COMPRESSIVE STRENGTH OF LIGHTWEIGHT FOAMED CONCRETE WITH KENAF FIBRE OF DIFFERENT TREATMENT PERIOD

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

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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.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"COMPRESSIVE STRENGTH OF LIGHTWEIGHT FOAMED CONCRETE WITH KENAF FIBRE OF DIFFERENT TREATMENT PERIOD"** was prepared by **CHAN JUN MING** 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.

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ABSTRACT

As global concern for sustainability grows, the importance of sustainable practices in the construction industry has become increasingly significant. The construction sector, a major contributor to environmental impact, is increasingly focusing on adopting sustainable materials and methods. Among these efforts, enhancing the mechanical properties of concrete has emerged as a key area of research. Continuous advancements and discoveries aim to improve concrete's strength, durability, and overall efficiency, in line with the broader sustainability goals of the construction industry. Kenaf fibre (KF), derived from Hibiscus cannabinus L., is a byproduct of the textile industry. Incorporating KF into lightweight foamed concrete (LFC) not only addresses the waste and disposal issues associated with the textile industry but also enhances the concrete's strength properties. This study investigates the strength properties of lightweight foamed concrete incorporated with untreated kenaf fibre (UKF) and kenaf fibre treated with 1.5 M sodium hydroxide (NaOH) for 6, 9, and 12 hours (TKF 6HR, TKF 9HR, TKF 12HR). Compressive strength, splitting tensile, and flexural strength tests conducted to assess the strength of lightweight foamed concrete (LFC). Additionally, scanning electron microscopy (SEM) analysis was performed to examine the microstructure of LFC incorporated with KF. The findings reveal that while there is a 23.98% reduction in workability, the TKF 12HR results in increases of 19.46%, 24.93%, 38.33%, and 33.98% in 28 days compressive strength, residual compressive strength, splitting tensile strength, and flexural strength, respectively, compared to the control sample. Furthermore, SEM analysis shows that the treated fibre leads to better bonding between the fibre and the cement matrix. In summary, KF is a sustainable material that can effectively enhance the strength properties of LFC.

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LIST OF SYMBOLS / ABBREVIATIONS

f	compressive strength, MPa
P	maximum load applied, N
A	area, m^2
T	splitting tensile strength, MPa
L	length of specimen, mm
D	diameter of specimen, mm
b	width of specimen, mm
d	depth of specimen, mm
v	specific volume, m^3

π	ratio of a circle's circumference to its diameter
ρ	density, kg/m^3
ω	compressible flow parameter

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
FRC	Fibre Reinforced Concrete
LFC-CTR	Lightweight foamed concrete control
LFC-UF	Lightweight foamed concrete with untreated kenaf fibre
LFC-TF	Lightweight foamed concrete with treated kenaf fibre
NaOH	Sodium Hydroxide

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Malaysia construction industry achieved a market size of $27.7 billion in 2022. It is expected to have an AAGR (Average Annual Growth Rate) of more than 5% during 2024 – 2027 (Malaysia construction market size, trend analysis by sector, competitive landscape and forecast to 2027, 2023). However, the booming construction industry comes at a massive cost to the environment. Concrete, a construction material extensively utilized is one of the main culprits causing environmental pollution during its raw material production stage. Cement, an inevitable component of the concrete has been reported to produce carbon dioxide with a factor of 0.73 to 0.85 relative to the mass of the cement produced. (He et al., 2019). Over the year, several efforts, researches and studies related to green technology in construction site had been done in order to control carbon emission by 2050.

The word “concrete” originated from the Latin *concretus* in which past participle of *concrescere* meaning “to grow together”. Concrete can be either made with either hydraulic cement or non-hydraulic cement. Hydraulic cement solidified in water by the process of hydration whereas, non-hydraulic cement will not harden in water but harden with aid of carbon dioxide (Civil Today, no date).

Tracing back to 6500 BC in which world first concrete – nonhydraulic cement concretes which composed of gypsum and lime was founded and used by Syrians and spread through various places including Middle East, Egypt and ancient Greece. Then, the romans enhanced the formula by adding coarse sand mixed with hot lime, water as well as small pieces of gravel. On the other hand, hydraulic lime was found by the Greeks and the Romans by using limestone with presence of argillaceous impurities such as volcanic ash. Ever since then the quality of cementing materials remains stagnant until a British civil engineer, John Smeaton carried out extensive studies and found that “hydraulicity” of lime can be achieved by the use of lime-stone with high percentage of clayey materials. Thenceforward, there was rapid advancement in development of hydraulic cement eventually, Joseph Aspidin patented Portland cement. (Li et al., 2022)

Concrete is typically produced by blending Portland cement with sand, crushed rock, and water. To provide further insight, it constitutes a composite material where coarse granular material (the aggregate or filler) is embedded in a robust matrix (cement or binder). This matrix serves to occupy the voids between the aggregate particles and secure their cohesion. (Li et al., 2022)

Concrete can be classified according to unit weight, compressive strength, additives, construction methods and non-structural functionality (Li et al., 2022). Two most general classification method which are unit weight and compressive strength will be elaborated. Concrete can be categorized to ultra-lightweight concrete (below 1,200 kg/m^3), lightweight concrete (between 1,200 kg/m^3 to 1,800 kg/m^3), normal-weight concrete (about 2,400 kg/m^3) and heavy weight concrete (above 3,200 kg/m^3). Next, concrete categorized by compressive strength can be classified into low-strength concrete (below 20 MPa), moderate-strength concrete (20 MPa - 50 MPa), high-strength concrete (50 MPa – 150 MPa) and ultra-high strength concrete (above 150 MPa). (Li et al., 2022).

Kenaf is fast growing plant with species name *Hibiscus cannabinus* L. and fall under the Malvaceae family. It is a lignocellulosic plant which readily harvest in 4 to 5 months and can grow up to 4 to 6 meters. (Vayabari et al., 2023). The characteristics of fast growing and easy cultivation of kenaf had directly caused kenaf fibre to be affordable. Kenaf serve various purpose, such as being utilized in construction materials, animal feeds, absorbents, source of food as well as antioxidants (Shafa’atu et al., 2019). In short, every part of kenaf plant is valuable for industrial and commercial purposes. The global market of kenaf is looking forward to reaching US$854 million by 2025 (Thomas, 2019).

Kenaf fibre is extracted from the bast of Kenaf plant by manual retting process or field retting with mechanical separation. It is a non-wood plant fibres with 7.1% of microfibrillar angle and 44.3 % of crystallinity index (Silva et al., 2021). It composed of cellulose, lignin, holocellulose, hemicellulose and extractives (Lolo et al., 2020). Kenaf fibre is a green and sustainable material due to its eco-friendly cultivation practices and biodegradable nature. Kenaf fibre also has a strength comparable to other natural fibres, such as jute and flax.

Despite being various use of kenaf fibre. It faces one challenges, which are the dumping of kenaf fibre waste in the industry. About 15% of fibre is generated as waste during the manufacturing process in textile industry (Todor et al., 2019). The kenaf planted in Malaysia has an area of 1500 hectares and the kenaf shoot biomass production is 3000 tonnes in year 2022 (Ministry of Plantation Industries and Commodities, 2023).

1.2 Importance of the Study

This research investigates the strength characteristics of lightweight foamed concrete incorporated with kenaf fibre, subject to varying treatment durations. Kenaf fibre, recognized for its natural and eco-friendly attributes, is evaluated for its capacity to enhance the performance of lightweight foamed concrete. This exploration aligns with the broader objective of identifying green materials that contribute positively to the mechanical properties and overall sustainability of lightweight foamed concrete formulations.

The integration of green materials in the construction sector holds the potential to mitigate adverse environmental effects and bring construction materials and practices closer to sustainability goals. This research focuses on determining the optimal treatment for kenaf fibre as a composite material in lightweight foamed concrete as well as scientific analysis behind the changes in mechanical properties.

1.3 Problem Statement

Conventional concrete is of heavy material that consist of crushed aggregate, sand, Portland cement and water it has higher strength. Whereas, lightweight foamed concrete is composed of sand, cement water. Without presence of crushed aggregate and with the presence of foam, lightweight foamed concrete (between 1,200 kg/m^3 to 1,800 kg/m^3) has a lower density than conventional concrete (about 2,400 kg/m^3). It is no doubt that due to its weight conventional concrete can be difficult to handle. Thus, lightweight concrete is most suited to be utilized at most of the non-load bearing structural due being convenient to handle and transport.

However, lightweight foamed concrete faced certain challenges. Lightweight foamed concrete has lower flexural strength and compressive strength compared to conventional concrete. Lightweight foamed concrete is susceptible to shrinkage which will cause surface cracks or cracks within the concrete.

1.4 Aim and Objectives

This study aims to produce and evaluate the performance of $1200 kg/m^3$ lightweight foamed concrete incorporated with 0.2% kenaf fibre with different treatment period of 6% sodium hydroxide (1.5 mol NaOH).

Objectives for this project include:

i. To achieve the optimal water-to-cement ratio and manufacture lightweight foamed concrete without kenaf fibre (LFC-CTR), lightweight foamed concrete with untreated kenaf fibre (LFC-UF), and lightweight foamed concrete with treated kenaf fibre (LFC-TF) with a target density of $1200 \pm 50\ \mathrm{kg/m^3}$.
ii. Analyse the compressive, flexural and tensile strengths of lightweight foamed concrete incorporated with kenaf fibre with different treatment duration.
iii. Determine the optimum treatment duration of kenaf fibre incorporated in lightweight foamed concrete

1.5 Scope and Limitation of the Study

The scope of this study involves investigating lightweight foamed concrete (LFC) variants, namely LFC-CTR, LFC-UF, and LFC-TF over different treatment periods, each with a density target of $1200 \pm 50\ \mathrm{kg/m^3}$. In the case of LFC-TF, 0.2% of kenaf fibre in volume fraction of lightweight foamed concrete is employed.

For this project, Ordinary Portland Cement with the brand of Orang Kuat will be employed. The cement size used for this experiment should not exceed 300 μm, and achieving this size can be accomplished by passing the cement through a 300 μm sieve. The length of kenaf fibre in this project is set at 3 cm with a ±1 cm tolerance. there should be no clump in the kenaf fibre as it will affect the strength and workability of concrete. Condition of kenaf fibre mentioned above is achieved by manual processing by hand. Lastly, 6% (1.5 mol) concentration of NaOH solution will be selected for treated kenaf fibre.

In order to investigate the performance of the concrete, compression tests, flexural tests, and splitting tensile tests are conducted.

Several limitations were identified at the start of this project. The first limitation is the time allocated for treating kenaf fibre. Due to time and resource constraints, intervals of 3 hours were chosen for treating the kenaf fibre, specifically at 6, 9, and 12 hours. The project is limited to these time intervals due to constraints in both time and resources.

Another limitation is that only one type of concentration and one type of treatment method will be used, specifically the 6% (1.5 mol) concentration of NaOH method. This choice is influenced by constraints in both time and budget.

Additionally, a limitation is associated with the cultivation method of kenaf fibre. The strength of natural fibre depends on chemical composition and structure, both of which vary with growing conditions, harvesting time, extraction method, treatment, and storage procedures (Wang et al., 2016).

1.6 Contribution of the Study

This study makes several important contributions to the construction industry, particularly in the area of sustainable building materials. First, it explores the potential of incorporating natural fibres, specifically kenaf fibre, into lightweight foamed concrete, offering an eco-friendly alternative to conventional concrete reinforcement materials. This addresses the growing demand for green construction practices aimed at reducing the environmental impact of traditional concrete, especially in terms of carbon emissions associated with cement production.

Additionally, by investigating the effects of different treatment durations using sodium hydroxide (NaOH) on kenaf fibre, the study provides valuable insights into optimizing fibre treatment processes. This contributes to enhancing the mechanical properties of lightweight foamed concrete, including its compressive, flexural, and tensile strengths, which are critical for the material's structural performance.

Moreover, the research adds to the understanding of how lightweight foamed concrete can be effectively produced with a target density of 1200 ± 50 kg/m³, making it suitable for non-load bearing applications. By analysing the performance of untreated and treated kenaf fibres in this context, the study offers practical guidance for future research and development of lightweight concrete materials that balance sustainability with structural efficiency.

Finally, the findings have broader implications for the use of agricultural waste, such as kenaf fibre, in industrial applications. By promoting the reuse of natural fibres and reducing waste, the study supports the circular economy model and contributes to resource conservation in construction.

1.7 Outline of the Report

This progress report consists of six chapters: introduction, literature review, methodology, trial mixes results, results and discussion and lastly, conclusion and recommendations.

In Chapter 1, the background of the study is presented by explaining the general context and significance of the research topic. The background introduces kenaf fibre as a sustainable material that can potentially enhance the properties of lightweight foamed concrete, aligning with the growing need for green construction solutions. The importance of the study is then highlighted, focusing on the role of green technology in construction and the potential for using natural materials like kenaf fibre. This research aims to contribute to the industry by addressing sustainability and improving the mechanical properties of lightweight foamed concrete through the incorporation of treated and untreated kenaf fibres. Then, the problem statement outlines the challenges faced by both conventional and lightweight foamed concrete, such as the heavy weight of conventional concrete and the lower strength of lightweight foamed concrete. Next, the aim and objectives of the study are directly related to the problem statement. The research aims to investigate the performance of lightweight foamed concrete with the incorporation of kenaf fibre, focusing on its mechanical properties. Specific objectives include achieving the optimal mix design for concrete variants

(LFC-CTR, LFC-UF, LFC-TF), analyzing their compressive, flexural, and splitting tensile strengths, and determining the optimal treatment duration for kenaf fibres to improve performance. Then, the scope and limitations of the study are discussed. The scope involves examining various lightweight foamed concrete mixes, testing their performance, and understanding how different treatment durations of kenaf fibre affect their mechanical properties. The study's limitations include the fixed concentration of NaOH for treating kenaf fibres, as well as constraints related to time, budget, and available resources. Finally, the chapter concludes with an outline of the report, briefly summarizing the content of the subsequent chapters.

Chapter 2 discusses the literature review on lightweight foamed concrete, including the materials used in its production, such as water, cement, sand, and foam, as well as the physical and mechanical properties of lightweight foamed concrete. It also covers the alkaline treatment of kenaf fibre. This chapter which provides a foundation for Chapter 3 and guides the direction of the project.

Chapter 3 outline the material preparation, mixing procedure, casting procedure as well as testing procedure.

Chapter 4 summarizes the compressive strength test results for lightweight foamed concrete incorporating kenaf fibre treated with NaOH for 12 hours, with different water-cement ratios. The optimum water-cement ratio is discussed, along with the reasoning behind the findings.

Chapter 5 compares the workability, compressive strength, splitting tensile strength, and flexural strength of LFC-CTR, LFC-UF, LFC-TF 6HR, LFC-TF 9HR, and LFC-TF 12HR. Additionally, SEM-EDX analysis results are discussed to further understand the morphologies and the reasons behind the differences in strength properties among LFC-CTR, LFC-UF, LFC-TF 6HR, LFC-TF 9HR, and LFC-TF 12HR.

Finally, Chapter 6 summarizes the experimental results from the various tests conducted. It also offers recommendations to improve the scope and depth of future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The utilization of lightweight materials has gained significant attention in recent years due to their potential to improve sustainability and cost-effectiveness in the construction industry. One famous example is lightweight foamed concrete, which offers reduced density, enhanced thermal insulation properties, improved workability, and transportation convenience compared to conventional concrete. However, there is still room for improvement in terms of the compressive strength and flexural strength of lightweight foamed concrete compared to conventional concrete. Kenaf fibre, a natural fibre derived from the Hibiscus cannabinus plant, exhibits characteristics of high tensile strength, low density, and biodegradability. The incorporation of kenaf fibre into concrete matrices could enhance the durability and mechanical properties (Mahzabin et al., 2018), thus making it a more competitive construction material.

This proposed final year project, titled "Compressive Strength of Lightweight Foamed Concrete with Kenaf Fibre of Different Treatment Periods," seeks to further investigate the effect of kenaf fibre on the compressive strength of lightweight foamed concrete. By subjecting kenaf fibre to different treatment periods ranging from 6 to 12 hours, this study aims to explore the optimal treatment duration for maximising the mechanical performance of lightweight foamed concrete.

This literature review provides a comprehensive overview of studies and research findings related to lightweight foamed concrete, kenaf fibre reinforcement, and the effects of various treatment methods on fibre-matrix interactions. By synthesizing existing knowledge and identifying missing pieces or insufficient information in the published research on the topic, this review sets the stage for subsequent experimental investigation. It helps to determine the direction of the current study while offering valuable insights into the potential benefits and challenges associated with incorporating kenaf fibre into lightweight foamed concrete formulations.

2.2 Lightweight Concrete

Lightweight concrete (LC) is generally defined as having a unit weight between 1200 $\mathrm{kg/m^3}$ and 1800 $\mathrm{kg/m^3}$(Li et al., 2022). It has a history of more than 2000 years and was present during the early Roman Empire. One of the most famous examples built with lightweight concrete is the Pantheon in Rome, Italy, which is an unreinforced concrete dome and was constructed in 128 A.D. (Thienel, Haller and Beuntner, 2020).

Often, the definition of lightweight concrete can be blurry due to various definitions provided by different parties. According to the American Concrete Institute's (ACI) 213R-14 "Guide for Structural Lightweight-Aggregate Concrete," structural lightweight concrete (SLC) is defined with a minimum cylinder strength of 17 MPa and an equilibrium density between 1120 and 1920 $\mathrm{kg/m^3}$. When SLC has a compressive strength of 40 MPa at 28 days, it will be classified as high-strength lightweight concrete (Akers et al., 2003).

However, Europe has its own rules for defining lightweight concrete (LC). LC is specified as a material in EN 206, and its application is governed by EN 1992, specifically Eurocode 2. According to EN 206, LC has an oven-dry density between 800 to 2000 $\mathrm{kg/m^3}$. EN 206 lists that LC is of the minimum strength class of LC8/9, which means a characteristic cylinder strength of 8 MPa and a characteristic cube strength of 9 MPa. In contrast, the design standard according to Eurocode 2 requests a minimum strength class of LC12/13.

This project uses the American Concrete Institute's definition for LWC due to its popularity in the University.

2.3 Production of Lightweight Concrete

Lightweight concrete can be further categorized into different categories according to their approaches in producing lightweight concrete.

The first technique involves excluding fine aggregates when casting the concrete. It consists only of coarse aggregate, Portland Cement, and water. The absence of fine aggregate creates unfilled voids between the coarse aggregate, thereby reducing the density of the concrete and resulting in lightweight concrete. This approach for producing lightweight concrete was proposed by Wimpey in the UK in 1924. Concrete produced using this method is known as no-fines concrete (Newman and Choo, 2003).

The second method involves replacing natural aggregates in concrete mix with aggregates containing a large proportion of voids, either wholly or partially. These specialized aggregates are known as lightweight aggregates, and they include materials such as pumice, expanded shale, slate, and clay. Concrete produced using this method is known as lightweight aggregate concrete (Newman and Choo, 2003).

The final approach to produce lightweight concrete involves the use of gas bubbles in a cement paste or mortar matrix to form a cellular structure containing approximately 30–50 percent voids. These gas bubbles remain in the cement paste even after it has hardened. The presence of these bubbles in the concrete reduces its density, resulting in lightweight concrete. Typically, this approach does not require the presence of coarse aggregate; it only requires fine aggregate (sand), Portland Cement, and water. Lightweight concrete formed using this method is further distinguish into aerated and foamed concrete (Newman and Choo, 2003).

Aerated concrete involves the use air-entraining method, it is a method that mix the mortar with gas forming chemical known such as Aluminium powder, Calcium Carbide and Hydrogen peroxide. Mixing these aerating agents provide a chemical reaction that generate gas and produce a porous structure to form a cellular structure. Whereas, the foaming method involves mechanically creating pores using either the mixed foaming process, where the foaming agent is mixed with mortar, or the pre-foaming process, where the foaming agent is mixed with the mixing water then only mixed with the base mix (Raj, Sathyan and Mini, 2019).

Other approaches not mentioned above in producing lightweight concrete include Perlite concrete (Ibrahim et al., 2020) and Polystyrene concrete (Prasittisopin, Termkhajornkit, and Kim, 2022). It can be noticed that, regardless of the type of lightweight concrete produced, all approaches share similarities. The basis of normal weight concrete mix is altered to achieve the purpose of reducing density for the normal concrete. Whatever the method used, water and cement are always present in the composition of lightweight concrete. Different approaches in producing lightweight concrete result in different morphologies. Figure 2.1 illustrates the various particle arrangements for different types of lightweight concrete.

In this project, the focus will be on lightweight foamed concrete. As this project's interest lies in investigating the compressive strength of lightweight foamed concrete with kenaf fibre of different treatment periods.

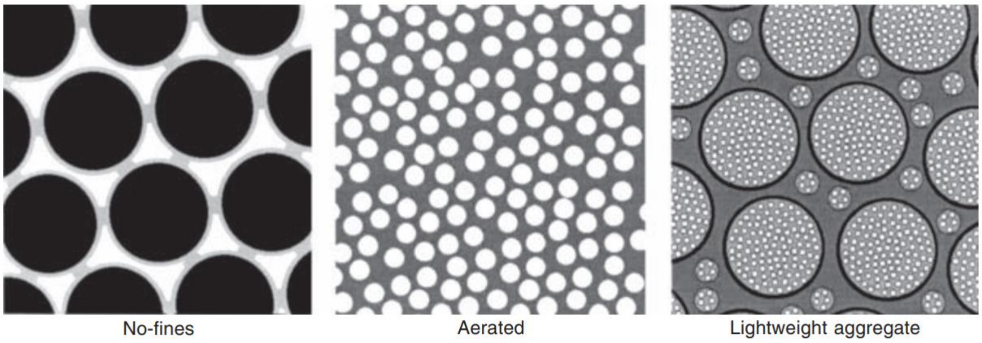


Figure 2.1: Different Properties of Lightweight Concrete (Newman and Choo, 2003).

2.4 Lightweight Foamed Concrete

Lightweight concrete has been a popular option for non-structural material in construction industry due to its lightweight and more economical nature. It provides several advantages, including quick and settlement-free construction, effective thermal insulation, excellent freeze/thaw resistance, and good fire resistance (Raj, Sathyan and Mini, 2019).

A concrete is classified as lightweight foamed concrete when it has an air content of more than 25% (Newman and Choo, 2003).

There are two approaches in introducing air bubbles into the concrete mix. The first approach involves mixing formed foam from a foam generator with mortar mix, while the second method involves using synthetic or protein-based foam-producing admixture mixed with the other mix constituents in a high-shear mixer. The stability of foam plays an important role in ensuring the quality of lightweight foamed concrete. The bubbles should be evenly distributed in the concrete so that the air voids are evenly distributed in the hardened concrete. Typically, the bubble size ranges between 0.1 to 1 mm (Newman and Choo, 2003).

Conversely, Compaoré et al., published a journal in Results in Materials, stating that lightweight foamed concrete should have bubble sizes ranging between 1.0 to 3.0 mm evenly distributed in the hardened concrete. However, the idea that lightweight concrete has bubble sizes ranging between 0.1 to 1 mm is more suitable to be employed as a specification for foamed concrete. Application guide A39 specifies lightweight foamed concrete should have bubbles with diameters of 0.1 mm to 1.5 mm (Brady, Watts, and Jones, 2001). Several papers investigating the stability of foam with foam size also employed lightweight foamed concrete having bubble diameters ranging from 0.1 mm to 5 mm (Jones, Zheng, and Mohammad, 2016) and 0.1 mm to 1 mm (Jones, Ozlutas, and Zheng, 2016).

There is currently no specific standard protocol established for investigating the microstructure of foamed concrete within academic research and industry practices. The only standard available is an indirect method stated in ASTM C457 - Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. However, the method is deemed unsuitable for foamed concrete due to the rigorous surface preparation required, involving surface grinding and polishing during the specimen preparation stage. This process often leads to the coalescence of the fragile thin walls between voids, ultimately resulting in inaccurate outcomes. (Jones, Zheng, and Mohammad, 2016).

