/10.17576/jsm-2021-5002-24.

Lim, S. K., Tan, C. S., Lim, O. Y. and Lee, Y. L., 2013. Fresh and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler. *Construction and Building Material*, [e-journal] 46, pp.39-47. https://doi.org/10.1016/j.conbuildmat.2013.04.015.

Li, Z., 2011. Fresh Concrete. In: J. Newman and B. S. Choo, eds. *Advanced Concrete Technology*. Hoboken: John Wiley & Sons, pp.109-110.

Maguesvari, M. U. and Narasimha, V. L., 2013. Studies on Characterization of Pervious Concrete for Pavement Applications. Procedia - Social and Behavioral Sciences, [e-journal] 104, pp.198-207. https://doi.org/10.1016/j.sbspro.2013.11.112.

Meena, R., Sharma, S., Sharma, A. and Kumar, M., 2020. Study on Lightweight Concrete- Review. *International Journal of Engineering Research & Technology (IJERT),* [e-journal] 9(9), pp.786-787. https://doi.org/10.17577/IJERTV9IS070348.

Mo, K. H., Alengaram, U. and Jumaat, Z., 2014. Utilization of ground granulated blast furnace slag as partial cement replacement in lightweight oil palm shell concrete. *Materials and Structures,* 14 May, p.3. https://doi.org/10.1617/s11527-014-0336-1.

Mustaffa, W., Mekhilef, S., Saidur, R. and Safari. A., 2011. Biomass Energy in Malaysia: Current State and Prospects. *Renewable and Sustainable Energy Review,* [e-journal] 15(7), pp.3360-3370. https://doi.org/10.1016/j.rser.2011.04.016.

Mwango, A. and Kambole, C., 2019. Engineering Characteristics and Potential Increased Utilisation of Sawdust Composites in Construction—A Review. *Journal of Building Construction and Planning Research,* [e-journal] 7(3), pp. 59-88. https://doi.org/10.4236/jbcpr.2019.73005.

Mydin, M. O., Sahidun, N., Yusof, M. M. and Noordin, N. M., 2015. Compressive, Felxural and Splitting Tensile Strengths of Light Weight Foam Concrete With Inclusion of Steel Fiber. *Jurnal Teknologi*, [e-journal] 75(5), pp. 45-50. https://doi.org/10.11113/jt.v75.4962.

Othman, R. et al., 2021. Relation between Density and Compressive Strength of. *Materials,* [e-journal] 14(11), pp.1-22. https://doi.org/10.3390/ma14112967

Paknehad, S. et al., 2022. *Investigation the Properties of Foam Concrete: A review.* Birjand, s.n.

Panesar, D. K., 2019. Supplementary cementing materials. In: S. Mindess, ed. *Developments in the Formulation and Reinforcement of Concrete (Second Edition).* Canada: Elsevier Ltd., [e-journal] pp.409-423. https://doi.org/10.1016/B978-0-08-102616-8.00003-4

Patnaikuni, C. K., N.V.S.Venugopal and Y.S.Prabhakar, 2018. Studies on the Assessment of Cement Parameters of Different Brands of Cements. *International Journal of Civil Engineering and Technology,* [e-journal] 9(6), pp.807-812.

Pollard, R., 2022. *Characteristics, Construction and Design of the Hagia Sophia Dome.* [online] Available at: <https://study.com/learn/lesson/hagia-sophia-dome-characteristics-design.html>[Accessed 22 August 2022].

Pradhan, D. and Dutta, D., 2013. Influence of Silica Fume on Normal Concrete. *Journal of Engineering Research and Applications,* [e-journal] 3(5), pp.79-82.

Ragavendra, Reddy, I. and Dongre, A., 2017. *Fibre Reinforced Concrete- A Case Study.* Hydreabad, s.n.

Raj, A., Sathyan, D. and K.M. Mini, 2019. Physical and functional characteristics of foam concrete: A review. *Construction and Building Materials,* [e-journal] 221, pp.787-799. https://doi.org/10.1016/j.conbuildmat.2019.06.052.