The bubbles in lightweight foamed concrete can be measured using a high-resolution digital camera and image analysis software. This method was first used by Kearsley and Visagie (1999) and Nambiar and Ramamurthy (2007). Similarly, Jones, Zheng, and Mohammad (2016) also adopted the same method to investigate the microstructure of foamed concrete, using image analysis software called ImageJ.

2.5 Materials/Compositions for Lightweight Foamed Concrete

Lightweight foamed concrete consists of Portland Cement, fine aggregate, water and foam. Subchapter 2.6, 2.7, 2.8, 2.9 and 2.10 section will provide a comprehensive overview of all the materials required to produce lightweight foamed concrete, as well as how they interact with each other.

2.6 Cement

Cement is a type of adhesive substance used in various applications, particularly in building and civil engineering construction. It typically refers to finely ground powders that solidify into a hard mass when mixed with water (Mason and Lea, 2018).

Cement originates from cement clinker as the main component, alongside other minor components such as gypsum by Sulphur Trioxide content (to control the setting characteristics) and admixtures. The four primary components of Portland cement clinker are of a lime component, usually limestone that has been extracted from a quarry; an alumina source, usually derived from shale or clay; silica, which is often added as sand and partly derived from the clay; and a source of iron, which has, up until recently, mostly been a waste product of the steelmaking process (Hewlett and Liska, 2019).

Limestone serves as the primary raw material for manufacturing Portland Cement. It is extracted from the ground through blasting, then prepared for use by crushing and grinding to a size suitable for combining with silica, alumina, and iron oxide in the cement kiln. The final products will differ depending on the kind of limestone used to make cement clinkers. Depending on their place of origin, all limestones have different microstructures. However, the majority of limestone exhibits same similarities, with a Calcium Carbonate content of more than 90%. It is to be noted that in some cases, are present in limestone, which can affect the nature of the cement. Therefore, care should be taken in selection of limestone in cement production. For example, magnesium oxide is one such impurity found in limestone. These impurities form when groundwater rich in magnesium passes through the already formed limestone. A magnesium oxide content of more than 4% can cause expansion issues after the hydration of cement (Hewlett and Liska, 2019).

Other than materials mentioned above, there are other deposits found in limestone and other raw materials required for cement clinker production. Table 2.1 outlines the deposits content in limestone along with its percentage, while Table 2.2 outlines raw materials required for cement clinker production. The four main oxides in cement clinker are SiO_2, Al_2O_3, Fe_2O_3, and CaO. This information is obtained through the use of an X-ray fluorescence analyser, which conducts qualitative and quantitative analysis of chemical elements based on the measurement of the intensities of their X-ray spectral lines emitted by secondary excitation (Hewlett and Liska, 2019).

Table 2.1: Deposits Content in Limestone (Hewlett and Liska, 2019).

	Limestone 1	Limestone 2	Limestone 3	Limestone 4	Limestone 5	Limestone 6	Limestone 7
SiO_2	2.9	12.1	13.7	2.5	2.3	7.4	4.7
Al_2O_3	0.7	1.8	3	0.3	0.3	2.3	1.3
Fe_2O_3	0.4	1.9	2.7	0.6	0.2	0.6	0.6
CaO	53.6	43.4	41.1	52.4	53.3	49.4	50.7
MgO	0.3	2.4	3	1.1	0.3	-	1
SO_3	0.3	0	0.1	0	0.1	-	0.2
Na_2O_e	0.1	0.2	0.8	0	0	0.3	0.2
LOI	42.6	33	33	43	43	39.5	41.6
Total	100.9	94.9	97.4	99.9	99.4	99.5	100.2

Table 2.2: Raw Materials Required for Cement Clinker Production (Hewlett and Liska, 2019).

Raw Material	Limestone	Chalk	Marl	Clay/Shale	Sand	Iron Oxide	Bauxite
Provides:	CaO	CaO	CaO	SiO_2	SiO_2	Fe_2O_3	Al_2O_3
	SiO	SiO_2	Al_2O_3	Al_2O_3	Al_2O_3		SiO_2
	Al_2O_3	Al_2O_3	SiO_2	Fe_2O_3	K_2O		Fe_2O_3
	MgO			K_2O	Na_2O		
	K_2O			Na_2O	CaO		
	Na_2O						

2.6.1 C-S-H Gel in Cement

Calcium silicate hydrate (CSH) gel is the primary product formed during cement hydration, making up over 60% of the volume of hydrated Portland cement. It is essential for the durability and strength of cement and concrete. Although CSH is critical for strength development in concrete, researchers still struggle to fully understand its structure due to due to its variable composition or stoichiometry, which makes it difficult to classify its nanostructure (Madadi and Wei, 2022).

Cement clinker consists of 4 major compound which are ‘alite’, ‘belite’, ‘celite’ and ‘felite’ given by their short form C_3S (Tricalcium silicate, C_2S (dicalcium silicate), C_3A Tricalcium aluminate and C_4AF (Tricalcium aluminate). In short, C_3S contribute to early strength of cement, C_2S contribute to later strength of the cement, C_3A react rapidly with water and release high amount of heat that will potentially cause cracking in concrete and C_4AF hydrates rapidly. C_3S and C_2S hydrate and form C-S-H gel in cement (Hewlett and Liska, 2019).

2.7 Type of Cement

To cater to various cement applications based on their properties, different countries employ different standards to regulate cement quality. These standards categorize cements based on their chemical and physical properties. However, terminology for Portland cement may vary across different countries, as the specifications outlined in various standards may not always align.

2.7.1 Cement Categorization According to European Standard

European standard EN 197-1:2011 titled “Composition, specifications and conformity criteria for common cements” is used to categorize the type of cement. Table 2.3 shows the standard defines 5 primary types of cement along with 27 unique common cements, 7 sulphate-resistant common cements, 3 unique low early strength blast furnace cements, and 2 sulphate-resistant low early strength blast furnace cements (Hewlett and Liska, 2019).

Table 2.3: 5 Primary Types of Cement Based on EN 197.

Main Types		Clinker (%)
CEM I	Portland cement	95-100
CEM II	Portland-composite cement	65-94
CEM III	Blastfurnace cement	5-64
CEM IV	Pozzolanic cement	45-89
CEM V	Composite cement	20-64

2.7.2 Cement Categorization According to Australian Standard

AS 3972 is the Australian standard that categorize Portland and blended cement by putting more emphasis on their performance characteristics rather than the raw materials.

Table 2.4 shows the cement categorized by Australian standard. AS 3972 only specifies upper limit for Magnesium Oxide, Sulphur Trioxide and Chloride content in cement. MgO and SO_3 can affect cause expansion issues after the hydration of cement as well as prolong the setting time of cement. On the other hand, chloride can cause steel reinforcement corrosion in concrete.

2.7.3 Cement Categorization According to American Standard

In the United States, there are several guidelines for the classification of concrete. ASTM C1157/C1157M-11 specifies type of hydraulic cement based on performance, while ASTM C150/C150M-15 categorize cementitious materials related to Portland cement based on performance and chemical compounds. Table 2.5 shows the type of cement according to ASTM C150/C150M-15. Table 2.6 shows chemical compounds for Portland cements According to ASTM C150/C150M-15. Additionally, ASTM C595-15 specifies blended cements based on performance and constituent materials. Table 2.7 shows types of blended cement according to ASTM C595.

Table 2.4: Cement Categorized in AS 3972.

Designation	Characteristics
Type GP-general purpose cement	Cement containing Portland cement clinker, calcium sulfate and mineral additions up to 7.5% of which 5% may be minor additional constituents.
Type GL-general purpose limestone cement	Cement containing Portland cement clinker, calcium sulfate, limestone between 8 and 20% and minor additional constituents up to 5%.
Type GB-general purpose blended cement	Cement containing Type GP cement plus greater than 7.5% fly ash or slag or up to 10% amorphous silica
Type HE-high early strength cement	General purpose or blended cement fulfilling the performance requirements for high early strength.
Type LH-low heat cement	General purpose or blended cement fulfilling the performance requirements for low heat development.
Type SR-sulfate resisting cement	General purpose or blended cement fulfilling the performance requirements for sulfate resistance.
Type SL-shrinkage limited cement	General purpose or blended cement fulfilling the performance requirements low shrinkage.

Table 2.5: Type of Cement According to ASTM C150/C150M-15.

Type I	For use when the special properties specified for any other type are not required.
Type IA	Air entraining cement for the same uses as Type I, where air entrainment is desired.
Type II	For general use, more especially when moderate sulfate resistance is desired.
Type IIA	Air entraining cement for the same uses as Type II, where air entrainment is desired.
Type II(MH)	For general use, more especially when moderate heat of hydration and moderate sulfate resistance is required.
Type II(MH)A	Air-entraining cement for the same uses as Type II(MH), where air-entrainment is desired.
Type III	For use when high early strength is desired.
Type IIIA	Air entraining cement for the same uses as Type III, where air entrainment is desired.
Type IV	For use when a low heat of hydration is desired.
Type V	For use when high sulfate resistance is desired.

Table 2.6: Chemical Compounds for Portland Cements According to ASTM C150/C150M-15.

	Cement Type					
	I and IA	II and IIA	II(MH) and II(MH)A	III and IIIA	IV	V
Al_2O_3 maximum (%)	-	6.0	6.0	-	-	-
Fe_2O_3 maximum (%)	-	6.0	6.0	-	6.5	-
MgO maximum (%)	6.0	6.0	6.0	6.0	6.0	6.0
SO_3 maximum (%)when C_3A is 8% or less	3.0	3.0	3.0	3.5	2.3	2.3
SO_3 maximum (%)when C_3A is $> 8\%$	3.5	-	-	4.5	-	-
Loss on ignition	3.0	3.0	3.0	3.0	2.5	3.0
Insoluble residue (%)	0.75	0.75	0.75	0.75	0.75	0.75
C_3S maximum (%)	-	-	-	-	35	-
C_2S maximum (%)	-	-	-	-	40	-
C_3A maximum (%)	-	8	-	15	7	5
$(C_3A + C_4AF)$ maximum or solid solution $(C_4AF + C_2F)$ maximum, whichever is appropriate (%)	-	-	-	-	-	25

Table 2.7: Blended Cement According to ASTM C595.

Type	Blended Ingredients
Type IP and Type P Portland-pozzolan cement	15%-40% by weight of pozzolan (fly ash)
Type IS Portland blast furnace slag cement	25%-70% by weight of blast furnace slag
Type I (SM) Slag-modified Portland cement	0%-25% by weight of blast furnace slag (modified)
Type S Slag cement	70%-100% by weight of blast furnace slag

2.8 Fine Aggregate

The purpose of fine aggregate in lightweight foamed concrete is to provide strength to the concrete. This is achieved through the formation of a matrix between the cement and fine aggregate.

Generally, the fine aggregate used in lightweight foamed concrete is sand, defined as any mineral, rock, or soil particles ranging in diameter from 0.02 to 2 mm. Sand mainly consists of quartz due to its abundance in rocks and its comparative hardness. In some locations, other constituents such as feldspar, calcareous material, iron ores, and volcanic glass may also be major components of sand.

Over time, researchers have made several efforts to replace normal sand in lightweight foamed concrete with other fine aggregates as well as investigate how different fine aggregate affect the concrete as shown in Table 2.8 and Table 2.9 respectively.

Table 2.8: Investigation Done in Replacement of Fine Aggregate.

Author(s)	Material used	Results
(Sldozian et al., 2021)	Nano Modified Sand	Carbon nanotube on sand surface promote better hydration and increase concrete compressive strength.
(Al-Shwaiter, Awang, and Khalaf, 2022)	Palm Oil Fuel Ash	Improved mechanical properties, microstructure, and transport properties, increased the shrinkage, and decreased the sulphate resistance.
(Lim et al., 2015)	Different gradations of sand	For sand size ranging from 0.60mm to 2.36mm, flexural strength, compressive strength, and ductility was highest with fineness sand.
(Gencel et al., 2022)	Expanded perlite and glass sand	Improves physico-mechanical, flowability and durability properties.
(Lee et al., 2018)	Charcoal	Increase early compressive strength

Table 2.9: Investigation Done in Replacement of Fine Aggregate.

Author(s)	Material used	Results
Kashani, Ngo and Hajimohammadi, 2019)	Recycled glass fines	Reduced drying shrinkage with effect of slightly decreased water absorption.
(Lim et al., 2017)	Quarry waste	Compressive strength increases due to strengthen inter-particle bonds between cement matrices and the quarry dust particles, reduced foam volume to achieve same density. Refinement of pore structure led to increase in conductivity.
(Efendi, Kurniawan, and Wulandari, 2019)	Coconut shell	Decrease compressive strength of concrete.

2.9 Water

Water is present in three distinct states: gas, liquid, and solid. Comprised of hydrogen and oxygen, it ranks among the most plentiful and essential substances. The chemical equation of water is given by $\mathrm{H_2O}$. (Zumdahl, 2018).

Water serves three primary functions when added to a concrete mix. Firstly, it reacts with the cement powder to produce hydration products. Secondly, it acts as a lubricant, enhancing the workability of the fresh mixture. Lastly, it ensures the necessary space in the paste for the development of hydration products. Insufficient water in the concrete can reduce its workability, while excessive water can decrease compressive strength and result in spalling and cracking (Li et al., 2022).

Freshwater is the most suitable choice for concrete mixing. An effective method to assess its suitability is by checking for any distinct taste, odour, or colour. Additionally, if the water does not fizz or foam when shaken, it is considered appropriate for concrete mixing. In other words, potable water without sugar and suitable for human consumption is fit for use in concrete mix. (Li et al., 2022).

Several impurities present in water such as dissolved solids, suspended solids and dissolved organic material can harm the concrete and result in a non-ideal concrete mix.

Total Dissolved Solids (TDS) is measured by multiplying the conductivity of water by 0.7 with a unit of $\mu S/cm$ when water temperature is at $25°\mathrm{C}$. A TDS of less than 2000 ppm is assumed to be suitable for use in concrete mix for most cases. Dissolved solids like sulphate, carbonates, sodium, or potassium hydroxide (causing alkaline water). All these dissolved solids mentioned can either cause reduced workability of concrete or a reduction in 28-days strength as well as long-term strength (Li et al., 2022).

Conversely, excessive levels of suspended solids like silt, clay, debris from pipes, organic matter, and colloids can increase water requirements, induce drying shrinkage, and lead to efflorescence in concrete. While human faeces, animal waste, oils, solvents, and vegetable waste contribute to the presence of humic and fulvic acids, which are classified as organic impurities. Increased levels of organic impurities can retard the hydration of cement (Li et al., 2022).

Another essential use of water in concrete production is for curing and washing aggregate. The water quality needed for these tasks is less strict compared to water used in concrete mixtures. Guidelines for chemical limits for wash water can be found in ASTM C95 (Li et al., 2022).

2.10 Foam

Foam is an indispensable element in lightweight foamed concrete. The foaming agent generates foam, regulating the density and porosity of cellular concrete by introducing air bubbles inside the concrete (Amran, Farzadnia and Ali, 2015). Foam is created by the foaming method which involves mechanically creating pores using either the mixed foaming process, where the foaming agent is mixed with mortar, or the pre-foaming process, where the foaming agent is mixed with the mixing water then only mixed with the base mix. (Raj, Sathyan and Mini, 2019).

There are different types of foaming agent can be used for the pre-foaming method in experiment. The foaming agents will be either synthetic surfactants or is protein-based substance (He et al., 2019). In general, Synthetic foaming agents result in foamed concrete specimens that are more stable compared to those produced with protein-based agents, given a constant water-to-cement ratio (Falliano et al., 2018; Chica and Alzate, 2019).

Preformed foam comes in two forms: dry and wet foam. Dry foam is produced by passing the foaming agent solution through high-density restrictions while simultaneously introducing compressed air into a mixing chamber (Ramamurthy, Nambiar and Ranjani, 2009). A pumpable foamed concrete is produced using dry foam because it is highly stable and has bubbles smaller than 1 mm, making it easy to blend with the base material (Aldridge, 2005). Wet foam on the other hand is created by applying a foaming agent solution onto a fine mesh, resulting in bubbles sized between 2 and 5 mm. However, wet foam tends to be less stable (Ramamurthy, Nambiar and Ranjani, 2009).

This suggests that dry foam could be a suitable choice for this project because it provides greater stability to the mix.

2.10.1 Foamed Concrete Preparation

Often, the most direct approach to achieve foamed concrete with desired properties is through trial and error. However, there are guidelines available based on previous researches are available for reference during the mix design process. The design assistance provided by American Concrete Institute (ACI) 523-1975 correlates plastic density with compressive strength. This allows for the selection of cement content and water-cement ratio based on desired strength and density (ACI, 1975). The ACI 523-1975 guideline was founded on the concept put forth by McCormick, in which he introduced a method suggesting a rational approach to proportioning based on solid volume calculations given a specific mix proportion and density. While, ASTM C 796-97 outlines a procedure for determining the volume of foam required to create a cement slurry with a specified water-cement ratio and desired density. Similarly, Kearsley and Mostert (2005) introduced a series of equations that incorporate the density and volume of foamed concrete based on the mixture composition, allowing for the calculation of foam volume and cement content.

Pre-formed foaming is at advantage compared to mixed foaming techniques for two reasons: it requires less foaming agent, and there's a direct link between the amount of foaming agent used and the air content in the mixture (Ramamurthy, Nambiar and Ranjani, 2009).

The benefits mentioned above justified on reason pre-formed forming technique was used for this project. Pre-formed foaming was selected for this project because this technique has a characteristic in which the amount of foaming agent used correlates with the air content in the mixture. This implies that by controlling the foaming agent's quantity during mixing, the mixture's air content can be controlled, thereby achieving lightweight foamed concrete with the desired density of 1200 kg/m³ (Ramamurthy, Nambiar and Ranjani, 2009).

2.11 Properties of Lightweight Foamed Concrete.

Properties of foamed concrete can be divided into 5 main categories which are fresh state properties, physical properties, mechanical properties, durability as well as functional characteristics.

2.12 Fresh State Properties of Foamed Concrete

2.12.1 Consistency

In order to maintain the quality of the hardened concrete and prevent the artificial air bubbles from separating or bursting, it is important to ensure the consistency and stability of freshly mixed foamed concrete (Lim et al., 2015). Flow table test, in accordance to ASTM C1437-01 can be used to determine the consistence of fresh concrete (Wong et al., 2019). Likewise, ASTM C230 outlines Specification for Flow Table for Use in Tests of Hydraulic Cement which take reference of ASTM C1437 also can be used to determine suitable flow cone to be used (Nambiar and Ramamurthy, 2008).

Other than that, Marsh cone test can be used to measure the fluidity of fresh concrete (Jones, McCarthy and McCarthy, 2003). According to a study by Nambiar and Ramamurthy (2008), a mixture with spread flow values ranging from 40% to 60% and flow time values below 20 seconds is considered to have good consistency and can be placed in the mould without the need for compaction or vibration.

When the volume of the foam in the concrete mix increases, the consistency reduces. This is due to higher air content reduced self-weight and increase cohesion of the mix. Moreover, there will be increased stiffness due adhesion force created between the bubbles and solid particles in concrete mix (Nambiar and Ramamurthy, 2008).

2.12.2 Stability

A foamed concrete mix is considered to be stable when its ratio of measured fresh density to design density is close to one and does not experience segregation and bleeding issues. The condition segregation refers to when a concrete mix experience separation of solids and air phases. A concrete mix tend to be not stable and has segregation issue when the mix has density as low as 500 $\mathrm{kg/m^3}$ and below (Jones, Ozlutas and Zheng, 2016).

The consistency of the concrete mix has a direct impact on the stability of the mix, A study done by Nambiar and Ramamurthy shown that a foamed concrete with spread flow of 45% is of good consistency and stability. Likewise, stability of mix can be assessed by comparing calculated and actual plastic density of concrete and ensure it is within 50 $\mathrm{kg/m^3}$. The difference between calculated and actual w/c ratio of the concrete mix also can serve as an indication of the stability of concrete. It is because when a mix has higher w/c ratio than actual w/c ratio it indicates that air bubbles in the foam collapse.

Based on the review of previous researcher, the density of lightweight foamed concrete in this project has set to a tolerance value of $\pm 50\ \mathrm{kg/m^3}$ to ensure the stability of concrete.

2.13 Physical Properties

The term "physical" refers to aspects of the structure, size, or shape of something that can be touched and seen. When discussing the physical properties of a substance, it pertains to characteristics such as weight, volume, hardness, and similar attributes (Collins, 2019). There are 3 main physical properties of foamed concrete which refer to drying shrinkage, air-void system and density in most of the situation.

2.13.1 Drying Shrinkage

Shrinkage is a characteristic of cement-based materials that occurs in both the plastic and hardened stages of concrete. This shrinkage induces tensile stress within the concrete, leading to cracking and the formation of gaps that allow harmful agents such as chlorides and sulphates to penetrate. These aggressive agents can diminish the long-term performance and serviceability of the concrete (Tran et al., 2021). Shrinkage can be further divided to plastic shrinkage, autogenous shrinkage, drying shrinkage, and carbonation shrinkage (Mastali et al., 2018).

In general, drying shrinkage is defined as the shortening per unit length caused by moisture loss (Li et al., 2022). It occurs as a result of internal moisture loss in the porous structure in order to achieve equilibrium with the external environment's relative humidity (Bella, 2016).

Drying shrinkage is the primary focus of foamed concrete in comparison to other types of shrinkage because the lack of coarse aggregates causes it to exhibit ten times greater drying shrinkage than normal weight concrete (Amran, Farzadnia and Ali, 2015). Researcher have found that the drying shrinkage of foamed concrete can be reduced by adding fibre. The amount of fibre added to the concrete is negatively correlated with the drying shrinkage of the foamed concrete. (Falliano, 2019).

2.13.2 Air-void System

An air void is an empty space within a cementitious mixture that contains air. According to ACI concrete terminology and ASTM C125-15b, air content is the percentage of air voids in cement paste, mortar, or concrete, excluding pore space in aggregate particles. This is usually expressed as a percentage of the overall volume of the paste, mortar, or concrete (Al-Jabari, 2022).

Porosity, permeability and pore size distribution is the factor that define the pore structure of cementitious material. The pore structure of foamed concrete includes gel pores, capillary pores, and air voids. The same porosity and density values of concrete can be achieved by using a large number of small air-voids or a smaller number of larger air-voids. (Kearsley and Visagie, 2002). The air-void distribution is one of the most important micro properties that influence foamed concrete strength. Foamed concrete with narrower air-void distributions demonstrates greater strength. The merging of bubbles within foamed concrete reduces the compressive strength of the concrete (Ramamurthy, Nambiar and Ranjani, 2009). Moreover, when there are more pores or interconnected pores within the concrete, the water absorption of the concrete increases. (Raj, Sathyan and Mini, 2019).

2.13.3 Density

Density is the mass of a substance per unit volume. Density for concrete can be classified in whether fresh or hardened density.

Fresh density is used for mix design and casting control casting processes. Fresh density may not be suitable to calculate by theoretical equation due to issues such as continued expansion of the foam after its discharge and foam loss during mixing. While most of the physical properties of foamed concrete depend on its hardened density (Ramamurthy, Nambiar and Ranjani, 2009).

2.14 Mechanical Properties

Mechanical properties of foamed concrete consist of compressive, flexural and tensile strengths, modulus of elasticity.

2.14.1 Compressive Strength

Compressive strength is the capacity of a material to withstand a direct pressure exerted by an applied compression force (Marković et al., 2016). Foamed concrete strength is influenced by the ratios of cement to sand and water to cement, the type and particle size distribution of sand, the curing process and the type of foaming agent applied (Hamidah, 2005).

The compressive strength decreases exponentially with a reduction in density of foamed concrete. The compressive strength decreases with an increase in void diameter for foamed concrete with dry density between $500\mathrm{kg/m^3}$ to $1000\mathrm{kg/m^3}$. Whereas, composition of the paste plays important role in the compressive strength when foamed concrete has dry density higher than $1000\mathrm{kg/m^3}$ due to lesser air-voids and they are further apart (Kearsley, 2002).

For concrete with the same density, using finer sand as fine aggregate provides the foamed concrete with the highest compressive strength (Lim et al., 2015). This is because the pores in foamed concrete can be distributed uniformly in fine sand, whereas the pores in foamed concrete with coarse sand are larger and cannot be distributed evenly (Nambiar and Ramamurthy, 2006). Thus, fine sand with particle size of 0.60 mm will be used as fine aggregate in this project.

2.14.2 Flexural and Tensile strengths

Splitting tensile test outlines by ASTM C496 is a standard method for assessing the tensile strength of concrete. While concrete is well known for its high compressive strength, its tensile strength is comparatively lower. This test helps to determines concrete's ability to withstand cracking and splitting forces. It is known that foamed concrete has lower splitting tensile strength compared to light weight aggregate concrete and normal weight concrete. Higher value of splitting tensile strength was observed when fly ash was used as fine aggregate. (Nambiar and Ramamurthy, 2009).

The flexural strength to compressive strength ratio of cellular concrete typically falls within the range of 0.25 to 0.35 (Valore, 1954). Similarly, the tensile strength of normal strength concrete is approximately 10% of its compressive strength, with this value decreasing further in higher strength concrete. Fibre-reinforced concrete and polymer concrete have higher tensile strength compared to normal concrete (Li et al., 2022).

2.14.3 Modulus of Elasticity

The static modulus of elasticity for foamed concrete with density between $500\mathrm{kg/m^3}$ to $1500\mathrm{kg/m^3}$ lies between $1.0\mathrm{kN/mm^2}$ to $8.0\mathrm{kN/mm^2}$ (Jones and McCarthy, 2005). Foamed concrete with the same compressive strength as normal weight concrete exhibits only about 25% of the modulus of elasticity of normal weight concrete. It was reported that use of polypropylene fibres in concrete can increase modulus of elasticity by two to four times (Nambiar and Ramamurthy, 2009).

2.15 Durability

The durability of foamed concrete primarily depends on factor such as the proportion of connected pores relative to the total number of pores. This factor affects permeation characteristics foamed concrete such as water absorption, porosity properties and sorptivity.

2.15.1 Water Absorption

Water absorption is defined as the amount of water that concrete can absorb at atmospheric pressure. Concrete with water absorption lower than 5% is considered as concrete of good quality (Wilson and Tennis, 2021) and water absorption between 4-6% is acceptable (Tracz and Śliwiński, 2012).

The artificial pores play a minor role in determining the water absorption properties of foamed concrete since not all pores are interconnected (Nambiar and Ramamurthy, 2006) The primary factor influencing water absorption properties is the paste phase of the concrete. It was observed that an increase in the porosity of foamed concrete leads to greater oxygen and water vapour permeability (Nambiar and Ramamurthy, 2009).

2.15.2 Sorptivity

Sorptivity measures a material's ability to absorb and transport water through capillary action. It provides insight into the microstructure of concrete and influences its durability. Sorptivity has gained popularity as a method for assessing concrete's resistance to aggressive environments over time (Uzoegbo, 2020).

Sorptivity provide a better interpretation of water transmission property for foamed concrete rather than permeability. Sorptivity depend on filler type, pore structure and permeation mechanisms. The greater the foam volume in the mix, the lower the sorptivity for the produced foamed concrete (Nambiar and Ramamurthy, 2007). Foamed concrete with fly ash as fine aggregate has higher sorptivity than those with sand (Jones and McCarthy, 2005).

Relationship between sorptivity and compressive strength: Concrete with lower sorptivity has lower permeability and has higher compressive strength (Balakrishna et al., 2020).

2.16 Functional Characteristics

Three main functional properties being popular study of foamed concrete was thermal insulation, noise insulation and fire resistance.

Thermal insulation is often associated with thermal conductivity. Thermal conductivity is the ability of a material to transfer heat from one side to the other. It is denoted by the thermal conductivity coefficient λ. A material with good thermal insulation has low thermal conductivity and vice versa (Asadi et al., 2018).

Generally, building materials with high thermal insulations is preferable since it increase the energy-efficiency. Material with high thermal insulation properties also applicable in other field such as oil, gas, and petrochemical industries. Construction material with high thermal insulation able to limit the transfer of energy between the internal and external environment (Bahadori, 2014).

Foamed concrete has lower thermal conductivity than normal density concrete depending on its mix composition (Zhang et al., 2015). Overall, the foam used for foamed concrete production forms a negative correlation with the density of concrete as well as thermal conductivity for foamed concrete (Rommel, 2020).

According to ISO 1999:2013 model, a 18 years exposure of an 8-h average exposure (LEX) of 80 dBA or 75 dBA for 24-h L_{EX} is estimated to result in 2.1 dB or less of hearing loss in 99% of children. Therefore, sound insulation plays an important as a construction material. Foamed concrete was reported to has lower ability in resisting transmission of air borne sound since, transmission of air-borne sound was depended on mass law in which with each the doubling of the wall's mass or the sound's frequency, the sound insulation effect of a wall increases by 6 db. Foamed concrete offer better sound absorption properties but weaker sound deflects properties than normal concrete. Overall audible frequency transmission of foamed concrete only higher than normal concrete by 2 to 3% (Nambiar and Ramamurthy, 2009).

Foamed concrete has better fire resistance properties compared to normal concrete due to low unit weights and high air contents (Nambiar and Ramamurthy, 2009). Construction buildings made of high fire resistance materials can limit fire spread and intensity while maintaining structural integrity and functionality during and after a fire, this also helps to accumulate more evacuation time for occupants during a fire.

2.17 Fibre Reinforced Concrete (FRC)

Fibre reinforced concrete also known as Fibre-Reinforced Cementitious Composites (FRC) was beginning to gain popularity on 1960s. The fibres added to the concrete has two main purposes, which is overcome low tensile strength and low energy consumption capacity or toughness of concrete. By overcoming these two weaknesses of concrete it helps to control shrinkage crack and enhance mechanical property for concrete. Fibre reinforced concrete can be generally classified into 3 groups based on the fibre added into the concrete. 3 main groups are concrete with fibre volume fractions lesser than 1%, concrete with fibre volume fractions between 1 to 2% and high content fibre reinforced concrete with fibre volume fraction ranging from 5 to 20% (High-Performance Fibre-Reinforced Cementitious Composites, HPFRC). Concrete with low fibre volume fraction helps to reduce shrinkage cracking, moderate fibre volume fraction improved mechanical properties, modulus of rupture (MOR), fracture toughness, and impact resistance. While HPFRC has high strain-hardening property and can be used in highways, roadways & bridges (Li et al., 2022).

2.17.1 Factor Influencing FRC Properties

2.17.1.1 Type of Fibre

Fibre type can be view from the perspective of size and material. From the perspective of size, fibres having the diameter of 0.2 to 1 mm is classified as macrofibre, while microfibre is classified that those has diameter ranging few to tens of micrometres (Li et al., 2022).

Overtime, different materials has been used for FRC including steel, glass, cellulose, polypropylene and carbon. Table 2.10 shows different of fibre used for FRC and their respective properties.

Table 2.10: Properties for Different Fibre (Li et al., 2022).

Fibre	Diameter (μm)	Specific Gravity	Tensile Strength (GPa)	Elastic Modulus	Fracture Strain (%)
Steel	5-500	7.84	0.5-2.0	210	0.5-3.5
Glass	9-15	2.6	2.0-4.0	70-800	2.0-3.5
Fibrillated polypropylene	20-200	0.9	0.5-0.75	5-77	8.0
Cellulose	-	1.2	0.3-0.5	10	-
Carbon (high strength)	9	1.9	2.6	230	1.0
Cement matrix for comparison	-	2.5	3.7×10^{-3}	10-45	0.02

A FRC can achieve multiple-cracking and strain-hardening response when the fibres used are strong enough to carry the total load at the location of the first matrix transverse crack and there is a force transfer from fibre to matrix, resulting in tensile stress in the concrete matrix due to the strong fibre-cement interface (Li et al., 2022).

2.17.1.2 Fibre Volume Fraction

The addition of a low fibre volume enhances the energy-absorbing properties, whereas a high fibre volume fraction ratio improves the tensile strength of the matrix and alters the failure mode (Li et al., 2022). A study conducted by Pirah et al. (2023) shows that the inclusion of 0.2% kenaf, coir, sisal, and flax fibres, respectively, as volume fraction, can increase the compressive, splitting tensile, and flexural strength of concrete due to the fibres bridging the cracks.

2.18 Kenaf Fibre

Kenaf fibre is extracted from the bast, stem or core of Kenaf plant by manual retting process or field retting with mechanical separation. It is a non-wood plant fibres with 7.1% of microfibrillar angle and 44.3 % of crystallinity index (Silva et al., 2021). It composed of cellulose, lignin, holocellulose, hemicellulose and extractives (Lolo et al., 2020). Kenaf fibre is a green and sustainable material due to its eco-friendly cultivation practices and biodegradable nature. Kenaf fibre also has a strength comparable to other natural fibres, such as jute and flax.

Despite being various use of kenaf fibre. It faces one challenges, which are the dumping of kenaf fibre waste in the industry. About 15% of fibre is generated as waste during the manufacturing process in textile industry (Todor et al., 2019). The kenaf planted in Malaysia has an area of 1500 hectares and the kenaf shoot biomass production is 3000 tonnes in year 2022 (Ministry of Plantation Industries and Commodities, 2023).

2.18.1 Composition of Kenaf Fibre

Kenaf fibre extracted from different parts of the kenaf plant (*Hibiscus cannabinus, L., family Malvaceae*) varies in its organic composition of cellulose, hemicellulose, and pentosan as shown in Table 2.11. However, they all share a common characteristic: cellulose as the main component, hemicellulose and pentosan as the secondary component (Tezara et al., 2016). Likewise, composition of kenaf fibres as shown in Table 2.12 obtained from Malaysian Agricultural Research and Development Institute also has Cellulose as main component, Hemicellulose and Lignin as secondary component, Wax, Hydrotope and Pectin as minor component (Wang et al., 2016).

Cellulose is a non-branched macromolecule composed of Carbon (C), Hydrogen (H) and Oxygen (O_2). Figure 2.2 illustrates chemical structures of cellulose, hemicellulose, lignin and pectin. The general chemical formulae for cellulose are $C_6H_{10}O_5$. The strength of Kenaf Fibre depends on the content of cellulose content in fibre (Akil et al., 2011).

Hemicellulose is polysaccharide in cell wall that tightly binds to cellulose microfibrils through hydrogen bonds and Van der Waals forces. (Liu et al., 2020). It is located at the primary cell wall and is hydrophilic. Hemicellulose function as to strengthen cell wall, control bio and thermal degradation, and moisture absorption of kenaf fibre. While Pentosan percentage indicate the pentose-based carbohydrate in the fibre, including xylose (Akil et al., 2011).

Lignin is a phenolic compound featuring an —OH group attached to an aromatic ring (Britannica, 2024). Typically, lignin provides support and mechanical strength to plants. In kenaf fibre, lignin is found between the cellulose and hemicellulose and functions to bind them together (Tezara et al., 2016).

Table 2.11: Organic Composition of Kenaf Fibre (Tezara et al., 2016).

Organic composition of fibres				Inorganic (ash content) (%)	Fibre length (Average) (mm)	Composition of whole stem (%)
Fractions	Cellulose (%)	Hemicellulose (%)	Pentosan (%)			
Bast	56.4	26.2	13.4	2.2	2.48	34.3
Stem	48.7	28.1	19	1.8		
Core	46.1	29.7	20.7	1.6	0.72	65.7

Table 2.12: Composition of Kenaf Fibres Obtained from Malaysian Agricultural Research and Development Institute (Wang et al., 2016).

Fibre	Wax (%)	Hydrotrope (%)	Pectin (%)	Hemicellulose (%)	Lignin (%)	Cellulose (%)
Kenaf A	0.94	1.29	0.57	16.28	14.67	66.24
Kenaf B	2.27	2.38	1.95	12.60	19.24	61.56
Kenaf C	1.70	1.47	0.46	18.98	16.47	60.93
Kenaf D	1.30	1.24	2.68	17.45	16.61	60.68
Kenaf E	1.19	1.97	0.65	19.91	15.82	60.46
Kenaf F	0.72	0.89	0.38	15.26	16.93	65.79
Kenaf G	1.07	0.81	0.69	17.88	15.94	63.60
CV %	39.71	39.47	84.69	14.52	8.49	3.93

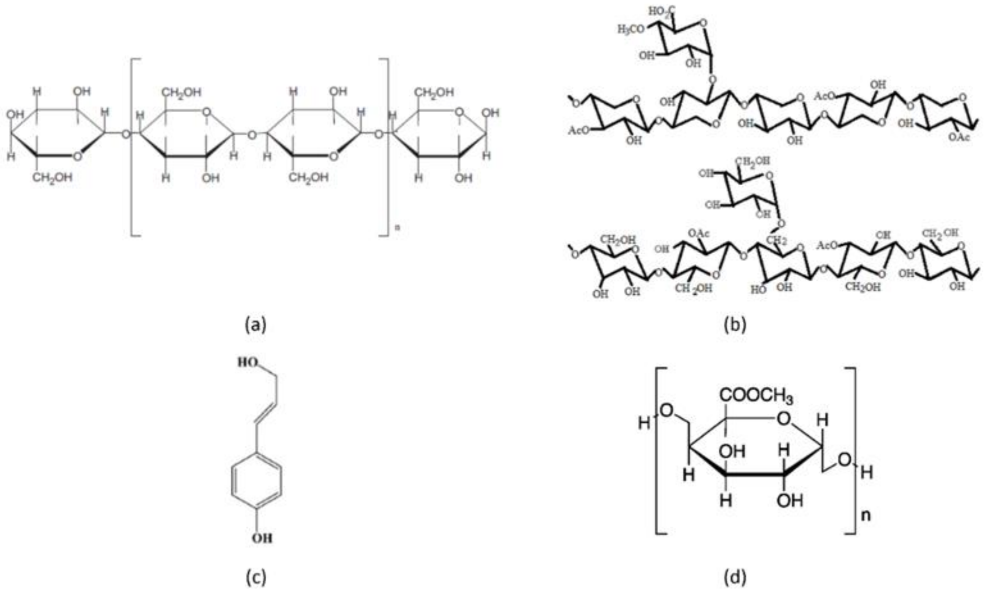


Figure 2.2: Chemical Structure for (a) cellulose; (b) hemicellulose; (c) lignin; (d) pectin (Tezara et al., 2016).

Figure 2.3 shows the ultrastructure of a plant cell and the arrangement of cellulose, hemicellulose, lignin, pectin, and other components in the plant (Balk et al., 2023).

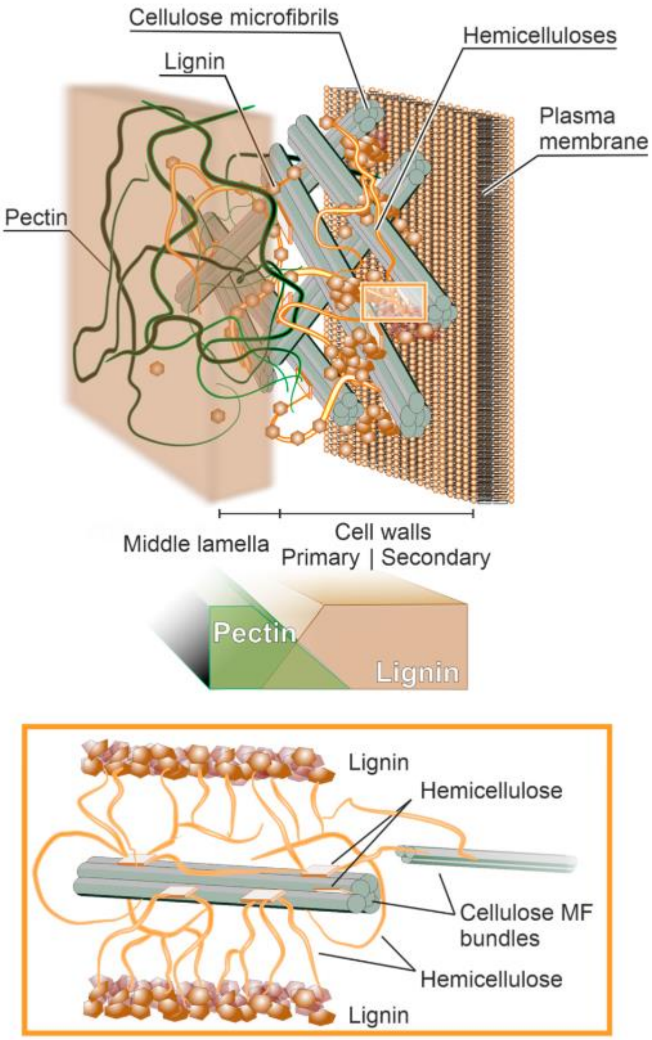


Figure 2.3: Ultrastructure of Plant Cell (Balk et al., 2023).

2.18.2 Properties of Kenaf Fibre

Kenaf fibre has high tensile strength, it can achieve tensile strength up to 930MPa.

Table 2.13 shows tensile strength, tensile modulus and elongation for kenaf fibre with different density reported by researchers. The inconsistency of results is due to variation in type of kenaf fibres used in terms of the place of origin as well as retting method (Saba, Paridah and Jawaid, 2015).

Table 2.13: Properties of Different Specimen of Kenaf Fibre (Saba, Paridah and Jawaid, 2015).

Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)
-	692	10.94	4.3
-	930	53	1.6
1.45	930	53	1.6
1.4	284-800	21-60	1.6
1.5	350-600	40	2.5-3.5
0.75	400-550	-	-
0.6	-	-	-
0.749	223-624	11-14.5	2.7-5.7
1.2	295	-	3-10

Kenaf fibre, like other types of natural fibre, is naturally hydrophilic. Kenaf fibre’s hydrophilic characteristic is attributed to its high cellulose and hemicellulose content which are polar molecules (Tezara et al., 2016). A hydrophilic material is one that forms hydrogen bonds with water. Water has partial positive charge at its Hydrogen atom and partial negative charge in Oxygen atom (Renshaw et al., 2022). A hydrogen bond formed when the partial positive charge of a water molecule is attracted to the partial negative charge of a fibre (in this case OH-hydroxyl group in cellulose (Oh and Park, 2022) and hemicellulose (Lu et al., 2021).

2.18.3 Bonding Between Fibre and Matrix

The hydrophilic nature of kenaf fibre presents a major drawback when it comes to forming an interphase bond with the matrix. A key challenge for fibre-reinforced concrete is the lack of strong interfacial adhesion between the kenaf fibre and the matrix. This issue arises because the hydrophilic kenaf fibre struggles to form a solid bond with the relatively nonpolar cement matrix due to fibre’s high hydrophilicity limits the wetting of the filler surface (Akil et al., 2011). Additionally, the high-water absorption of the hydrophilic kenaf fibre contributes to significant shrinkage issues (Mahzabin et al., 2018).

Impurities on the surface of fibre was also reported to weaken interfacial adhesion between the kenaf fibre and the matrix (Tezara et al., 2016).

2.19 Chemical Treatment for Kenaf Fibre

Chemical treatment for kenaf fibre serves as a method to modify the surface of the kenaf fibre, thereby affecting its mechanical properties and the bonding properties between kenaf fibre and matrices (Tezara et al., 2016). Several types of chemical treatments have been employed, including acetylation, isocyanate treatment, silane treatment, and alkaline treatment, with alkaline treatment being the most popularly studied method (Akil et al., 2011).

2.19.1 Alkaline Treatment

Alkaline treatment (or mercerization) involves immersing kenaf fibre in an alkaline solution for a certain period of time. Sodium hydroxide (NaOH) is widely used in alkaline treatment (Hamidon et al., 2019). Alkaline treatment can modify the surface of kenaf fibre by removing wax, oils, lignin, and some hemicellulose, thereby increasing the adhesion strength between the fibre and matrix (Akil et al., 2011).

Additionally, alkaline treatment disrupts the hydrogen bonding that maintains the crystalline structure of cellulose. This disruption of hydrogen bonds enhances the surface roughness of the fibre, leading to improved adhesion properties of kenaf fibre. (Akil et al., 2011; Castañeda and Mallol, 2013; Jarvis, 2023). Due to the alkali treatment and disruption of hydrogen bonding, the amorphous cellulose content of the fibre increased by converting crystalline cellulose to amorphous cellulose (Verma and Goh, 2021). Figure 2.4 illustrates the structures of amorphous and crystalline cellulose. An increase in the amount of amorphous cellulose indicates a higher surface area-to-volume ratio, thereby enhancing fibre-matrix bonding (Akil et al., 2011).

A study by Taib, Ariawan, and Ishak (2014) indicates that the crystallinity index of kenaf fibres improves with alkali treatment due to the removal of cementing materials, which releases the initial strain between cellulose chains and facilitates the formation of new hydrogen bonds, resulting in a tighter packing of cellulose chains. However, alkali treatment beyond 2 hours can reduce crystallinity due to the excessive extraction of hemicelluloses and lignin, which disrupts the arrangement of cellulose chains.

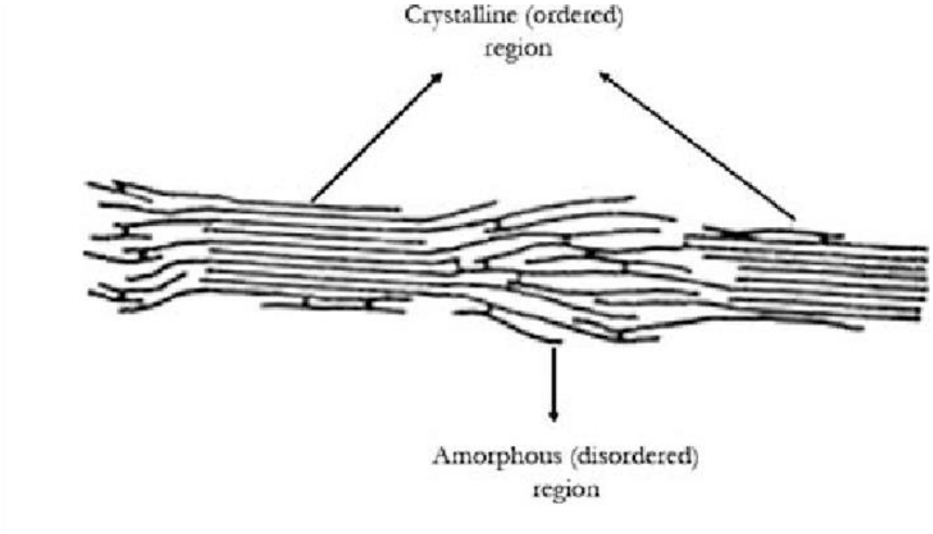


Figure 2.4: Crystalline and Amorphous Structure of Cellulose (Visakh, P.M. and Thomas, S., 2010).

The chemical equation under the ionization of hydroxyl group to alkoxide of natural fibre is given by Equation 2.1 (Hamidon et al., 2019).

$$\mathrm{Fibre} - \mathrm{OH} + \mathrm{NaOH} \rightarrow \mathrm{Fibre} - \mathrm{ONa}^{+} + \mathrm{H_2O} \qquad (2.1)$$

Researcher had conducted an experiment to test the optimal concentration for treating kenaf fibre. Treatment concentrations of 3% (0.75 mol), 6% (1.5 mol), and 9% (2.25 mol) NaOH for 3 hours were used in the experiment. Fibre was washed and let dry at room temperature for 48 hours before fibre bundle test. The results show that 6% (1.5 mol) NaOH is the most optimal treatment condition as it yields the highest fibre bundle tensile strength. A concentration of NaOH that is too low does not fully remove impurities from the surface of kenaf fibre, while a high concentration of NaOH damages the fibre and results in a lower tensile strength than that of untreated kenaf fibre (Edeerozey, 2007).

Furthermore, a study by Alavudeen et al. (2015) found that kenaf fibre treated with a 10% (2.5 M) NaOH solution for 8 hours exhibited the highest tensile strength compared to fibres treated with 5% (1.25 M) and 15%

(3.75 M) NaOH solutions for 2, 4, 6, and 8 hours. The authors suggest that the 10% (2.5 M) NaOH concentration increases the surface roughness of the fibres, which enhances adhesion between the fibres and the matrix.

Moreover, a study by Ibrahim et al. (2018) suggests that kenaf fibre treated for 3 hours in a 6% (1.5 M) NaOH solution has the highest tensile strength compared to fibres treated for 3 hours in 2%, 4%, and 8% NaOH solutions.