Ramadhansyah, P. J., Mohd Ibrahim, M. Y., Hainin, M. R. and Ibrahim, M. H., 2014. A Review of Porous Concrete Pavement: Applications and Engineering Properties. *Applied Mechanics and Materials.,* [e-journal] 554, pp.37-41. https://doi.org/10.4028/www.scientific.net/AMM.554.37.

Ramamurthy, K., Nambiar, E. K. and Ranjani, G. I. S., 2009. A classification of studies on properties of foam concrete,. *Cement and Concrete Composites,* [e-journal] 31(6), pp.388-396. https://doi.org/10.1016/j.cemconcomp.2009.04.006.

Rao, A. S. and Rao, G. A., 2014. Fracture Mechanics of Fiber Reinforced Concrete: An. *International Journal of Engineering Innovation & Research,* 3(4), pp.517-524.

Rasol, M. A., 2015. Effect of Silica Fume on Concrete Properties and Advantages for Kurdistan Region, Iraq. *International Journal of Scientific & Engineering Research,* 6(1), pp.170-173.

Reiterman, P., Holčapek, O., Zobal, O. and Keppert, M., 2019. Freeze-Thaw Resistance of Cement Screed with Various Supplementary Cementitious Materials. *Reviews On Advanced Materials Sceince,* [e-journal] 58(1), pp.66-74. https://doi.org/10.1515/rams-2019-0006.

Sahu, J., Abnisa, F., Daud, W. and Husin, W., 2011. Utilization Possibilities of Palm Shell as aSource of Biomass Energy in Malaysia by Producing Bio-oil in Pyrolysis Process. *Biomass and Bioenergy,* [e-journal] 35(5), pp.1863-1872. https://doi.org/10.1016/j.biombioe.2011.01.033.

Shafigh, P., Jumaat, M. Z. and Mahmud, H., 2010. Mix design and mechanical properties of oil palm shell lightweight aggregate concrete: A review. *International Journal of the Physical Sciences,* [e-journal] 5(14), pp.2127-2134. https://doi.org/10.5897/IJPS.9000373.

Shah, S. N. et al., 2021. Lightweight foamed concrete as a promising avenue for incorporating waste materials: A review. *Resources, Conservation and Recycling,* [e-journal] 164, pp.1-13. https://doi.org/10.1016/j.resconrec.2020.105103.

Singh, N., 2020. Properties of cement and concrete in presence of nanomaterials. In: *Smart Nanoconcretes and Cement-Based Materials.* s.l.:Elsevier Inc, [e-journal] pp.9-39. https://doi.org/10.1016/B978-0-12-817854-6.00002-7.

Srivastava, V., Kumar, R., Agarwal, V. C. and Mehta, P. K., 2015. Effect of Silica Fume on Workability and Compressive Strength ofOPC Concrete. *J. Environ. Nanotechnol,* [e-journal] 3(3), pp.32-35. https://doi.org/10.13074/jent.2014.09.143086.

Swati, S., 2020. *Foam Concrete: Manufacturing, Advantages and Disadvantages.* [online] Available at: <https://civilwale.com/foam-concrete/> [Accessed 1 August 2022].

Tabassum, N., Biswas, P., Islam, M. S. and Islam, M. M., 2018. A Study on the Compressive and Flexural Strength Behavior of Steel Fiber Reinforced Concrete Beam. *International Journal of Advanced Research* , [e-journal] 6(8), pp. 557-567. http://dx.doi.org/10.21474/IJAR01/7552.

Thienel, K. C., Haller, T. and Beuntner, N., 2020. Lightweight Concrete—From Basics to Innovations. *Materials (Basel),* [e-journal] 13(5). https://doi.org/10.3390/ma13051120.

Tiong, H. Y., Lim, S. K. and Lim, J. H., 2017. *Strength Properties of Foamed Concrete Containing Creushed Steel Slag as Partial Replacement of Sand with Specific Gradation.* Selangor, MATEC Web of Conferences. https://doi.org/10.1051/matecconf/201710301012.

Ushane, K. S., Kumar, K. J. P. and Kavitha, C., 2014. Investigation of No-Fines Concrete in Building Blocks. *International Journal of Structural and Civil Engineering Research,* 3(4), pp.170-177.