Meanwhile, a study by Taib, Ariawan, and Ishak (2014) found that kenaf fibre treated with 6% (1.5 M) NaOH for 3 hours exhibited the highest flexural strength among fibres treated for 1, 2, 3, 4, and 5 hours. The authors also suggested that extended immersion in an alkali solution may have caused excessive removal of the binding substances, potentially weakening the macrofibril structure and damaging the fibre cell walls.

2.20 Lightweight Foamed Concrete with Kenaf Fibre

Over time, there are only limited studies to examine the impact of different types of NaOH-treated kenaf fibres in foamed concrete. A summary of their findings is presented in Table 2.14.

A study conducted by Othuman et al. (2022) observed that the inclusion of kenaf fibres in lightweight foamed concrete reduced the workability of the fresh concrete while decreasing water absorption and porosity. Another study by Pirah et al. (2023) also supported that the inclusion of kenaf fibres in lightweight foamed concrete increases its compressive strength, flexural strength, and splitting tensile strength. The results further show that these strengths are positively correlated with the tensile strength of the fibres incorporated into the lightweight foamed concrete. The study also found that, overall, as the cellulose content of the fibres increases, their tensile strength improves, indicating that cellulose contributes most significantly to the tensile strength of the fibres.

Table 2.14: Investigation Conducted on Kenaf Fibre Treatment with NaOH.

Author	Kenaf Fibre Condition and Treatment	Result and observation
(Mahzabin et al., 2018)	6% (1.5 mol) NaOH, 12 hours immersion period, $5\text{mm} \pm 1\text{mm}$ length. Target density $1350\text{kg/m}^3 \pm 50\text{kg/m}^3$	• LFC-UF has highest drying shrinkage, LFC-TF has lowest drying shrinkage and LFC-CTR has intermediate drying shrinkage at 25 days. • LFC-TF has better fibre-matrix adhesion than LFC-UF. • Upon 30 wet/dry cycling LFC-TF has highest 28 days compressive strength followed by LFC-UF and LFC-CTR.
(Awang, Ahmad and Al-Mulali, 2015)	0.1mol NaOH over night with 0.25% and 0.40% out of the total volume of the mix. Target density 1000kg/m^3.	• LFC-TF has lower compressive strength compared to LFC-CTR due to higher water demand to achieve same workability as LFC-CTR. • LFC-TF with 0.40% content of kenaf fibre by volume has greater tensile splitting strength and flexural strength than LFC-TF with 0.25% content of kenaf fibre by volume. • LFC-TF has lower drying shrinkage compared to LFC-CTR. • Fibre in lightweight foamed concrete reduce workability

2.21 Water Cement Ratio

The water-cement (w/c) ratio is a critical factor influencing the fresh properties of concrete, including workability, fluidity, consistency, and stability. The fresh properties of concrete are essential for ensuring proper handling, placement, and compaction, which ultimately impact the hardened properties and durability of the material. Various studies have explored the relationship between the w/c ratio and the fresh properties of different types of concrete, including lightweight foamed concrete.

According to Neville (2011), an increase in the w/c ratio generally enhances the workability and fluidity of fresh concrete. A higher w/c ratio results in more water available in the mix, which reduces internal friction between aggregate particles and the cement paste, thus making the mixture easier to mix, transport, and place. This is supported by Mehta and Monteiro (2014), who note that a higher w/c ratio reduces the viscosity of the cement paste, leading to improved flowability and spreadability. They explain that this increased workability is beneficial in situations where concrete must flow easily, such as in heavily reinforced sections or complex formworks. Moreover, a study conducted by Haach, Vasconcelos, and Lourenço (2011) also indicates that the flow table value of a mortar mix increases as the water-cement ratio increases.

However, while a higher w/c ratio improves workability, it may also lead to potential drawbacks, such as increased segregation, bleeding, and a reduction in overall strength and durability. Mehta and Monteiro (2014) further explain that excessive water in the concrete mix can cause the heavier aggregates to settle more easily, resulting in segregation. Additionally, water that is not consumed during the hydration process may rise to the surface, causing bleeding. Both phenomena can adversely affect the homogeneity and strength development of the hardened concrete.

Studies specific to lightweight foamed concrete, such as those by Kearsley and Wainwright (2001), illustrate the sensitivity of this material to variations in the w/c ratio. In lightweight foamed concrete, which includes entrained air to reduce density and improve thermal insulation properties, the balance between workability and stability is particularly crucial. Kearsley and Wainwright (2001) found that while a higher w/c ratio can improve workability, making the mix easier to pour and finish, it can also result in a weaker foam structure and reduced mechanical properties. The air-entrained nature of foamed concrete means that excess water can lead to the collapse of air bubbles, affecting both the fresh and hardened properties of the concrete. A study conducted by Singh, Munjal, and Thammishetti (2015) also supports Kearsley and Wainwright's (2001) findings that as the w/c ratio of a concrete mix increases, the compressive strength initially increases. However, the compressive strength begins to decrease once the w/c ratio exceeds the optimum level, as the excess water leads to increased porosity in the concrete, thereby reducing its strength.

In conclusion, the relationship between the w/c ratio and the fresh properties of concrete is a complex balance. A higher w/c ratio generally improves workability and fluidity, which can be advantageous in specific applications requiring ease of handling and placement. However, this improvement in workability often comes at the expense of reduced strength, increased segregation, and potential durability issues. For lightweight foamed concrete, where the integrity of the air-entrained structure is vital, finding the optimal w/c ratio is particularly important to ensure both adequate workability and sufficient strength. Thus, the selection of an appropriate w/c ratio should consider the specific requirements of the concrete application, the desired fresh properties, and the long-term performance objectives.

2.21.1 Optimum W/C Ratio

According to ACI 224R-90 a minimum water/cement ratio of 0.35 was required to ensure the workability of concrete as well as ensuring the hydration process. Low water/cement ratio will result in a mix that is too stiff and break the bubbles during the mix thereby difficult to achieve the target density. Whereas, high water/cement ratio cause low matrix strength and poor adhesion (Nambiar and Ramamurthy, 2006).

Others study found that the optimum sand to cement ratio is 1 and the optimum water to cement ratio is 0.4 for foamed concrete reinforced with polypropylene fibres (Allouzi, Qatawna and Kasasbeh, 2020).

Meanwhile, Tiong et al. (2018) suggest that a water-cement (w/c) ratio of 0.60 is the optimal ratio for lightweight foamed concrete with a density of 1200 ± 50 kg/m³, as it achieves the highest compressive strength among the tested ratios, which ranged from 0.56 to 0.64. Similarly, Lee et al. (2022) also support that a w/c ratio of 0.60 is the optimal ratio for lightweight foamed concrete with a density of 1200 ± 50 kg/m³, achieving the highest compressive strength compared to w/c ratios ranging from 0.56 to 0.64. Table 2.15 shows the mix proportions used by previous researchers in related studies.

Table 2.15: Cement/Sand/Water Ratio and Composition in Previous Studies.

Author	Cement/Sand/Water ratio and composition
(Mahzabin et al., 2018)	• 1: 1.5: 0.45 with 1% superplasticizer • Type I Portland cement (ASTM C150-07) • Foaming agent/water ratio 1:30 • Kenaf Fibre content 0.45% by volume
(Awang, Ahmad and Al-Mulali, 2015)	• 1: 1.5: 0.45 • Ordinary Portland Cement • Protein based foaming agent with 60-80 gram/litre • Kenaf Fibre content 0.25% and 0.4% by volume
(Tiong et al., 2018)	• 1:1:0.6 • Ordinary Portland Cement (52.5N) • Foaming agent/water ratio 1:20 • Lightweight foamed concrete with a density of 1200 ± 50 kg/m³
(Lee at al., 2022)	• 1:1:0.6 • Ordinary Portland Cement (52.5N) • Lightweight foamed concrete with a density of 1200 ± 50 kg/m³

2.22 Summary

In summary, type of cement, fine aggregate, water and fibre type plays important role in determining the fresh and hardened density of lightweight foamed concrete.

Fine aggregate of 0.6 mm will be used as it produce lightweight foamed concrete with greater strength.

Treated kenaf fibre gives better fibre-matrix adhesion. Higher volume fraction of treated kenaf fibre in the lightweight foamed concrete increase tensile splitting strength and flexural strength. However, high volume fraction of kenaf fibre reduce workability of concrete mix. Table 2.16 shows summary table for literature review.

Table 2.16: Summary Table for Literature Review.

Author (s)	Findings
(Lim et al., 2015)	Sand size with 0.60mm or below will be most optimum to produce lightweight foamed concrete with highest flexural strength, compressive strength, and ductility.
(Aldridge, D, 2005; Fu et al., 2020; Ramamurthy, Nambiar and Ranjani, 2009)	Preformed method with dry foam will be preferred to be used in this project because it is highly stable and has bubbles smaller than 1 mm, making it easy to blend with the base material.
(Ramamurthy, Nambiar and Ranjani, 2009)	Pre-formed foaming is at advantage compared to mixed foaming techniques for two reasons: it requires less foaming agent, and there's a direct link between the amount of foaming agent used and the air content in the mixture.
(Akil et al., 2011; Awang, Ahmad and Al-Mulali, 2015; Hamidon et al., 2019; Mahzabin et al., 2018)	Alkaline treatment of fibre enhances fibre-matrix adhesion in reinforced foamed concrete.

Table 2.17: (Cont).

(Edeerozey, 2007)	Among 0.75 mol, 1.5 mol and 2.25 mol NaOH treatment for kenaf fibre, 1.5 mol of NaOH treatment gives kenaf fibre with highest tensile strength.
(Awang, Ahmad and Al-Mulali, 2015)	Kenaf fibre of 0.4% as volume fraction in fibre reinforced concrete gives better tensile splitting strength and flexural strength compared to 0.2 %, but high kenaf fibre content will reduce workability.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter will focus on the overall strategy of the project and outline the materials, steps, procedures, and methods for carrying out the project. The American Society for Testing and Materials (ASTM) standards will be used as guidelines for this project.

3.2 Flow Chart

A flowchart was created to break down essential steps and provide a broader overview for proceeding with the experiment in this project. Figure 3.1 shows flowchart for this project.

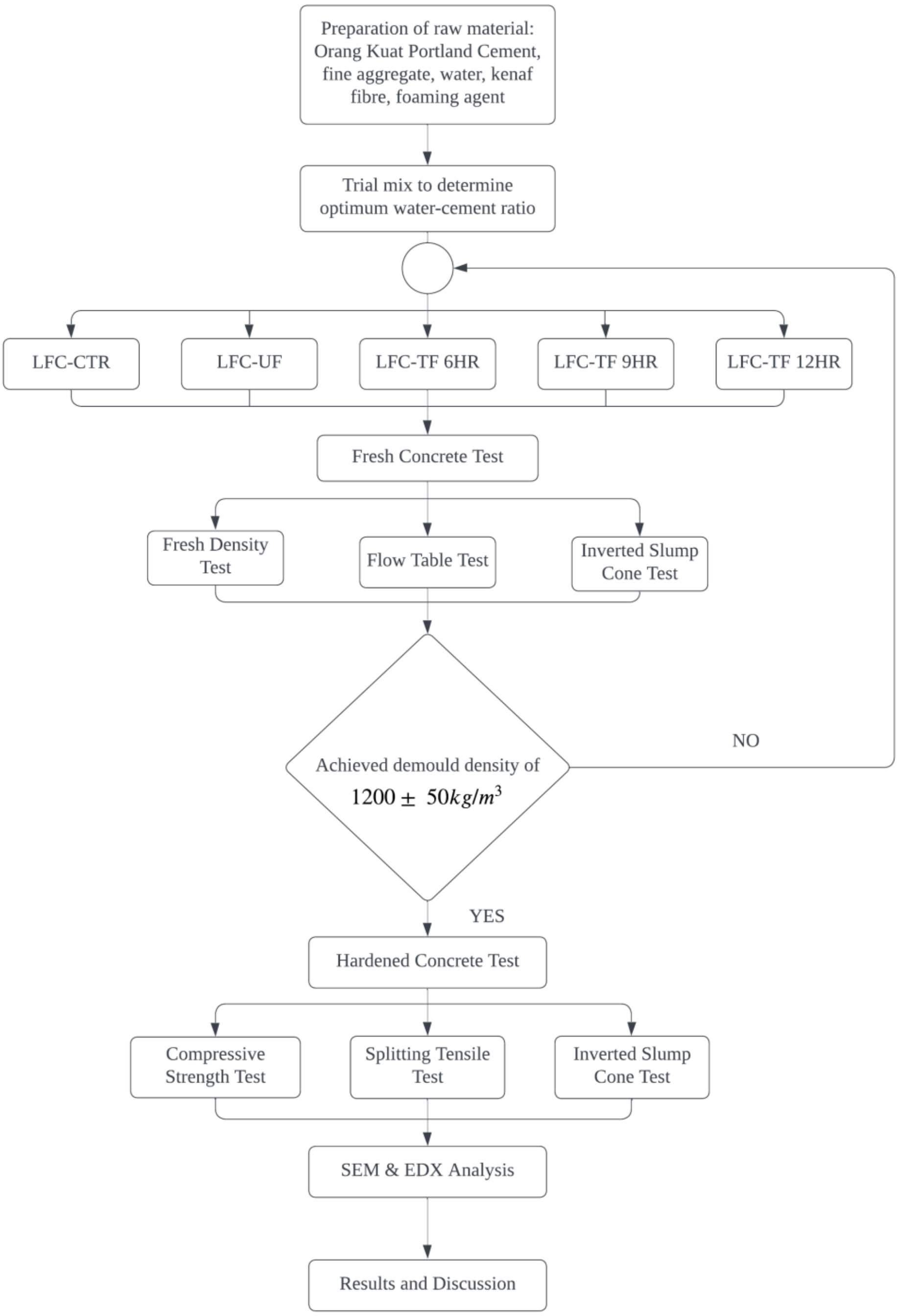


Figure 3.1: Flowchart of Project.

3.3 Raw Materials

The project used water, cement, sand as fine aggregate, kenaf fibre, and a foaming agent as raw materials.

3.3.1 Water

The project used tap water because it did not contain high levels of TDS, TSS, odour, or oil. It was also free from high levels of chemicals that could have impacted the hydration process of the concrete.

3.3.2 Ordinary Portland Cement (OPC)

The project used 52.5N "ORANG KUAT" Ordinary Portland Cement (OPC) from YTL Sdn. Bhd., in compliance with ASTM C 150 and MS EN 197-1 standards. Additionally, "ORANG KUAT" OPC was certified under MS ISO 14001 and OHSAS 18001 and met the requirements of Malaysian Standard MS 522: Part 1: 2003. Before use, the cement was sieved through a 300 μm sieve to remove any clinkers that may have reacted with water. After sieving, the cement was stored in an airtight container to prevent exposure to moisture. Sieving the cement ensured that only finer particles were used in the mix, providing a larger surface area for hydration, which accelerated strength development. Figure 3.2 shows the "ORANG KUAT" OPC, while Table 3.1 and Table 3.2 show the properties and chemical composition of CEM I 52.5N OPC.

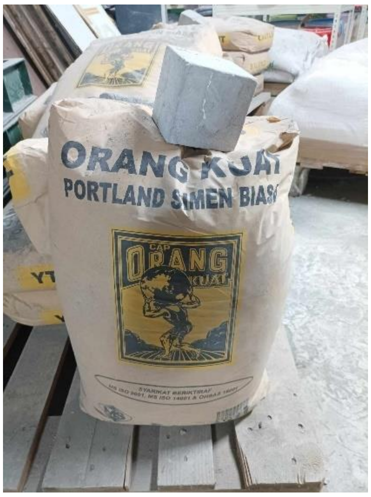


Figure 3.2: YTL Orang Kuat, CEM I Branded OPC.

Table 3.1: Properties of YTL Orang Kuat, CEM I Branded OPC (YTL Cement, 2024).

Test	Unit	Standard: MS EN 197-1:2014 CEM I 52.5N	Results
Chemical Composition			
Insoluble Residue	%	Not more than 5.0	0.4
Loss On Ignition (LOI)	%	Not more than 5.0	3.4
Sulphate Content	%	Not more than 3.5	3.1
Chloride Content	%	Not more than 0.1	0.01
Physical Properties			
Setting Time: Initial	mins	Not less than 45	155
Soundness	mm	Not more than 10	0.6
Compressive Strength (Mortar Prism): 2 days	MPa	Not less than 20	27.7
: 28 days	MPa	Not less than 52.5	58

Table 3.2: Chemical composition and physical properties of Typical CEM I 52.5N OPC (Karaxi et al., 2018).

Composition (% mass)	Cement
SiO_2	19.47
Al_2O_3	4.75
Fe_2O_3	3.43
CaO	63.16
MgO	1.43
SO_3	2.68
Na_2O	0.28
K_2O	0.62
Loss on Ignition	3.26
Specific Surface Area (cm^2/g)	3635

3.3.3 Fine Aggregate

The project used sand as the fine aggregate. The sand was dried in an oven for 24 hours to reduce its water content. After drying, the sand was sieved with a 600 μm sieve and then stored in a container. Figure 3.3 shows the oven used to dry the fine aggregate, while Figure 3.4 shows the process flow for handling the fine aggregate.

Fine aggregate refers to particles with a size of 4.75 mm or smaller. In this project, a 600 µm size was used because previous literature had shown that sand of this size yields the highest compressive strength.

A sieve analysis of the fine aggregate was performed to determine its fineness modulus. This analysis used different sieve sizes to assess the distribution of the aggregate by size. The sieve sizes used, from top to bottom, were 0.6 mm, 0.3 mm, 0.15 mm, 0.063 mm, and a pan, arranged in descending order from the largest sieve on top to the finest at the bottom. 500 g of oven-dried sand was placed on the top sieve and tightly sealed with the sieve lid to prevent sand from escaping during vibration. The shaker machine ran for 15 minutes after the sieve stack was firmly secured using screws. After the 15 minutes were up, the sieve stack was removed from the shaker machine, and each sieve was weighed to obtain the particle size distribution of the sand. Figure 3.5 shows the process in conducting sieve analysis.

Figure 3.3: Oven for Dry Sand.

Figure 3.4: Process Flow for Handling Fine Aggregate.

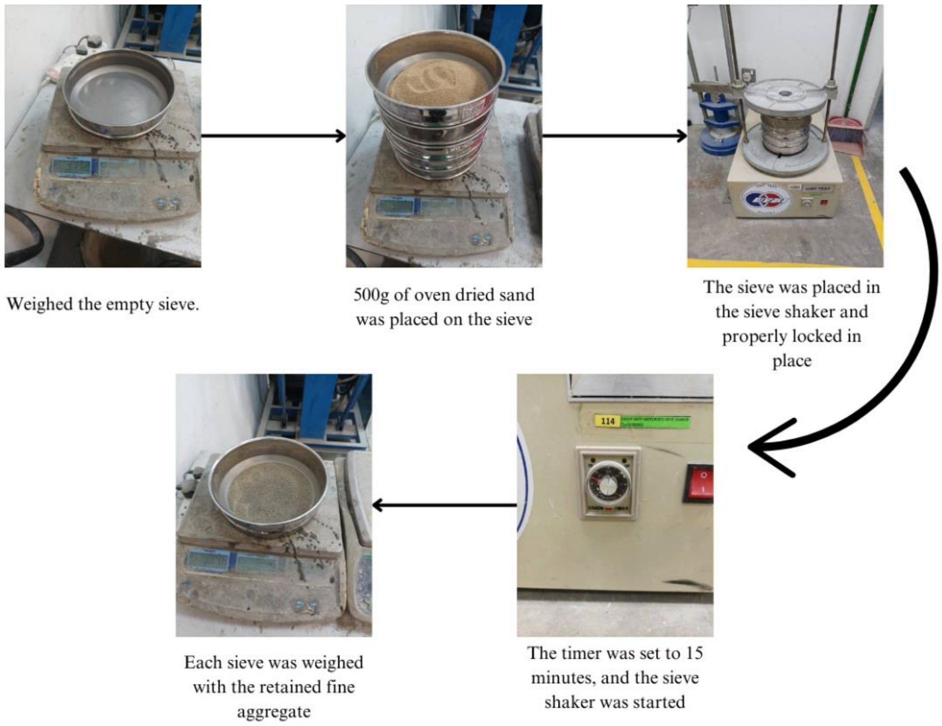


Figure 3.5: Process Flow for Sieve Analysis.

3.3.4 Kenaf Fibre

The kenaf fibre obtained for this project came from the bast of the kenaf plant. The fibre was manually trimmed to a length of 3 ± 1 cm. After trimming, the kenaf fibre underwent alkali treatment. The alkali solution was prepared by diluting NaOH solid to a 1.5 mol NaOH solution using tap water, and the kenaf fibre was then immersed in the alkali solution in a container for 6, 9, and 12 hours. The weight of kenaf fibre to NaOH solution ratio was set to 1:20. Oven drying was not permitted because kenaf fibre is highly flammable. Therefore, the kenaf fibre was spread on a metal tray and left outdoors to air dry. Both dried and untreated kenaf fibres were then split manually by hand to ensure consistency in the fibre-reinforced foamed concrete. Figure 3.6 shows the step-by-step process from fibre trimming to the treatment of fibre with NaOH solution. Figure 3.7 shows that as the duration of treatment increases, the kenaf fibre becomes darker in colour. The untreated kenaf fibre appears light brown, while fibres treated for 6 and 9 hours exhibit brown colours, and fibres treated for 12 hours display a dark brown colour.

Figure 3.6: Process Flow for Treatment of Kenaf Fibre.

a) b) c) d)

Figure 3.7: Kenaf Fibre with Different Treatment Duration: a) Untreated; b) Treated with 6 hours; c) Treated with 9 hours; d) Treated with 12 hours.

3.3.5 Foaming Agent

The project used SIKA® AER - 50//50 as the foaming agent. It was pressurized at 5 Bar (0.5 MPa) with a mixing ratio of foam to water of 1:20 in a foam generator machine to produce foam. This method, known as the dry foam method, involved producing foam by forcing a mixture of the foaming agent and water through a specialized nozzle using compressed air. Figure 3.8 illustrates the SIKA® AER-50//50 foaming agent, while Figure 3.9 shows the process flow for foam generation. Table 3.3 shows the product information and application information for SIKA® AER-50//50 foaming agent.

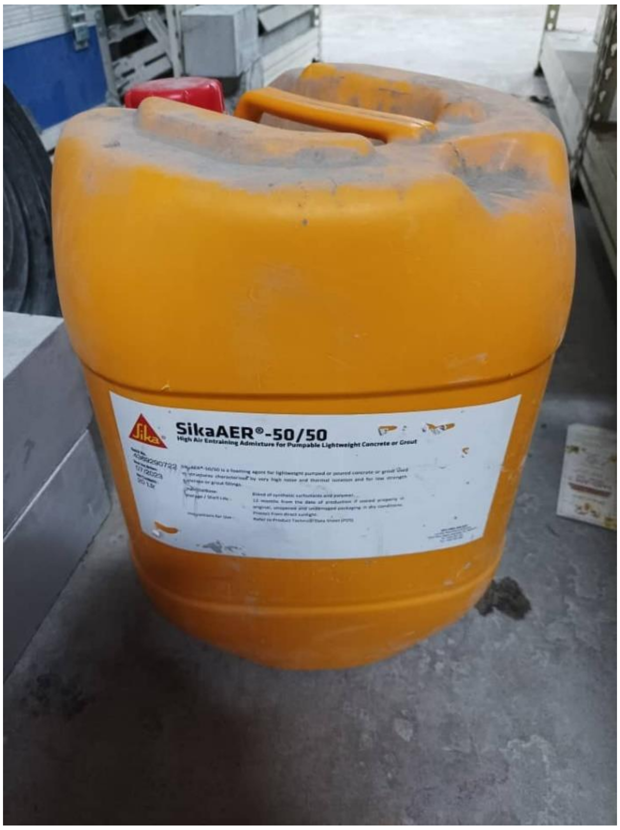
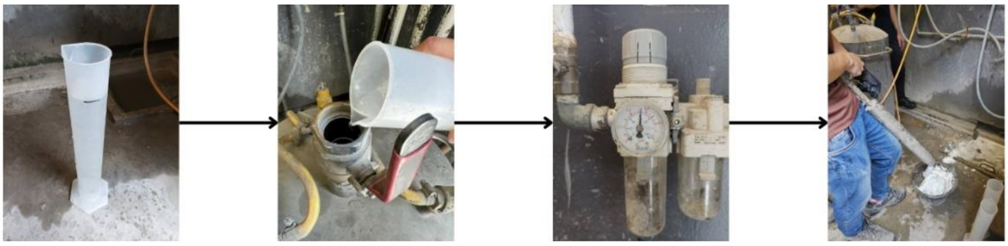


Figure 3.8: SIKA® AER-50//50 Foaming Agent.