Velayutham, G. and Cheah, C. B., 2014. *The Effects of Steel Fibre on the Mechanical Strength and Durability of Steel Fibre Reinforced High Strength Concrete (SFRHSC) Subjected to Normal and Hygrothermal Curing.* Penang, EDP Sciences. https://doi.org/10.1051/matecconf/20141002004.

Wong, S. et al., 2019. *Compressive strength prediction of lightweight.* Palembang, IOP Publishing Ltd.. https://doi.org/10.1088/1757-899X/620/1/012043.

Yao, W., Li, J. and Wu, K., 2003. Fiber Reinforced Concrete at Low Fiber Volume Fraction. *Cement and Concrete Research,* 33(1), pp.27-30. https://doi.org/10.1016/S0008-8846(02)00913-4.

YTL Cement, 2022. *Cement-Bag.* [online] Available at: <https://ytlcement.my/cement-bag/> [Accessed 2 September 2022].

Yuan, Q., Liu, Z., Zheng, K. and Ma, C., 2021. *Portland cement concrete.* Amsterdam: Elsevier Ltd.

Zhang, H., 2011. Concrete. In: H. Zhang, ed. *Building Materials in Civil Engineering.* Sawston: Woodhead Publishing, pp.81-149.

APPENDICES

Appendix A

Appendix A-1: Sieve Analysis for Fine Aggregate.

Sieve Size (mm)	Retained Weight (g)	Retained Weight (%)	C. Percentage Retained (%)	Percentage of Passing (%)
0.600	198.6	39.77	39.77	60.23
0.300	126.2	25.27	65.04	34.96
0.150	117.0	23.43	88.47	11.53
0.063	37.8	7.57	96.04	3.96
Pan	19.8	3.96	100.00	0
Total	499.4			

where
C. Percentage Retained = Cumulative percentage retained

Appendix B-2: Compressive Strength and Performance Index of Trial Mix for LFC-CTR.

W/C	Compressive Strength (MPa)		Performance Index (MPa/1000 kg/m^3)	
	7 days	28 days	7 days	28 days
0.52	9.68	14.84	6.15	9.28
0.56	11.82	18.09	7.28	11.14
0.60	11.00	16.40	6.69	10.05
0.64	10.09	14.60	6.24	9.01
0.68	9.92	14.34	6.08	8.75

Appendix C-3: Compressive Strength and Performance Index of Trial Mix for LFC-30SF.

W/C	Compressive Strength (MPa)		Performance Index (MPa/1000 kg/m^3)	
	7 days	28 days	7 days	28 days
0.52	9.39	15.59	5.88	9.71
0.56	9.84	16.19	6.02	9.95
0.60	9.09	15.54	5.55	9.48
0.64	8.50	12.92	5.19	7.93
0.68	8.20	12.18	5.08	7.52

Appendix D-4: Compressive Strength and Performance Index of LFC-CTR and LFC-30SF.

Curing Ages (days)	LFC-CTR		LFC-30SF	
	Compressive Strength (MPa)	Performance Index (MPa/1000 kg/m^3)	Compressive Strength (MPa)	Performance Index (MPa/1000 kg/m^3)
7	10.18	6.49	10.33	6.47
28	12.86	8.04	15.30	9.56
56	13.71	8.60	15.56	9.73

Appendix E-5: Splitting Tensile Strength and Performance Index of LFC-CTR and LFC-30SF.

Curing Ages (days)	LFC-CTR		LFC-30SF	
	Splitting Tensile Strength (MPa)	Performance Index (MPa/1000 kg/m^3)	Splitting Tensile Strength (MPa)	Performance Index (MPa/1000 kg/m^3)
7	5.67	3.46	6.48	3.97
28	7.90	4.87	9.91	6.09
56	8.14	4.95	10.38	6.43

Appendix F-6: Flexural Strength and Performance Index of LFC-CTR and LFC-30SF.

Specimens	LFC-CTR		LFC-30SF	
	Flexural Strength (MPa)	**Performance Index (MPa/1000 kg/m^3)**	**Flexural Strength (MPa)**	**Performance Index (MPa/1000 kg/m^3)**
7	5.61	3.55	6.48	3.96
28	8.42	5.35	9.15	5.65
56	8.99	5.70	9.24	5.67