A mixing ratio of the foaming agent to water was 1:20.

Foaming agent mix poured into foam generator

Foaming generator pressurized at 5 Bar

Foam collected by bucket

Figure 3.9: Process Flow for Foam Generation.

Table 3.3: Product Information and Application Information for SIKA® AER-50//50 foaming agent (Sika®, 2020).

Product Information	
Composition	Blend of synthetic surfactants and polymer
Packaging	20 L pail, 200 L drum
Appearance / Colour	Light straw liquid
Shelf Life	12 months from the date of production
Storage Conditions	Store properly in original, unopened, and undamaged packaging in dry conditions. Protect from direct sunlight.
Total Chloride Ion Content	Nil (less than 0.1% by weight)
Application Information	
Recommended Dosage	Sika® Aer 50/50 can be dosed at between 1.6–2.0 L per cubic meter of lightweight concrete.

3.4 Mould

A concrete mould was used to produce concrete forms in specific shapes, designs, and dimensions. These moulds were commonly made from materials such as plastic, metal, or silicone. In this project, a cube mould with a 100 mm length was used to produce concrete for the compressive strength test. A cylinder mould with a 200 mm length and 100 mm diameter was used to produce concrete for the flexural strength test. A prism mould with a 160 mm length, 40 mm width, and 40 mm depth was used to produce concrete for the flexural strength test. Figure 3.10, Figure 3.11 and Figure 3.12 shows cube, cylinder and prism moulds used in this experiment.

The bolts and nuts of the metal mould were properly secured, and the inner surface of the mould was cleaned before moulding the concrete. A thin layer of oil was applied to facilitate easier removal of the concrete and reduce the effort required to clean the inner surface. Applying mould oil also helped ensure a smooth concrete surface when the mould was removed. Figure 3.13 illustrates a thin layer of oil applied on mould’s surface.

Figure 3.10: Cube Mould.

Figure 3.11: Cylinder Mould.

Figure 3.12: Prism Mould.

Figure 3.13: Oil Applied on Mould’s Surface.

3.5 Trial Mix

A trial mix consisted of a batch of concrete mix prepared before the final concrete casting and testing. The trial mix was tested only for compressive strength and helped determine the optimal water-to-cement ratio for the concrete mix.

In this project, trial mixes with water ratios ranging from 0.52 to 0.64, with incremental intervals of 0.04, were employed for LFC-TF with a 12-hour treatment duration.

3.6 Cast Concrete Procedure

The mixing procedure for LFC-CTR, LFC-UF, and LFC-TF began with material preparation. All materials, including cement, fine aggregate, water, kenaf fibre, foaming agent, and water for foam production, were measured to the desired weight to achieve a density of 1200 kg/m³ ± 50 kg/m³. The cement, sand, and water were then added to the mixing bowl.

A flow table test was conducted prior to the addition of the foaming agent into the mortar mix. The test involved rotating the handle and recording the number of drops required for the cement paste to reach the edge of the metal plate. ASTM C230 served as the guideline for this test.

The foaming agent and water were added to the foam generator, with the pressure set to 0.5 MPa. Once the pressure reached 0.5 MPa, foam was extracted and filled into a bucket. The foam, kenaf fibre, and cement mixture were then mixed by hand with gloves, gently to avoid damaging the foam. Once the foam was mixed evenly, the concrete was poured into a 1-litre container to measure the fresh density and ensure it reached the target density of 1200 kg/m³.

After that, a slump test was performed to measure the consistency and workability of the fresh concrete. The slump cone was placed upside down in the centre of a metal tray, and the concrete mix was poured into the cone. Next, the slump cone was steadily lifted, and the diameter of the circle was recorded.

The mix was poured into different moulds. Then, the concrete in the moulds was left at room temperature for one day before demoulding. Afterward, the concrete was weighed to calculate its density, ensuring it fell within the target range of 1200 kg/m³ ± 50 kg/m³. Lastly, the concrete was stored in a water tank for the curing process. Figure 3.14 shows the process flow for the casting process.

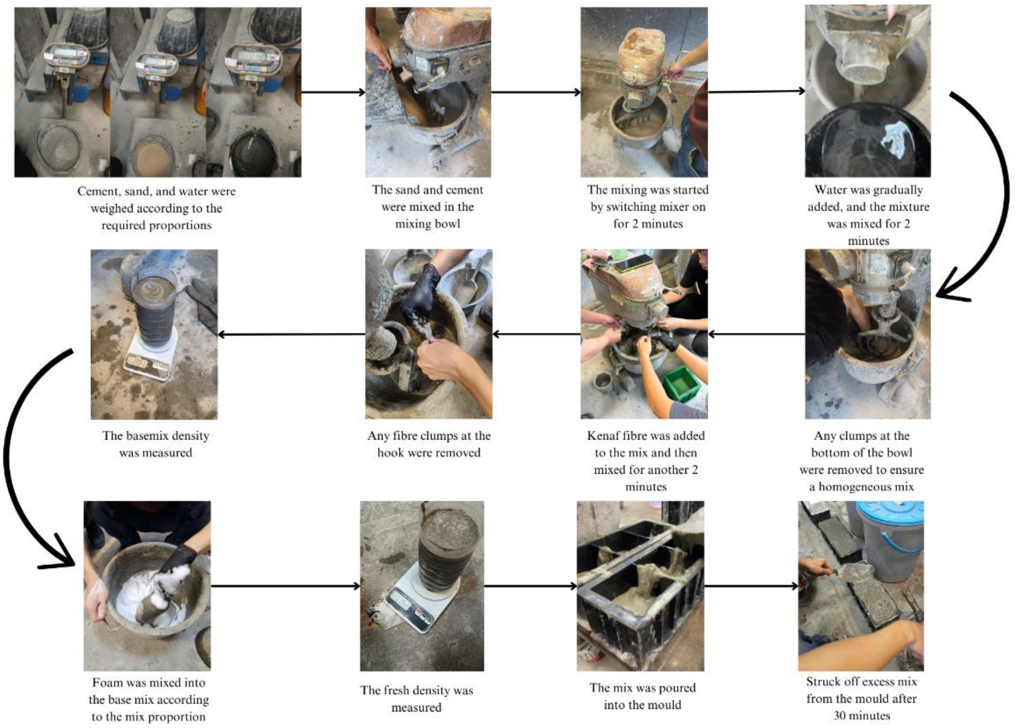


Figure 3.14: Process Flow of Concrete Casting.

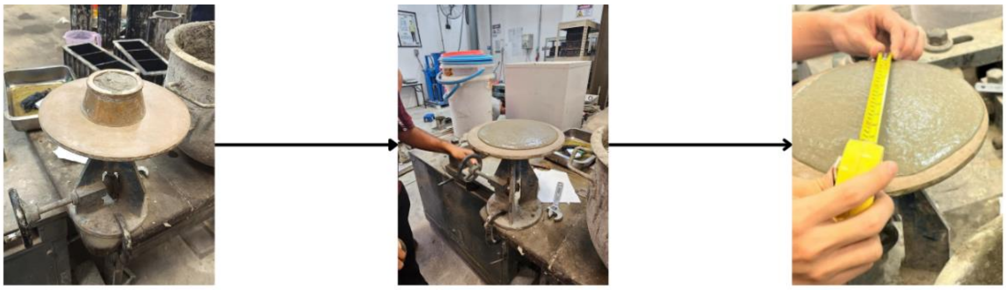
3.7 Fresh Concrete Test

3.7.1 Fresh Density Test

The fresh density test followed ASTM C796 standards. A straightforward method to measure the fresh density directly involved preparing a 1-liter volume container by filling it with 1 litre of water, then marking and trimming according to the water level. Next, the container filled with kenaf fibre was weighed. The fresh density was calculated by subtracting the weight of the container from the measured weight.

3.7.2 Flow Table Test

The flow table test was conducted before adding the foaming agent to the mortar mix. The test required rotating the handle and noting the number of drops needed for the cement paste to reach the edge of the metal plate. ASTM C230 provided the guidelines for this test. Figure 3.15 shows the process flow for flow table test.



Filled the mould and struck off the surface of the concrete with a trowel.

The mould was then removed from the concrete by a steady upward pull, and the table was dropped 25 times or until the concrete reached full spread

Measured and recorded the spread diameter and number of drops.

Figure 3.15: Process Flow for Flow Table Test.

3.7.3 Inverted Slump Cone Test

A slump test was performed to measure the consistency and workability of the fresh concrete. The slump cone was placed upside down in the center of a metal tray, and the concrete mix was poured into the cone, with any excess concrete at the top of the cone being scraped off. Next, the slump cone was steadily lifted. Then, the diameter of the circle was recorded from four different angles. The slump cone test was carried out according to ASTM C 1611. Figure 3.16 shows process flow for inverted slump cone test.

Filled the inverted slump cone and struck off the surface of the concrete with a trowel

The inverted slump cone was then removed from the concrete by a steady upward pull

The three largest diameters of the spread were measured

Figure 3.16: Process Flow for Inverted Slump Cone Test.

3.8 Concrete Curing

This project used concrete curing periods of 7 and 28 days. Curing was conducted to maintain the concrete at optimal temperature and moisture levels, allowing the hydration process to occur and helping the concrete develop strength. The concrete was fully submerged in water to ensure all parts of the concrete were at the same temperature and moisture level. Figure 3.17 illustrates the water curing process for the concrete specimen. After the curing periods of 7 and 28 days, the concrete was weighed, as illustrated in Figure 3.18.

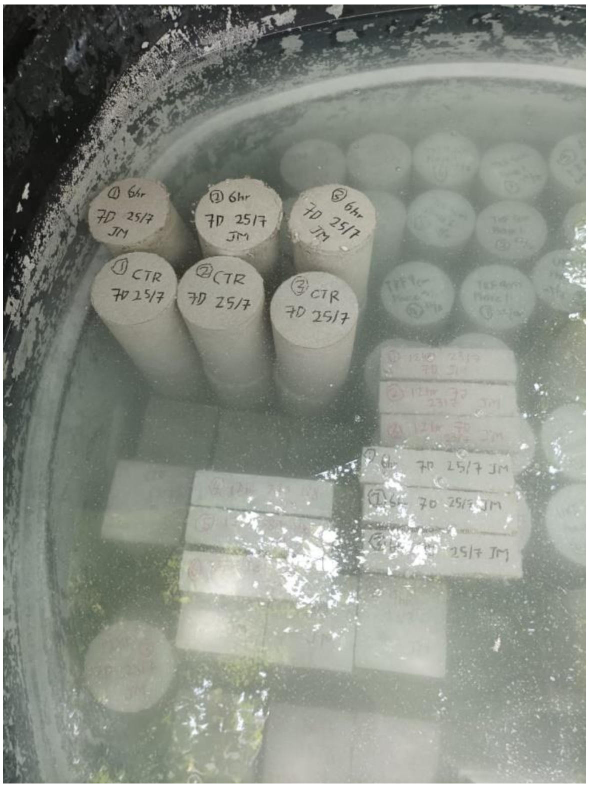


Figure 3.17: Concrete Specimen in Water Curing Tank.

Figure 3.18: Concrete Weighed Using a Weighing Machine.

3.9 Hardened Concrete Test

Compressive strength tests, splitting tensile strength tests, and flexural strength tests were carried out for concrete cured for 7 and 28 days. All concrete was oven-dried for 24 hours prior to the tests. The initial weight and the oven-dry weight of the concrete were recorded.

3.9.1 Compressive Strength Test

Cubes were used for the compressive strength test in this project. The compressive strength test was carried out in accordance with BS EN 12390-3. Before performing the compressive strength test, a flat surface of the concrete cube was selected as the base and top of the testing cubes to prevent uneven load distribution. The load applied on the sample was set at a constant rate of 0.1 kN/s. The maximum loading that caused failure of the block was recorded, and this maximum loading was then used to calculate the pressure applied using Equation 3.1. Figure 3.19 illustrate the equipment and setup for conducting compressive strength test.

$$f = \frac{P}{A} \tag{3.1}$$

Where

$\mathrm{f} = \text{Compressive strength, MPa}$

$\mathrm{P} = \text{Maximum load applied, N}$

$\mathrm{A} = \text{Area of contact, } \mathrm{m}^2$

Figure 3.19: Compressive Strength Test.

3.9.2 Splitting Tensile Test

The splitting tensile test was carried out according to ASTM C496. Firstly, cylindrical concrete specimens were prepared according to ASTM C192/C192M specifications, ensuring they were properly cured and had reached the required testing age (7 days and 28 days). It was important to verify that the specimen dimensions met ASTM C496 requirements, with a typical length-to-diameter ratio of 2:1 (200 mm to 100 mm was used for this project). The specimens were then marked with two lines at right angles along their length to align the loading strips accurately. Next, the specimen was placed horizontally in the testing machine on the loading strips, ensuring the marked lines aligned properly. After that, the load was applied at a steady rate of 0.2 kN/s until the specimen split. Finally, the maximum load at failure was recorded, along with the mode and type of split, whether straight or slanted. Figure 3.20 illustrate the equipment and setup for splitting tensile test.

The splitting tensile strength was calculated using Equation 3.2.

$$T = \frac{2P}{\pi \times L \times D} \qquad (3.2)$$

Where

T = Splitting tensile strength, Mpa

P = Maximum applied load, N

L = Length of the specimen, mm

D = Diameter of the specimen, mm

Figure 3.20: Splitting Tensile Test.

3.9.3 Flexural Strength Test

The flexural strength test was carried out according to ASTM C1609. To prepare for the test, concrete beam specimens were created according to ASTM C1609. ASTM C1609 specifies that the specimen should be a rectangular beam. The preferred dimensions specified by ASTM C1609 were not used, as the standard permits the use of other dimensions than those suggested in the guidelines. In this project, a concrete prism with a size of 160 mm in length, 40 mm in width, and 40 mm in height was used. Figure 3.21 illustrates the INSTRON Universal Testing Machine used for the flexural test of concrete specimens, while Figure 3.22 illustrates the setup of the specimen for the flexural test using the INSTRON Universal Testing Machine.

When setting up the test, the specimen was placed on the machine supports so that it was perpendicular to the supports, ensuring that the span length and support conditions were in line with the standard's requirements. A uniform load was then applied at a consistent rate at the center of the concrete with 2-point load supports on each side. During the test, the specimen's deflection was observed as the load was applied, and the load data was recorded throughout the process. The test was completed by continuing to apply the load until the specimen failed, and the maximum load at the point of failure was recorded.

The flexural strength was calculated using Equation 3.3.

$$f = \frac{PL}{bd^2} \tag{3.3}$$

Where

$\mathrm{f} = \text{Peak strength, MPa}$

$\mathrm{P} = \text{Maximum load, N}$

$\mathrm{b} = \text{Width of specimen, mm}$

$\mathrm{d} = \text{Depth of specimen, mm}$

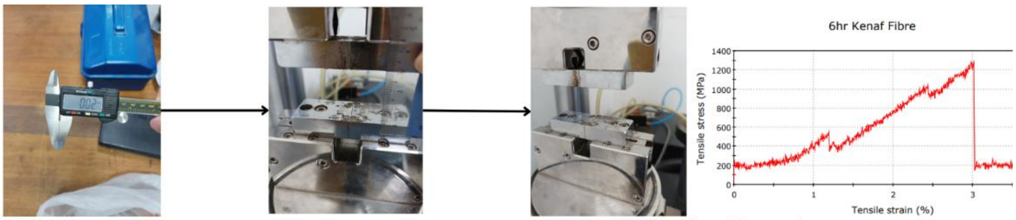
Figure 3.21: INSTRON Universal Testing Machine.

Figure 3.22: Setup of Specimen for Flexural Test.

3.10 Tensile Strength Test for Kenaf Fibre

Untreated and treated kenaf fibre with durations of 6, 9, and 12 hours were used for the tensile strength test. An INSTRON 5848 MicroTester Machine was used to test the tensile strength as illustrated in Figure 3.23. A single kenaf fibre has an irregular cross-sectional area that fluctuates along the fibre; ideally, the cross-sectional area should be obtained using an SEM machine. However, in this experiment, the diameter of the fibre was obtained using a digital vernier caliper. The diameters of different parts of the fibre along its length were measured, and the average value of the diameter was calculated. The test began with a pulling rate of 1 mm/min. Figure 3.24 shows process flow for the tensile strength test of kenaf fibre.

Figure 3.23: INSTRON 5848 MircroTester Machine.



The diameter of the kenaf fibre along its length was measured

Kenaf fibre was held at 30 mm in the INSTRON machine

Started the test and recorded the maximum pulling force from the user interface

Figure 3.24: Process Flow for the Tensile Strength Test of Kenaf Fibre.

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

SEM was used to produce detailed images of the kenaf fibre and concrete surface with high resolution. It helped provide a clearer view of the morphology and composition of the specimens. Figure 3.25 shows HITACHI S-3400N SEM machine used in this experiment.

EDX operated on the principle of high-energy electrons interacting with a sample. When electrons bombarded the sample, the sample emitted characteristic X-rays. By analysing the energy and intensity of these X-rays, the elements present in the sample were identified and quantified.

In this experiment, SEM and EDX, in compliance with ASTM C1723, were conducted on the fracture surfaces of the concrete samples following the compression tests, as well as on the kenaf fibre with different treatment durations. SEM samples needed to be electrically conductive and grounded to prevent the accumulation of electrostatic charge on the surface, which could result in electrostatically distorted images. In this case, the concrete and kenaf fibre samples were coated with a thin layer of gold using a sputter coater machine, as they are non-conductive materials. Figure 3.26 shows sputter coater machine used for gold coating. Once the surfaces of the concrete samples became conductive, they were placed in the vacuum chamber of the SEM machine, as shown in Figure 3.27. The samples were then scanned at a magnification of x500 and x1300 for normal imaging.

Figure 3.25: HITACHI S-3400N Scanning Electron Microscope Machine.

Figure 3.26: Sputter Coater Machine with Vacuum Pump (labelled “EDWARDS”).

Figure 3.27: Specimen were Placed into Vacuum Chamber of SEM Machine.

The EDX test was conducted after the SEM test and provided an elemental analysis that helped identify and quantify the elements present in both the kenaf fibres and the concrete matrix. Moreover, EDX can detect possible changes in the chemical composition of the kenaf fibres due to different treatment times.

3.12 Summary

In summary, the materials required to cast the concrete are water, cement, sand, a foaming agent, and treated and untreated kenaf fibre. Initially, a compressive strength test was conducted on the trial mix to determine the optimum water-to-cement (w/c) ratio. Subsequently, the tensile strength of fibre treated under different durations was tested to observe its correlation with the hardened properties of the concrete.

Moreover, fresh concrete tests, including the inverted slump cone test and the flow table test, were performed to assess workability. The concrete specimens were then cured for 7 and 28 days to evaluate their compressive, splitting tensile, and flexural strength. Finally, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) tests were conducted to study the morphology and elemental properties of the specimens.

CHAPTER 4

TRIAL MIX

4.1 Introduction

This chapter presents the fresh properties and compressive strength test results for LFC-TF 12HR under varying water-to-cement (w/c) ratios, with curing conditions of 7 and 28 days. The performance index is also computed to determine the optimum w/c ratio to be used later in the actual mix.

4.2 Sieve Analysis

Sieve analysis was done in this study to determine the fine aggregate grading used in this experiment. The results of sieving analysis were shown in Table 4.1 and Figure 4.1.

Table 4.1: Sieve Analysis Result.

Sieve Size (mm)	Retained Aggregate (g)	Retained Aggregate (%)	Cumulative Percentage Retained (%)	Percentage Pasing (%)
0.600	13.6	2.708	2.708	97.292
0.300	275.9	54.938	57.646	42.354
0.150	193.7	38.570	96.217	3.783
0.063	14.4	2.867	99.084	0.916
Pan	4.6	0.916	-	-
Total	502.2		255.655	

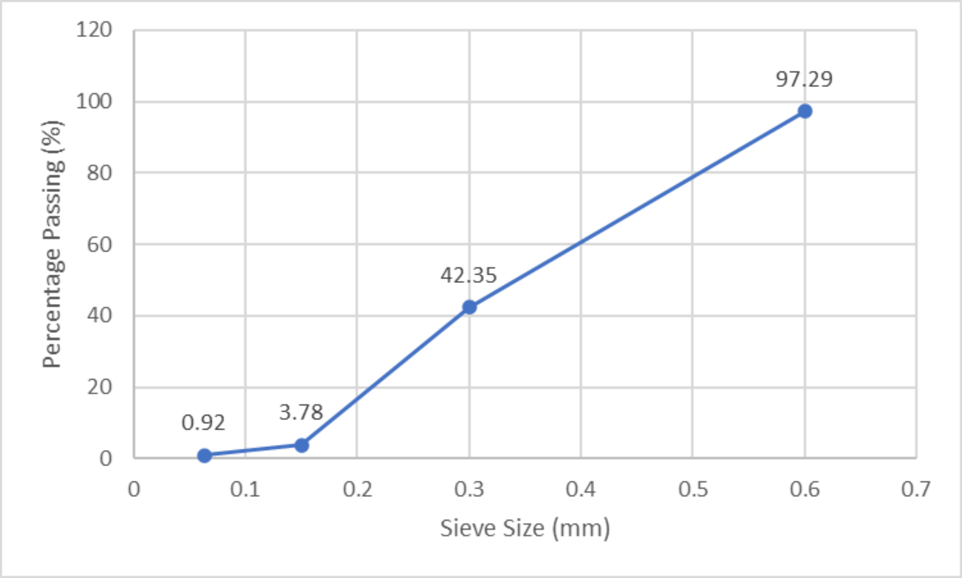


Figure 4.1: Sieve Analysis Graph.

The data in Table 4.1 shows that the fineness modulus of the fine aggregate is 2.56, indicating that the average size of the sand particles falls between the second sieve (0.30 mm) and the third sieve (0.15 mm).

4.3 LFC-TF 12HR

A range of water-cement (w/c) ratios of 0.52, 0.56, 0.60, and 0.64 was selected for the trial mix. The w/c ratio that yields the highest compressive strength will be considered the optimum for this experimental work. This range of w/c ratios, between 0.52 and 0.64, was selected based on a review of previous literature. According to Tiong et al. (2018) and Lee et al. (2022), the optimal w/c ratio for lightweight foamed concrete with a density of 1200 ± 50 kg/m^3 lies within this range.

4.3.1 Mix Proportion

The materials used to cast the LFC-TF 12HR included water, fine aggregates, Ordinary Portland Cement (OPC), treated kenaf fibre, and foam. The mix proportions were determined using the absolute volume method, and the required amount of foam to achieve the target density was calculated using the equation proposed by Wimpenny (2006). Table 4.2 shows the mix proportion for LFC-TF 12HR.

Table 4.2: Mix Proportions Based on 1 m³ concrete volume for LFC-TF 12HR.

W/C Ratio	Unit weight (kg/m^3)				
	Cement	Fine Aggregate	Water	Kenaf Fibre	Foam
0.52	475.25	475.25	247.13	2.38	18.93
0.56	467.82	467.82	261.98	2.38	18.49
0.60	460.62	460.62	276.37	2.38	18.07
0.64	453.64	453.64	290.33	2.38	17.66

4.3.2 Fresh Properties

The fresh properties were studied during the casting of the concrete. The average flow table spread and the average inverted slump diameter were measured to assess the workability and fluidity of the fresh concrete at different water-to-cement (w/c) ratios. Table 4.3 presents the fresh properties data collected for LFC-TF 12HR.

Table 4.3: Fresh Properties for Trial Mix LFC-TF 12HR.

W/C ratio	Average Flow Table Spread (mm)/(Number of drop)	Average Inverted Slump Diameter (mm)
0.52	232.5 / 25 times	432.0
0.56	245.0 / 19 times	522.7
0.6	245.0 / 15 times	522.0
0.64	245.5 / 16 times	610.0

The data provided for the fresh properties of lightweight foamed concrete (LFC-TF 12HR) with varying water-to-cement (w/c) ratios show that both the average flow table spread and the average inverted slump diameter increase as the w/c ratio rises. Specifically, the flow table spread values increase from 232.5 mm at a w/c ratio of 0.52 to approximately 245.5 mm at a w/c ratio of 0.64, while the number of drops needed to achieve these spreads decreases, indicating improved fluidity or workability with higher water content. Similarly, the inverted slump diameter, which measures the fluidity of the concrete, shows a significant increase from 432.0 mm at a w/c ratio of 0.52 to 610.0 mm at a w/c ratio of 0.64, further confirming that higher w/c ratios enhance the fluidity of the fresh concrete mix.

These observations align with findings in the literature, which suggest that increasing the w/c ratio reduces the viscosity of the concrete paste, thereby improving its workability. For instance, Neville (2011) notes that higher water content in a mix provides more lubrication between particles, reducing internal friction and making the concrete easier to handle and place. This result is consistent with the studies conducted by Haach, Vasconcelos, and Lourenço (2011), which found that the flow table value of a mortar mix increases as the water-cement ratio increases.

4.3.3 Consistency and Stability

Consistency and stability are crucial in lightweight foamed concrete because they directly affect the material's performance and durability. Consistency ensures that the concrete mix has uniform properties throughout, which is vital for achieving predictable workability, strength, and density. Stability, on the other hand, is essential to maintain the integrity of the foamed structure, preventing segregation, bleeding, or collapse of the air-entrained bubbles that provide its lightweight properties. A foamed concrete mix is considered to be stable when its ratio of measured fresh density to design density is close to one and does not experience segregation and bleeding issues. Without adequate consistency and stability, the concrete may experience variations in density and strength, leading to poor structural performance, reduced load-bearing capacity, and increased susceptibility to cracking and other forms of deterioration over time.

In this experiment, the consistency of lightweight foamed concrete is obtained by dividing the average fresh density by the target density, while stability is determined by dividing the average fresh density by the average hardened density. Table 4.4 presents the density of the concrete mix, as well as the consistency and stability values.

Table 4.4: Consistency and Stability for Trial Mix LFC-TF 12HR.

W/C Ratio	Average Fresh Density (kg/m^3)	Average Hardened Density (kg/m^3)	Consistency	Stability
0.52	1195.3	1190.4	0.9961	1.0042
0.56	1205.7	1214.8	1.0047	0.9925
0.60	1197.3	1199.8	0.9978	0.9980
0.64	1187.0	1216.6	0.9892	0.9757

The results presented in Table 4.4 indicate that all samples of lightweight foamed concrete exhibit high consistency and stability across the different water-to-cement (w/c) ratios. The consistency values range from 0.9892 to 1.0047, while the stability values range from 0.9757 to 1.0042. These values suggest that the concrete mixes maintain a uniform density and exhibit minimal variation between the fresh and hardened states, which is indicative of a well-proportioned mix with good cohesion and resistance to segregation. High consistency and stability are essential for ensuring uniform distribution of the cement paste and air voids, which directly contribute to achieving the desired compressive strength (Mehta and Monteiro, 2014).

4.3.4 Compressive Strength

The trial mix LFC-TF 12HR cube specimens were tested in accordance with BS EN 12390-3. To ensure that the compressive strength results were reliable, the density of all tested cubes was maintained at 1200 kg/m³ with a tolerance of ±50 kg/m³. Appendix A-1 shows the compressive test results for the trial mix, while Figure 4.2 illustrates the compressive strength of the trial mixes for LFC-TF 12HR with water-to-cement ratios ranging from 0.52 to 0.64, with increments of 0.04.

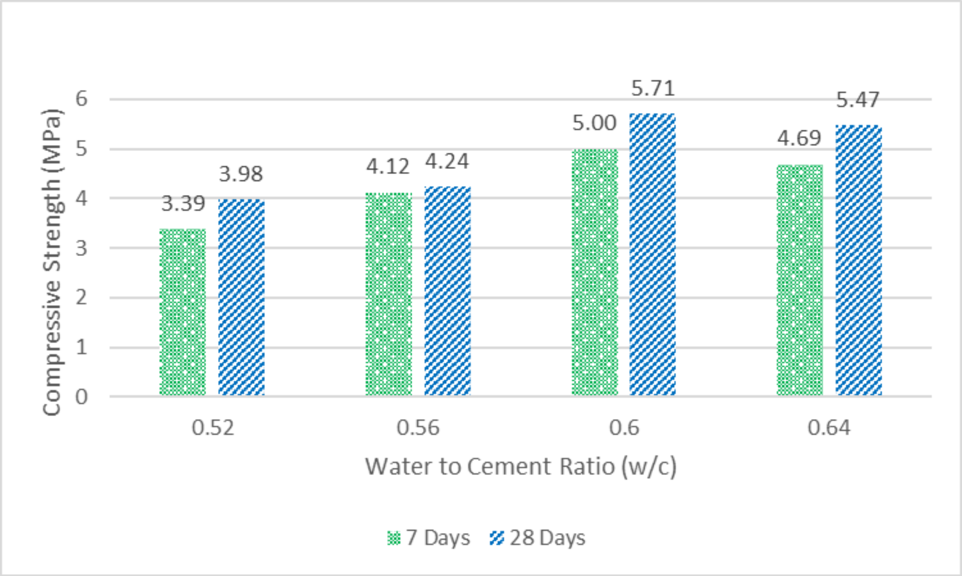


Figure 4.2: Compressive Strength of Trial Mixes for LFC-TF 12HR.

The data show that the compressive strength increases with an increasing w/c ratio up to 0.6, reaching a peak strength of 5.71 MPa at 28 days. Overall, there is a 43.5% increase in the 28-day compressive strength from a w/c ratio of 0.52 to 0.60. However, when the w/c ratio is further increased to 0.64, the compressive strength slightly decreases by 4.2%, resulting in a value of 5.47 MPa at 28 days.

These observations align with existing literature, which suggests that increasing the w/c ratio initially enhances the hydration process, thereby contributing to higher compressive strength (Neville, 2011). According to Mehta and Monteiro (2014), a moderate increase in water content improves the workability of the mix and ensures a more complete hydration of the cement particles, resulting in greater strength development over time.

The slight decline in compressive strength observed at a w/c ratio of 0.64 is consistent with findings that indicate that beyond a certain point, excess water can lead to increased porosity, which negatively impacts the overall strength of the concrete (Singh, Munjal and Thammishetti, 2015). Excess water in the mix can dilute the cement paste, leading to weaker bonding and more voids, ultimately reducing the concrete's load-bearing capacity (Mehta and Monteiro, 2014). This is reflected in the data, where a w/c ratio of 0.6 shows the highest compressive strength at both 7 and 28 days. Moreover, this result is consistent with previous studies by Tiong et al. (2018) and Lee et al. (2022), which found that the optimum w/c ratio for lightweight foamed concrete with a density of 1200 kg/m^3 ± 50 kg/m^3 is 0.60.

4.3.5 Performance Index

Since it is impossible for all lightweight foamed concrete specimens in this experiment to achieve the exact target density, and because concrete with higher density generally exhibits greater compressive strength due to reduced pore content (Kearsley, 2002), the performance index of each concrete mix was calculated to further verify the optimum water-to-cement (w/c) ratio. The performance index was calculated as the compressive strength per 1000 kg/m^3. Figure 4.3 presents the performance index of the trial mixes for LFC-TF 12HR with water-to-cement ratios ranging from 0.52 to 0.64, in increments of 0.04.

The analysis of the performance index (PI) for the LFC-TF 12HR trial mixes at 7 and 28 days indicates that the optimal water-to-cement (w/c) ratio is 0.60. The data show a positive correlation between the w/c ratio and PI values up to 0.60, where the performance index reaches its maximum. At this ratio, the PI is 4.10 MPa/1000 kg/m^3 at 7 days and 4.84 MPa/1000 kg/m^3 at 28 days, suggesting that this mix ratio yields the highest strength performance during the observed period. Beyond a w/c ratio of 0.60, a decline in PI is observed, with values decreasing to 3.85 MPa/1000 kg/m^3 and 4.50 MPa/1000 kg/m^3 for the 7-day and 28-day tests, respectively, at a w/c ratio of 0.64.

Therefore, a w/c ratio of 0.60 provides the highest strength performance, indicating that it is the optimal mix for achieving a balance between workability and strength development over time.

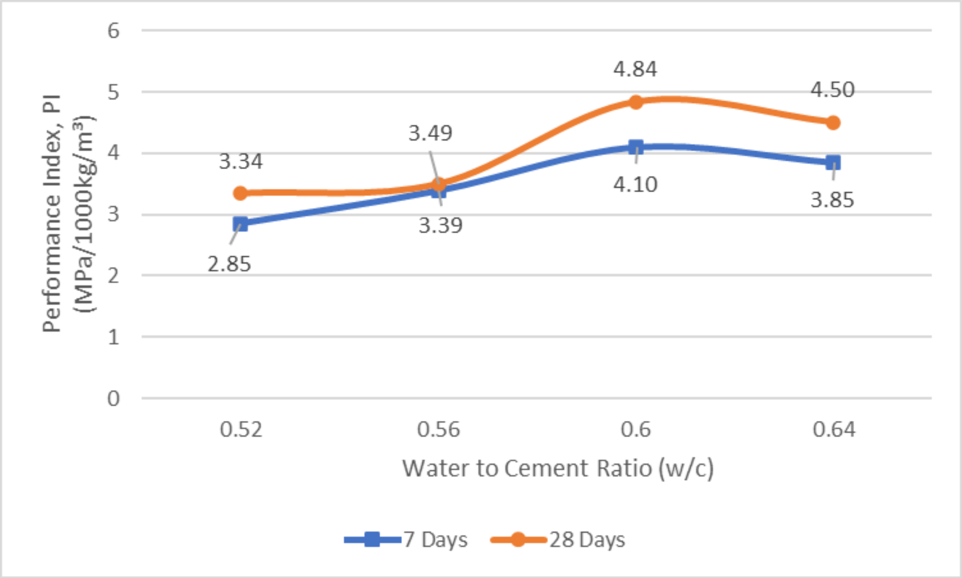


Figure 4.3: Performance Index of Trial Mixes for LFC-TF 12HR.

4.4 Summary

In summary, as the water-to-cement (w/c) ratio of LFC-TF 12HR increases from 0.52 to 0.60, the compressive strength also increases because the additional water facilitates more complete hydration within the concrete structure. However, the strength of LFC-TF 12HR decreases when the w/c ratio rises from 0.60 to 0.64 due to the excess water, which creates pores in the concrete and weakens its structural integrity. Additionally, the workability and flowability of LFC-TF 12HR increase as the w/c ratio increases. A w/c ratio of 0.60 is determined to be the optimum for LFC-TF 12HR and will be used for the actual mix.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

This chapter discusses the fresh properties of lightweight foamed concrete and lightweight foamed concrete incorporated with untreated kenaf fibre (LFC-UF) and kenaf fibre treated for different durations (LFC-TF 6HR, 9HR, 12HR). In addition, it covers the mechanical properties of LFC-CTR, LFC-UKF LFC-TF 6HR, 9HR, and 12HR, including compressive strength, splitting tensile strength, and flexural tests, with 7- and 28-day curing periods, along with their performance indices. Furthermore, the microstructure and morphology of LFC and kenaf fibre with different treatment durations are examined using Scanning Electron Microscopy (SEM) with Energy-Dispersive X-Ray (EDX) analysis. The tensile test results for fibres treated for 6, 9, and 12 hours are also included in this chapter.

5.2 Tensile Strength for Kenaf Fibre

Figure 5.1 illustrates the tensile strength of kenaf fibre (KF) treated with sodium hydroxide (NaOH) for different durations—6 hours, 9 hours, and 12 hours—showing a clear trend of increasing tensile strength with longer treatment times. The tensile strength for kenaf fibre treated for 6 hours (KF-6HR) is 846.45 MPa, which increases to 986.52 MPa for the fibre treated for 9 hours (KF-9HR) and reaches a maximum of 1142.54 MPa for the fibre treated for 12 hours (KF-12HR). Appendix A-6, Appendix A-7 and Appendix A-8 show the raw data for the tensile strength for kenaf fibre.

This trend suggests that extending the NaOH treatment duration significantly enhances the mechanical properties of kenaf fibres by improving the removal of non-cellulosic components such as lignin and hemicellulose. The 12-hour treatment duration yields the highest tensile strength among the tested durations, indicating its potential as the most effective treatment period for maximising fibre strength. However, while the results suggest that a longer treatment duration may continue to improve tensile strength, further investigation is needed to determine whether extending the duration beyond 12 hours would provide additional benefits or reach a point of diminishing returns. Similar research by Edeerozey (2007) and Taib, Ariawan, and Ishak (2014) found that treatment times longer than the optimal duration can weaken the macrofibril structure, damage the fibre cell walls, and lead to a loss in the strength of the kenaf fibre. Overall, the findings indicate that the tensile strength of kenaf fibres is strongly influenced by the duration of NaOH treatment, with the 12-hour duration emerging as the optimal treatment period within the scope of this study.

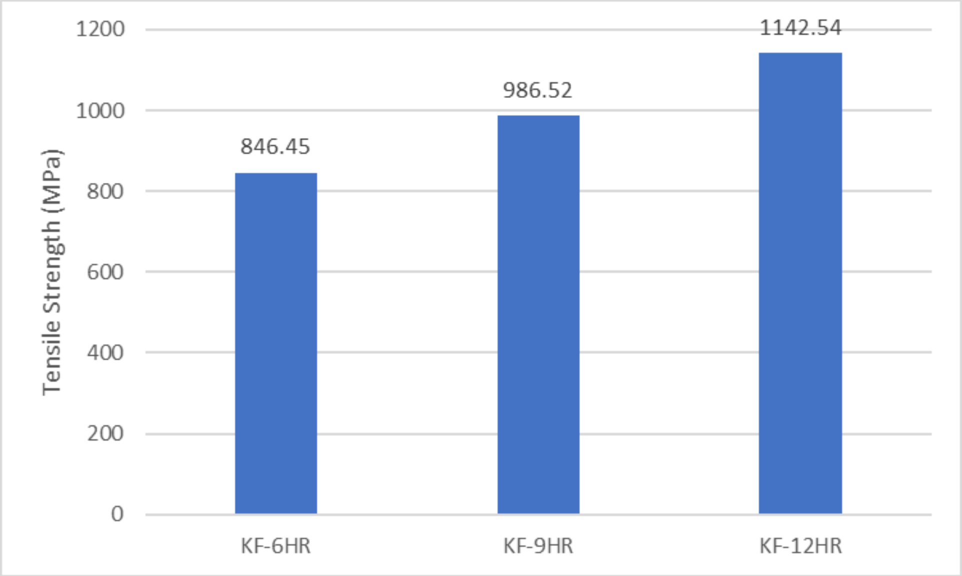


Figure 5.1: Tensile Strength for Kenaf Fibre with Different Treatment Duration.

5.3 Mix proportion

The materials used to cast the actual mix included water, fine aggregates, Ordinary Portland Cement (OPC), kenaf fibre treated for different durations, and foam. Table 5.1 presents the mix proportions for LFC-CTR, LFC-UF, LFC-TF 6HR, 9HR, and 12HR.

Table 5.1: Mix Proportion for Actual Mix.

Specimen	W/C Ratio	Unit Weight (kg/m^3)				
		Cement	Fine Aggregate	Water	Kenaf Fibre	Foam
LFC-CTR	0.6	461.54	461.54	276.92	0	18.11
LFC-UF	0.6	460.62	460.62	276.37	2.38	18.07
LFC-TF 6HR	0.6	460.62	460.62	276.37	2.38	18.07
LFC-TF 9HR	0.6	460.62	460.62	276.37	2.38	18.07
LFC-TF 12HR	0.6	460.62	460.62	276.37	2.38	18.07

5.4 Fresh Properties

The fresh properties were evaluated during the casting of the concrete. The average flow table spread and the average inverted slump diameter were measured to assess the workability and fluidity of the fresh concrete at different water-to-cement (w/c) ratios. Table 5.2 presents the fresh properties for the actual mixes (LFC-CTR, LFC-UF, LFC-TF 6HR, 9HR, and 12HR).

Table 5.2: Fresh Properties for Actual Mix.

Specimen	Average Flow Table Spread (mm)/ (Number of drop)	Average Inverted Slump Diameter (mm)
LFC-CTR	236.7 / 8 times	686.7
LFC-UF	237.3 / 13 times	686.0
LFC-TF 6HR	244.0 / 14 times	633.3
LFC-TF 9HR	227.5 / 13 times	581.7
LFC-TF 12HR	245.0 / 15 times	522.0

The data in the table shows the effects of untreated and treated kenaf fibres on the flowability and workability of lightweight foamed concrete (LFC), with the number of drops being a more crucial indicator of flowability than the spread in the flow table test. The control sample, LFC-CTR, which does not contain any fibres, requires only 8 drops to achieve an average flow table spread of 236.7 mm, serving as a baseline for comparison. The LFC-UF sample, containing untreated kenaf fibres, requires 13 drops to achieve a slightly higher flow spread of 237.3 mm, suggesting that the addition of untreated fibres increases resistance to flow, requiring more effort (as indicated by the number of drops) to achieve a similar spread. The overall trend indicates that as the treatment time of the kenaf fibres increases, the flowability of the lightweight foam decreases.

The average inverted slump diameter of LFC-TF 12HR also decreased by 24% compared to that of LFC-CTR. This data indicates a reduction in the workability of lightweight foamed concrete as the treatment time of the kenaf fibres increases. This decrease in workability is attributed to the longer treatment duration, which increases the surface roughness of the fibres and, consequently, the internal friction with the cement matrix (Hamidon et al., 2019).

5.5 Consistency and Stability

Table 5.3 shows the consistency and stability of the actual mix. Consistency is determined by dividing the average fresh density by the target density, while stability is calculated by dividing the average fresh density by the average hardened density. The consistency values range from 0.9865 to 1.0114, while the stability values range from 0.9911 to 1.0085. These values suggest that the concrete mixes maintain a uniform density and exhibit minimal variation between the fresh and hardened states, indicating a well-proportioned mix with good cohesion and resistance to segregation. High consistency and stability are essential for ensuring the uniform distribution of the cement paste and air voids, which directly contributes to achieving the desired compressive strength (Mehta and Monteiro, 2014).

Table 5.3: Consistency and Stability for Actual Mix.

Specimen	Average Fresh Density (kg/m^3)	Average Hardened Density (kg/m^3)	Consistency	Stability
LFC-CTR	1183.8	1187.7	0.9865	0.9967
LFC-UF	1210.3	1214.2	1.0086	0.9968
LFC-TF 6HR	1197.3	1208.1	0.9978	0.9911
LFC-TF 9HR	1213.7	1220.5	1.0114	0.9944
LFC-TF 12HR	1194.0	1183.9	0.9950	1.0085

5.6 Hardened Properties

Compressive strength, residual compressive strength, splitting tensile strength, and flexural strength tests were conducted, and all data were recorded. The concrete specimens were tested after 7 and 28 days of curing. Prior to testing, all specimens were oven-dried for one day following their respective curing periods. The performance index for each compressive strength, splitting tensile strength, and flexural strength was also calculated. The raw data for these tests can be found in the appendix.

5.6.1 Compressive Strength

Figure 5.2 illustrates the compressive strength of various lightweight foamed concrete (LFC) specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours), after curing periods of 7 and 28 days. The detailed data for compressive strength of actual mix can be found in Appendix A-2.

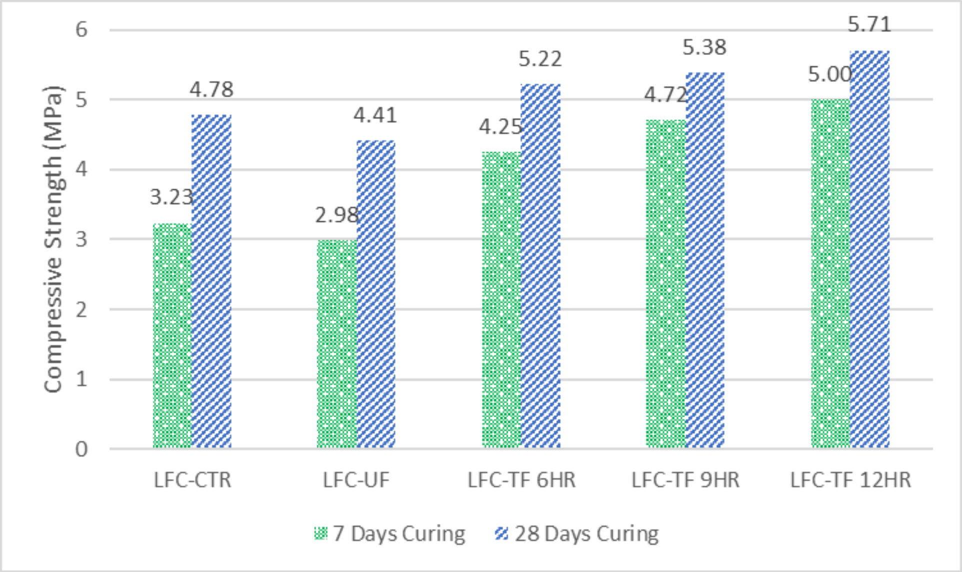


Figure 5.2: Compressive Strength for Actual Mix with Different Curing Period.

The results show that the compressive strength of all specimens increases as the curing period extends from 7 to 28 days, reflecting the ongoing development of strength and hydration of the concrete, as well as the formation of calcium silicate hydrate (C-S-H) gel and calcium hydroxide (CH).

The control sample (LFC-CTR) shows an increase in compressive strength from 3.23 MPa at 7 days to 4.78 MPa at 28 days, representing a percentage increase of approximately 47.99%, Similarly, the LFC-UF specimen, containing untreated kenaf fibres, shows an increase from 2.98 MPa to 4.41 MPa, also achieving a percentage increase of around 47.99%. The 7-day and 28-day strength of LFC-UF is lower than LFC-CTR, suggesting that untreated fibres may have poor bonding with the cement matrix. Theoretically, adding fibre to lightweight foamed concrete can increase compressive strength due to the bridging effect of the fibre (Zhong and Zhang, 2020). However, in this experiment, the addition of kenaf fibre reduced the compressive strength because untreated kenaf fibres may have surface properties that are not ideal for bonding with concrete, leading to poor bonding between the untreated fibres and the cement matrix. Researchers such as Tezara et al. (2016) have proposed that impurities on the surface of kenaf fibres can weaken the interfacial adhesion between the fibre and the matrix. Akil et al. (2011) suggested that the hydrophilic nature of kenaf fibres limits the wetting of the filler surface, ultimately preventing the formation of a strong interphase bond with the matrix. Similarly, Ajouguim et al. (2023) noted that non-cellulosic elements present in the fibres can negatively impact the cement hydration reaction, leading to a reduction in the mechanical properties of lightweight foamed concrete.

Overall, there is an increase in both the 7-day and 28-day compressive strength as the treatment duration of the kenaf fibres increases. The results show that LFC-TF 12HR exhibits the highest compressive strength, with values of 5.00 MPa and 5.71 MPa for the 7-day and 28-day compressive strength, respectively, reflecting an increase of 54.80% and 19.56% for the 7-day and 28-day compressive strength compared to LFC-CTR.

The increase in compressive strength observed in LFC-TF 6HR, 9HR, and 12HR may be attributed to a reduction in porosity due to the inclusion of kenaf fibres. This deduction is supported by Othuman et al. (2022), who found that the addition of kenaf fibres reduces the porosity of lightweight foamed concrete. Furthermore, LFC-TF 12HR has the highest compressive strength among the specimens, as the kenaf fibre treated for 12 hours exhibits the greatest tensile strength compared to fibres treated for other durations. This observation is consistent with the findings of Pirah et al. (2023), who reported that the compressive strength of lightweight foamed concrete is positively correlated with the tensile strength of kenaf fibres.

The increase in compressive strength from 7 days to 28 days for LFC-TF 12HR is only 14.2%, compared to 47.99% for LFC-UF. However, LFC-TF 12HR shows a 67.79% increase in 7-day strength and a 29.48% increase in 28-day strength compared to LFC-UF. These results suggest that the addition of treated kenaf fibres leads to a greater improvement in early strength but has a lesser effect on later strength development. This may be due to the treatment reducing the fibres' hydrophilicity by disrupting hydrogen bonds and removing non-cellulosic components, so the kenaf fibres incorporated within the concrete do not absorb moisture and thereby do not limit the hydration process of the lightweight foamed concrete. This accelerates hydration reactions, resulting in the formation of more calcium silicate hydrate gel and portlandite, which significantly enhances early compressive strength (Ajouguim et al., 2023).

5.6.2 Residual Compressive Strength

Figure 5.3 shows the residual compressive strength of various lightweight foamed concrete (LFC) specimens, including LFC-CTR (control), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) after 7 and 28 days of curing. The detailed data for residual compressive strength of actual mix can be found in Appendix A-3.

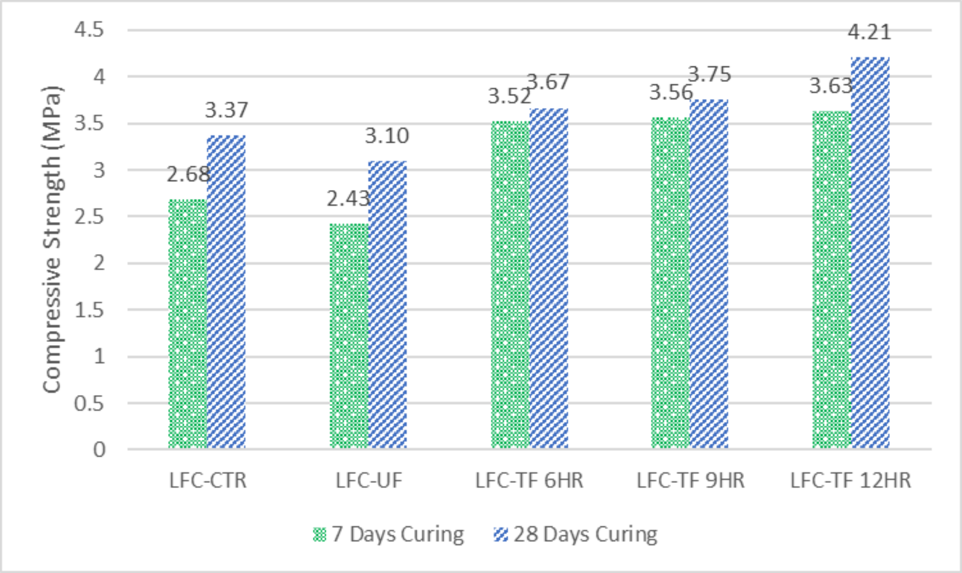


Figure 5.3: Residual Compressive Strength for Actual Mix with Different Curing Period.

The data indicate that residual compressive strength generally increases with longer curing periods, reflecting ongoing hydration and the development of internal bonding between the fibres and the cement matrix. The control sample (LFC-CTR) shows an increase from 2.68 MPa at 7 days to 3.37 MPa at 28 days, a 25.75% gain, while the LFC-UF specimen increases from 2.43 MPa to 3.10 MPa, a 27.57% improvement. Although the percentage increase for LFC-UF is slightly higher, the overall strength remains lower, suggesting that untreated fibres may not effectively enhance residual compressive strength due to poor fibre-matrix bonding and limited hydration resulting from the hydrophilicity of untreated kenaf fibres.

The lightweight foamed concrete incorporating treated fibre specimens shows different levels of residual compressive strength. LFC-TF 6HR increases from 3.52 MPa at 7 days to 3.67 MPa at 28 days, a modest gain of 4.26%, indicating that a 6-hour treatment improves early strength but provides limited long-term benefits. LFC-TF 9HR shows a rise from 3.56 MPa to 3.75 MPa, a 5.34% increase. LFC-TF 12HR achieves the highest residual compressive strength, increasing from 3.63 MPa at 7 days to 4.21 MPa at 28 days, a 15.99% gain, indicating that the 12-hour treatment duration optimises fibre-matrix bonding and enhances mechanical properties over time. The residual compressive strength for LFC-TF 12HR is higher than that of LFC-CTR by 35.45% and 24.93% for the 7-day and 28-day strengths, respectively.

The data show that the longer the treatment duration, the higher the residual compressive strength. This is because kenaf fibres with longer treatment durations have higher tensile strength to hold the concrete and bridge cracks, and reduced impurities allow for better cement matrix bonding with the fibres. Overall, the results suggest that while all specimens show increased residual compressive strength with curing, the effectiveness of the fibres depends on the treatment duration. Untreated fibres negatively affect the residual compressive strength compared to the control sample, whereas fibres treated for 12 hours show the greatest improvement.

5.6.3 Splitting Tensile Strength

Figure 5.4 shows the splitting tensile strength of various lightweight foamed concrete (LFC) specimens, including LFC-CTR (control), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) after 7 and 28 days of curing. Figure 5.5 illustrates the difference between LFC-TF 12HR and LFC-CTR upon splitting tensile failure. It shows that LFC-TF 12HR has a smaller crack line than LFC-CTR, which is because the fibres still holding the concrete together upon failure due to the cement matrix bonding with the kenaf fibres. The detailed data for splitting tensile strength of actual mix can be found in Appendix A-4.

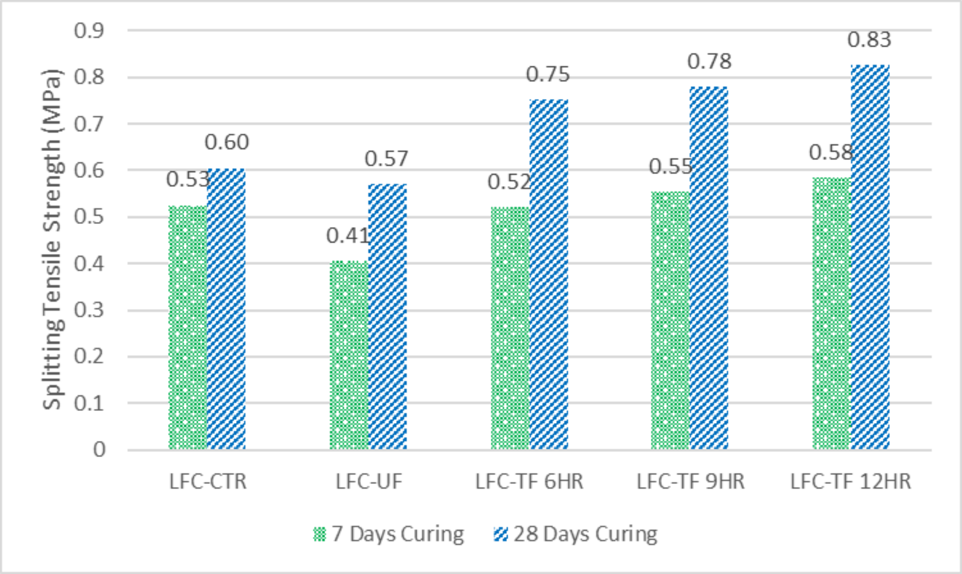


Figure 5.4: Splitting Tensile Strength for Actual Mix with Different Curing Period.

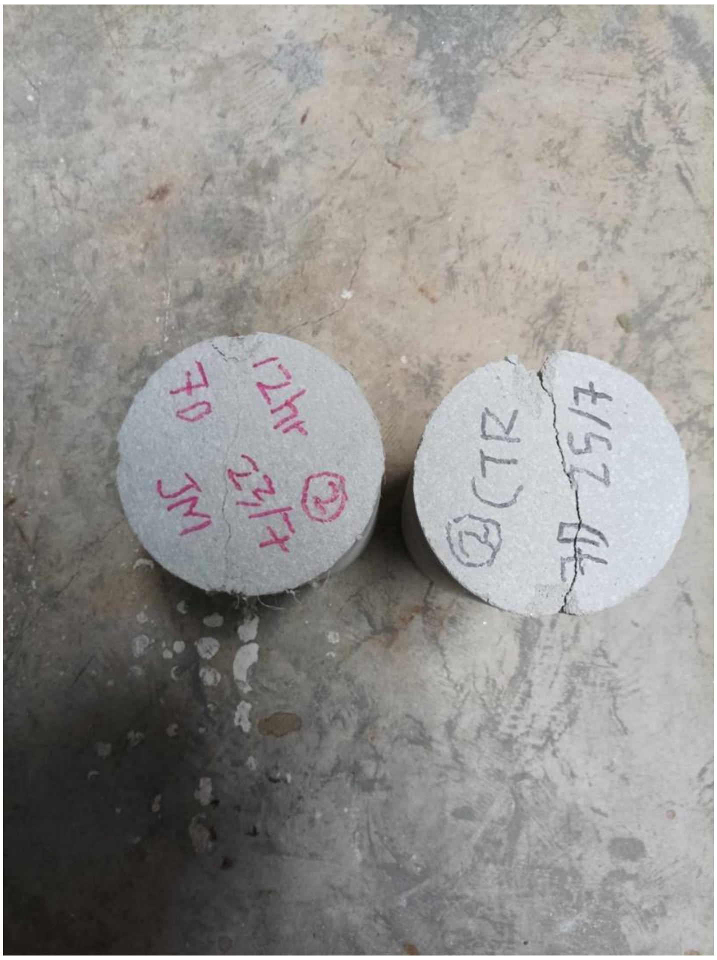


Figure 5.5: Comparison Between LFC-TF 12HR (Left Side) and LFC-CTR (Right Side).

The data reveals a general trend of increasing splitting tensile strength with longer curing periods, reflecting continued hydration and the development of internal bonding between the fibres and the cement matrix. The control sample (LFC-CTR) shows an increase from 0.53 MPa at 7 days to 0.60 MPa at 28 days, representing a 13.21% gain, consistent with the expected strength development as hydration progresses. The LFC-UF specimen, containing untreated kenaf fibres, shows a larger percentage increase of 39.02%, from 0.41 MPa to 0.57 MPa, but the overall tensile strength remains lower than the control, suggesting that untreated fibres do not effectively contribute to strength due to poor bonding with the cement matrix.

The specimens with treated fibres show an improvement in tensile strength as the duration of kenaf fibre treatment increases. The LFC-TF 6HR specimen demonstrates a substantial increase from 0.52 MPa at 7 days to 0.75 MPa at 28 days, a 44.23% rise, indicating that a 6-hour treatment enhances fibre-matrix bonding and positively contributes to strength development. The LFC-TF 9HR specimen increases from 0.55 MPa at 7 days to 0.78 MPa at 28 days, a 41.82% gain, suggesting that a 9-hour treatment may offer further benefits in fibre bonding and strength enhancement. The LFC-TF 12HR specimen exhibits the highest splitting tensile strength, increasing from 0.58 MPa at 7 days to 0.83 MPa at 28 days, a 43.10% gain. The splitting tensile strength of LFC-TF 12HR is greater than that of LFC-CTR by 9.43% and 38.33% at 7 days and 28 days, respectively. These results indicate that the 12-hour treatment duration optimises the reinforcing effect of the fibres, thereby improving the splitting tensile strength of lightweight foamed concrete.

The data shows that the longer the treatment duration, the higher the splitting tensile strength. This is because kenaf fibres with longer treatment durations have greater tensile strength to hold the concrete and bridge cracks, while reduced impurities allow for better bonding with the cement matrix. Similar studies by Nensok, Mydin, and Awang (2022) and Awang, Ahmad, and Al-Mulali (2015) also show improvements in splitting tensile strength with the alkali treatment of fibres.

In contrast to the results for compressive strength, where lightweight foamed concrete exhibited a smaller increase between 7 and 28 days, the lightweight foamed concrete containing treated kenaf fibre shows a greater increase in splitting tensile strength over the same period. This indicates a continuous enhancement in the strength of the fibre-matrix bond throughout the 7 to 28-day curing period. Consequently, a strong bond between the concrete matrix and the fibres facilitates effective stress transfer, allowing the fibres to bridge cracks during the pullout process (Lin et al., 2023).

Overall, the data suggest that while all specimens exhibit an increase in splitting tensile strength with curing, the effectiveness of the fibres varies with the treatment duration. LFC-UF shows lowest overall strength, despite a higher percentage increase, due to poor fibre-matrix bonding and reduced hydration efficiency. The 12-hour treatment (LFC-TF 12HR) shows the most significant improvement, indicating it as the most effective duration for enhancing tensile strength of lightweight foamed concrete.

5.6.4 Flexural Strength

Figure 5.6 shows the splitting tensile strength of various lightweight foamed concrete (LFC) specimens, including LFC-CTR (control), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) after 7 and 28 days of curing. Figure 5.7 shows LKC-TF 12HR after undergoing a flexural test, with visible cracks running vertically along the middle. The presence of kenaf fibres along the crack line appears to help hold the concrete together even after it has started to crack. This suggests that the kenaf fibres improve the flexural strength of the concrete by bridging the cracks and resisting further crack propagation. Moreover, the fibres act as reinforcement within the cement matrix, absorbing tensile forces and distributing them more evenly across the specimen. The detailed data for flexural strength of actual mix can be found in Appendix A-5.

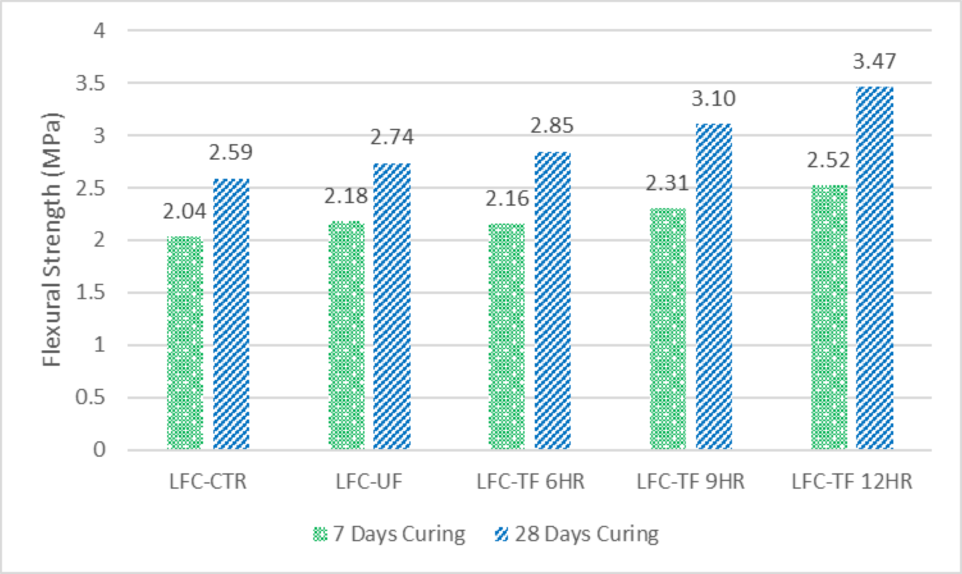


Figure 5.6: Flexural Strength for Actual Mix with Different Curing Period.

Figure 5.7: Failure of LFC-TF 12HR in Flexural Test.

The data show that all specimens exhibit an increase in flexural strength as the curing period extends, suggesting ongoing hydration and strengthening of the concrete matrix over time. The control sample (LFC-CTR) shows a 26.96% increase in flexural strength, from 2.04 MPa at 7 days to 2.59 MPa at 28 days. In comparison, the LFC-UF specimen, containing untreated kenaf fibres, shows a 25.69% increase, from 2.18 MPa to 2.74 MPa. While this percentage increase is similar to that of the control, the untreated fibres contribute to slightly higher flexural strength, possibly due to some reinforcement effect despite poor adhesion with the cement matrix. Similar results were reported by Pirah et al. (2023), who found that the flexural strength of lightweight foamed concrete increased with the inclusion of untreated kenaf fibres.

The specimens with treated fibres show an increase in flexural strength as the treatment duration increases. The LFC-TF 6HR specimen shows a 31.94% increase, from 2.16 MPa at 7 days to 2.85 MPa at 28 days, indicating that a 6-hour treatment enhances bonding with the cement matrix more effectively than untreated fibres. The LFC-TF 9HR specimen exhibits a 34.20% increase, from 2.31 MPa at 7 days to 3.10 MPa at 28 days, suggesting that a 9-hour treatment optimises fibre-matrix adhesion and provides greater reinforcement. The LFC-TF 12HR specimen achieves the highest flexural strength, with a 37.70% increase from 2.52 MPa to 3.47 MPa, indicating that a 12-hour treatment maximises bonding between the fibres and the matrix, resulting in the most significant enhancement in flexural strength. These findings are consistent with studies by Nensok, Mydin, and Awang (2022) and Awang, Ahmad, and Al-Mulali (2015), which also reported improvements in flexural strength with treated kenaf fibres. This improvement occurs because kenaf fibres with longer treatment durations have greater tensile strength to hold the concrete and bridge cracks during flexural testing, while reduced impurities allow for better bonding with the cement matrix. A strong bond between the concrete matrix and fibres facilitates effective stress transfer, allowing the fibres to bridge cracks during the pullout process (Lin et al., 2023).

Overall, these findings demonstrate that increasing the treatment duration of kenaf fibres enhances the flexural strength and mechanical performance of lightweight foamed concrete, with the 12-hour treatment proving to be the most effective in this study.

5.7 Performance Index

Since it is impossible for all lightweight foamed concrete specimens in this experiment to achieve the exact target density, and because concrete with higher density generally exhibits greater compressive strength due to reduced pore content (Kearsley, 2002), the performance index of each concrete mix was calculated to further verify the optimum fibre treatment duration to be incorporated in lightweight foamed concrete. The performance index is calculated as the compressive strength per 1000 kg/m³.

5.7.1 Performance Index of Compressive Strength

Figure 5.8 illustrates the performance index of compressive strength for different lightweight foamed concrete (LFC) specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours), after curing periods of 7 and 28 days. Figure 5.9 shows the percentage change in the average performance index of LFC-UF (untreated kenaf fibre) and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) compared to LFC-CTR after curing periods of 7 and 28 days.

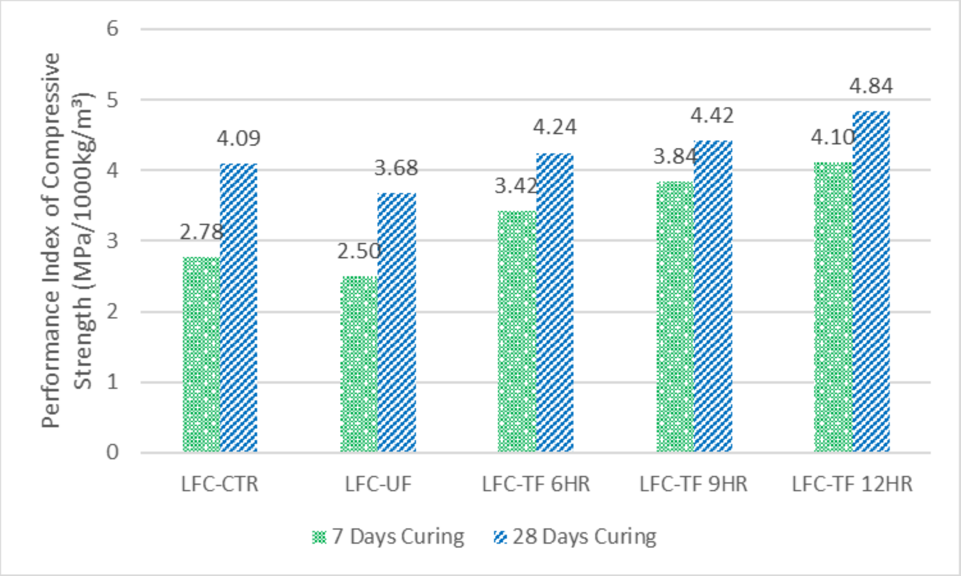


Figure 5.8: Average Performance Index of Compressive Strength for Actual Mix with Different Curing Period.

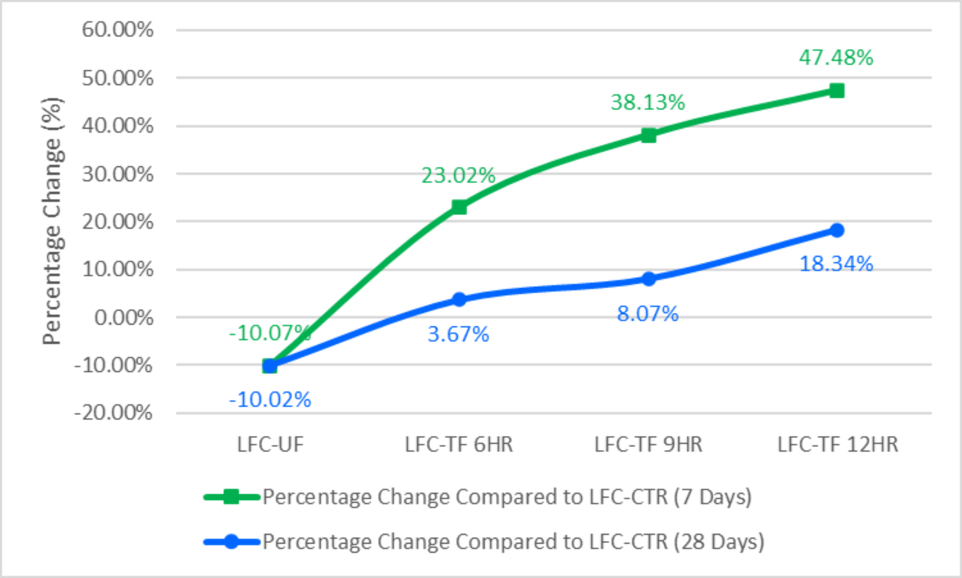


Figure 5.9: Percentage Change in Average Performance Index of Compressive Strength with Different Curing Period.

The data show that LFC-UF has a reduced performance index of compressive strength by 10.07% (from 2.78 to 2.50 MPa per 1000 kg/m³) and 10.02% (from 4.09 to 3.68 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. This reduction highlights the limited effectiveness of untreated kenaf fibres in improving compressive strength. In contrast, LFC-TF 12HR exhibits the highest performance index, with gains of 47.48% (from 2.78 to 4.10 MPa per 1000 kg/m³) and 18.34% (from 4.09 to 4.84 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. The performance index of compressive strength increases with longer fibre treatment duration.

The overall trend aligns with the compressive strength results and is consistent with the trend in Figure 5.2, as all concrete specimens demonstrate high consistency, stability, and minimal variation in density.

5.7.2 Performance Index of Residual Compressive Strength

Figure 5.10 illustrates the performance index of residual compressive strength for different lightweight foamed concrete (LFC) specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours), after curing periods of 7 and 28 days. Figure 5.11 shows the percentage change in the average performance index of

LFC-UF (untreated kenaf fibre) and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) compared to LFC-CTR after curing periods of 7 and 28 days.

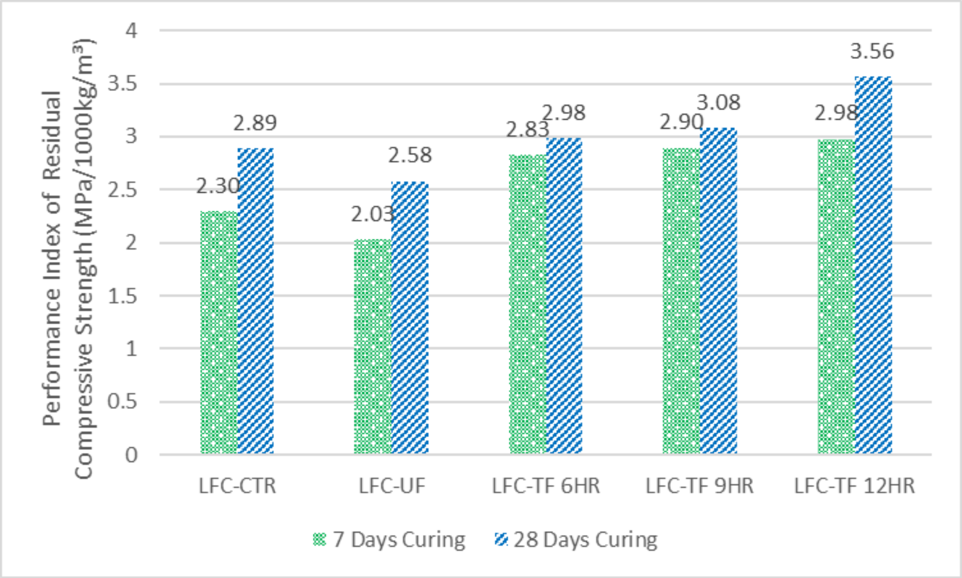


Figure 5.10: Average Performance Index of Residual Compressive Strength for Actual Mix with Different Curing Period.

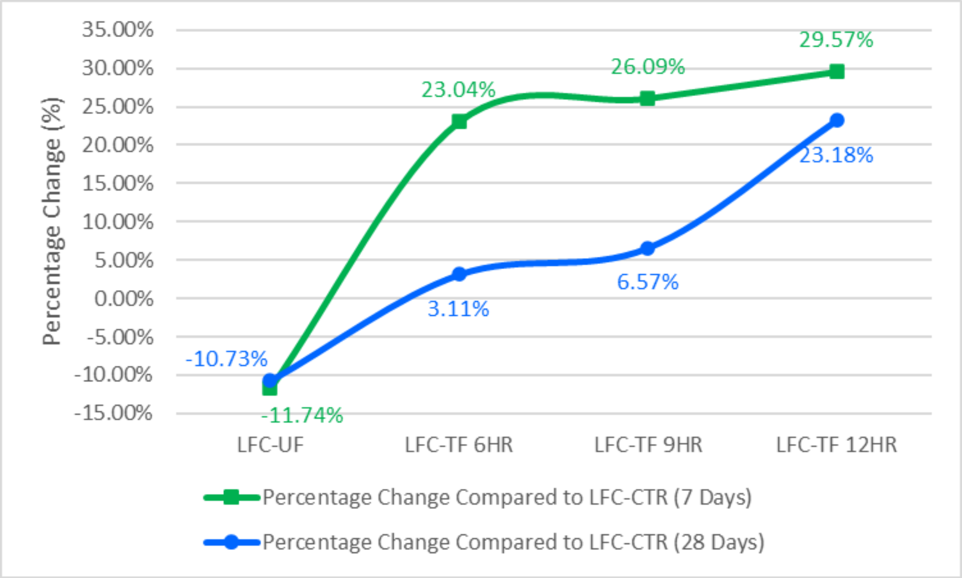


Figure 5.11: Percentage Change in Average Performance Index of Residual Compressive Strength with Different Curing Period.

The data show that LFC-UF has a reduced performance index of residual compressive strength by 11.74% (from 2.30 to 2.03 MPa per 1000 kg/m³) and 10.73% (from 2.89 to 2.58 MPa per 1000 kg/m³) compared to

LFC-CTR at 7 and 28 days, respectively. This reduction highlights the limited effectiveness of untreated kenaf fibres in improving residual compressive strength. In contrast, LFC-TF 12HR exhibits the highest performance index, with gains of 29.57% (from 2.30 to 2.98 MPa per 1000 kg/m³) and 23.18% (from 2.89 to 3.56 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. The performance index of residual compressive strength increases with longer fibre treatment duration.

The overall trend aligns with the residual compressive strength results and is consistent with the trend in Figure 5.3, as all concrete specimens demonstrate high consistency, stability, and minimal variation in density.

5.7.3 Performance Index of Splitting Tensile Strength

Figure 5.12 illustrates the performance index of splitting tensile strength for different lightweight foamed concrete (LFC) specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours), after curing periods of 7 and 28 days. Figure 5.13 shows the percentage change in the average performance index of LFC-UF (untreated kenaf fibre) and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) compared to LFC-CTR after curing periods of 7 and 28 days.

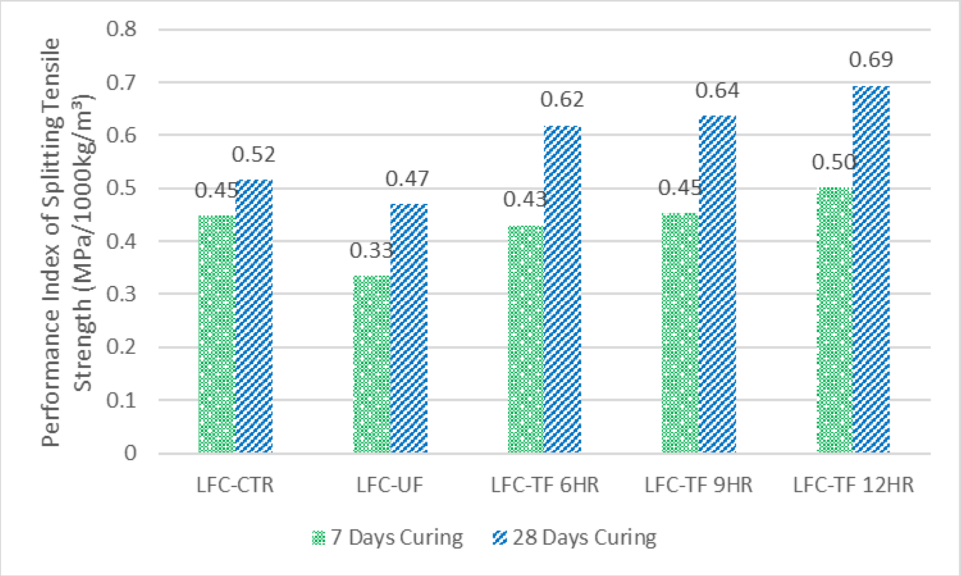


Figure 5.12: Average Performance Index of Splitting Tensile Strength for Actual Mix with Different Curing Period.

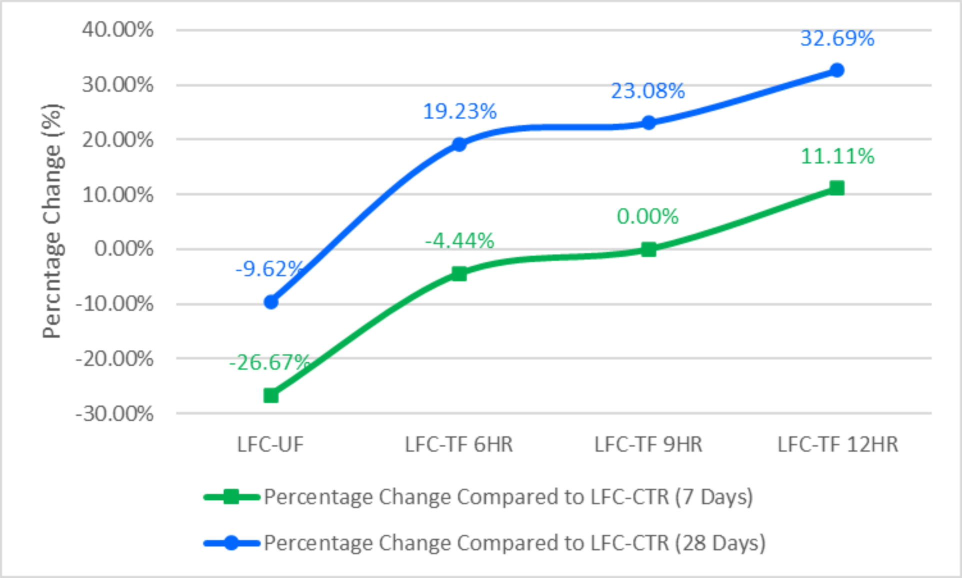


Figure 5.13: Percentage Change in Average Performance Index of Splitting Tensile Strength with Different Curing Period.

The data show that LFC-UF has a reduced performance index of splitting tensile strength by 26.67% (from 0.45 to 0.33 MPa per 1000 kg/m³) and 9.62% (from 0.52 to 0.47 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. This reduction highlights the limited effectiveness of untreated kenaf fibres in improving splitting tensile strength. In contrast, LFC-TF 12HR exhibits the highest performance index, with gains of 11.11% (from 0.45 to 0.50 MPa per 1000 kg/m³) and 32.70% (from 0.52 to 0.69 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. The performance index of flexural strength increases with longer fibre treatment duration.

The overall trend aligns with the splitting tensile strength results and is consistent with the trend in Figure 5.4, as all concrete specimens demonstrate high consistency, stability, and minimal variation in density.

5.7.4 Performance index of Flexural Strength

Figure 5.14 illustrates the performance index of flexural strength for different lightweight foamed concrete (LFC) specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours), after curing periods of 7 and 28 days. Figure 5.15 shows the percentage change in the average performance index of LFC-UF (untreated kenaf fibre) and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours) compared to LFC-CTR after curing periods of 7 and 28 days.

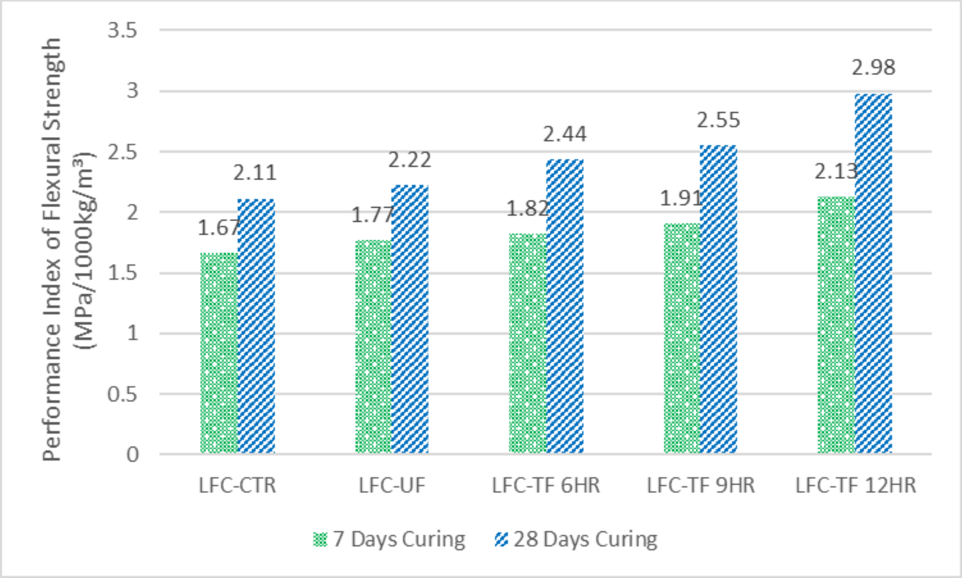


Figure 5.14: Average Performance Index of Flexural Strength for Actual Mix with Different Curing Period.

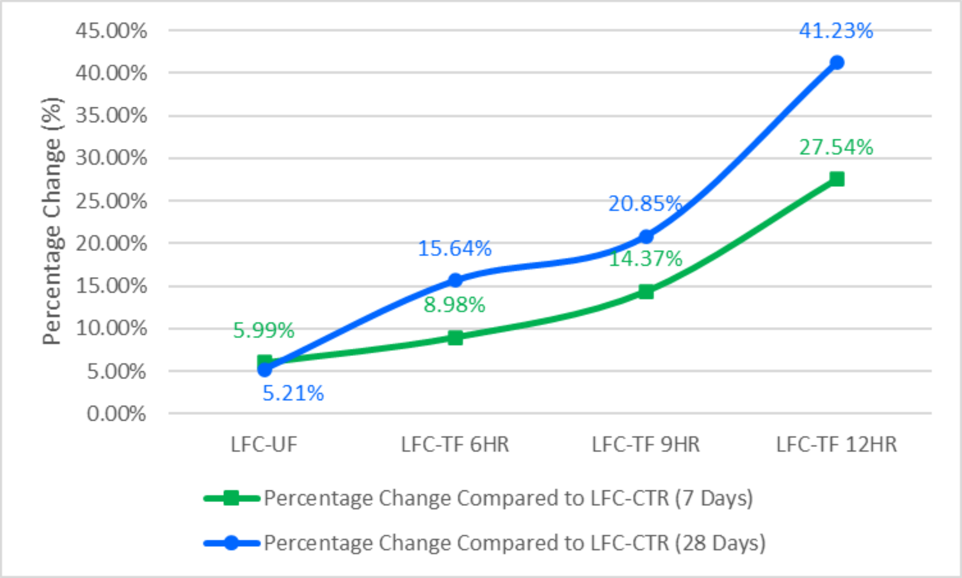


Figure 5.15: Percentage Change in Average Performance Index of Flexural Strength with Different Curing Period.

The data show that LFC-UF has a increased performance index of flexural strength by 5.99% (from 1.67 to 1.77 MPa per 1000 kg/m³) and 5.21% (from 2.11 to 2.22 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. This increase highlights the untreated fibres contribute to slightly higher flexural strength, possibly due to some reinforcement effect despite poor adhesion with the cement matrix. In contrast, LFC-TF 12HR exhibits the highest performance index, with gains of 27.54% (from 1.67 to 2.13 MPa per 1000 kg/m³) and 41.23% (from 2.11 to 2.98 MPa per 1000 kg/m³) compared to LFC-CTR at 7 and 28 days, respectively. The performance index of flexural strength increases with longer fibre treatment duration.

The overall trend aligns with the flexural strength results and is consistent with the trend in Figure 5.6, as all concrete specimens demonstrate high consistency, stability, and minimal variation in density.

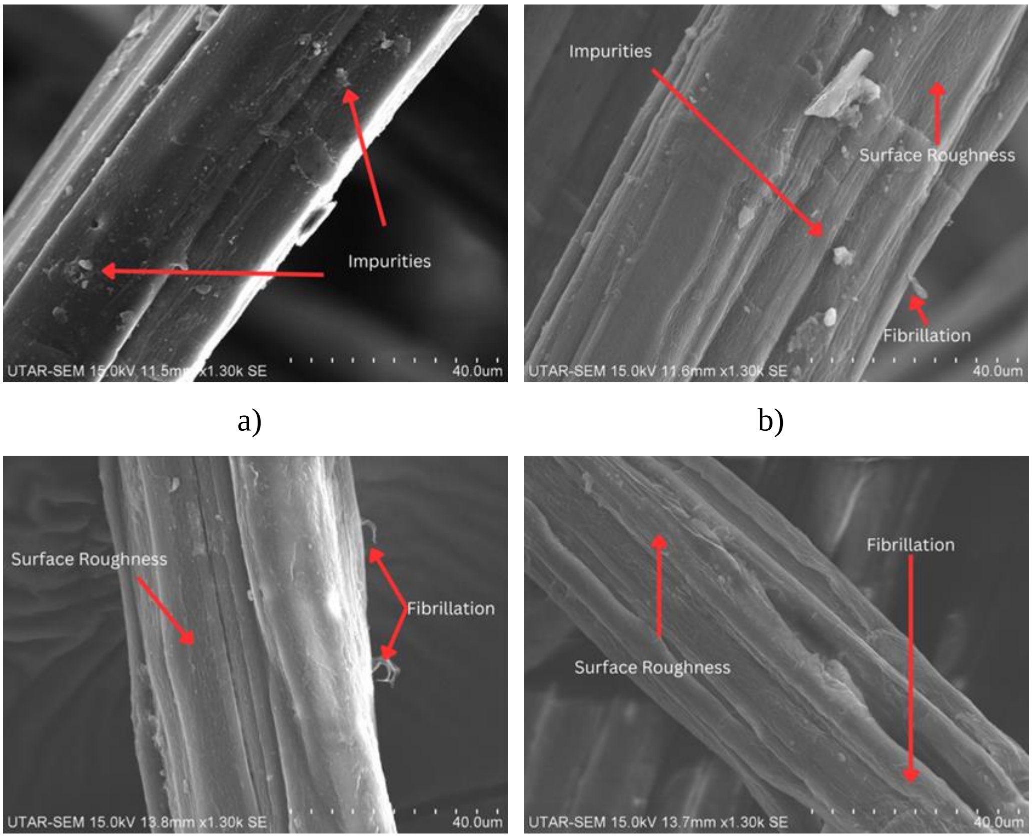
5.8 Scanning Electron Microscope (SEM)

A Scanning Electron Microscope (SEM) analysis was carried out to provide a clearer view of the morphology and composition of the actual mix specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours), as well as untreated fibres (UF) and fibres treated for 6, 9, and 12 hours (TF-6HR, TF-9HR, and TF-12HR).

5.8.1 Kenaf Fibre

Figure 5.16 presented the SEM analysis of kenaf fibres treated for different durations, under a magnification of 1300×. The untreated kenaf fibre displayed a relatively smooth surface with minimal disruption, indicating the presence of natural waxes, oils, non-cellulosic materials, and impurities such as hemicellulose and lignin, which helped maintain the fibre's structural integrity. In contrast, the fibre treated with NaOH for 6 hours showed initial signs of roughening, with some surface impurities removed and slight fibrillation evident. This suggested that the alkali treatment began to break down the outer layers, while the core structure remained largely unaffected.

As the treatment duration was extended to 9 hours, the fibre exhibited more pronounced surface roughness and noticeable fibrillation, indicating a more significant removal of non-cellulosic materials and increased exposure of the cellulose structure. This enhanced surface roughness improved the fibre’s potential for mechanical interlocking and bonding with the cement matrix in composite applications. The fibre treated for 12 hours showed the most substantial morphological changes, with extensive fibrillation and roughness resulting from the maximum removal of impurities and exposure of the cellulose. While this provided the greatest potential for improved bonding with the cement matrix, it also suggested that over-treatment could weaken the fibre.



a) b)

c) d)

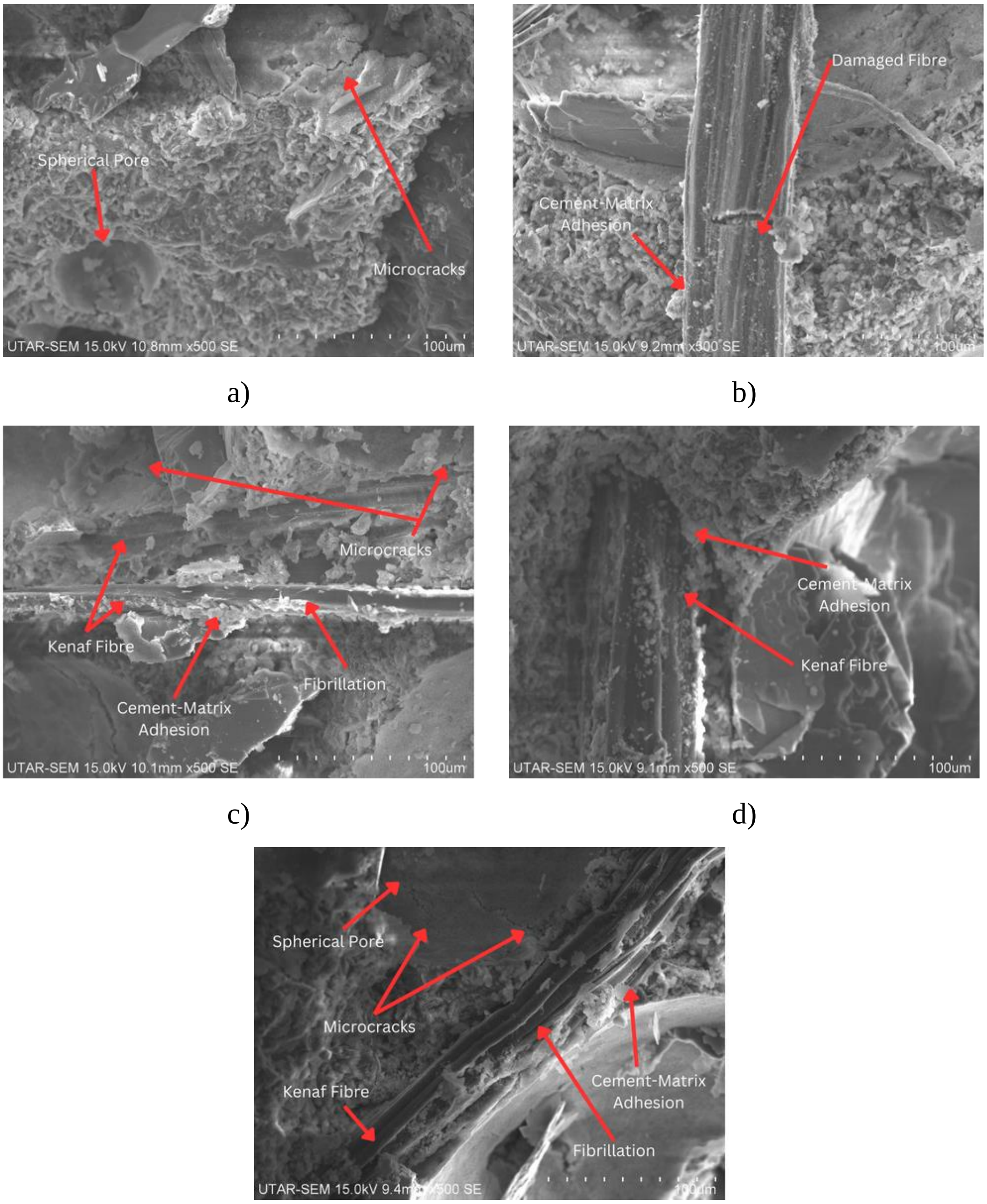
Figure 5.16: SEM Images of Kenaf Fibre with Different Treatment Duration: a) Untreated; b) Treated with 6 hours; c) Treated with 9 hours; d) Treated with 12 hours.

5.8.2 Lightweight Foamed Concrete

Figure 5.17 presented the SEM analysis of actual mix, under a magnification of 500×. The SEM images reveal distinct differences in the morphology of the lightweight foamed concrete (LFC) specimens based on the presence and treatment duration of kenaf fibres. The control sample, which contains no fibres, displays a relatively homogeneous matrix with a porous texture, characterised by visible micropores typical of lightweight foamed concrete. This lack of fibre reinforcement suggests lower resistance to cracking and limited mechanical interlocking within the matrix. The LFC with untreated kenaf fibres shows some embedded fibres with smooth surfaces, indicating limited interaction and adhesion with the cement matrix due to the presence of natural waxes, oils, and impurities. The visible gaps between the fibres and the matrix suggest poor bonding, which could result in weaker mechanical properties and reduced stress transfer capabilities.

In contrast, the LFC containing kenaf fibres treated with sodium hydroxide (NaOH) for 6 hours shows increased surface roughness of the fibres, suggesting partial removal of non-cellulosic components such as hemicellulose and lignin. This results in better adhesion between the fibres and the cement matrix, with fewer visible gaps, enhancing mechanical interlocking and stress transfer. The 9-hour treated fibres display even more pronounced roughness and fibrillation, indicating further removal of impurities and better integration with the matrix.

The LFC with 12-hour NaOH-treated fibres shows the most significant morphological changes, with extensive roughness and fibrillation, and deep interlocking within the cement matrix. This indicates maximum removal of non-cellulosic materials, providing a greater surface area for bonding and the best potential for stress transfer and crack bridging under mechanical loading



a) b)

c) d)

e)

Figure 5.17: SEM Images of Kenaf Fibre with Different Treatment Duration Incorporated in Lightweight Foamed Concrete: a) Control; b) Untreated; c) Treated with 6 hours; d) Treated with 9 hours; e) Treated with 12 hours.

5.9 Energy Dispersive X-Ray Analysis (EDX) Test

An Energy Dispersive X-Ray Analysis (EDX) was conducted to determine the elemental composition of the actual mix specimens, including LFC-CTR (control sample), LFC-UF (untreated kenaf fibre), and LFC-TF (kenaf fibres treated for 6, 9, and 12 hours). Table 5.4 presents EDX analysis result for actual mix at 28 days curing period.

The data show that the addition of kenaf fibre into the lightweight foamed concrete increases the amount of carbon present. This is due to the presence of cellulose in the kenaf fibre, which is a complex carbohydrate consisting of oxygen, carbon, and hydrogen. It is notable that LFC-TF samples generally have higher carbon content than LFC-CTR and LFC-UF, owing to the presence of treated kenaf fibres. However, the carbon content is slightly lower at 12.75% (atomic) in the 12-hour treated sample, which may be due to further removal of cellulosic material during extended treatment.

The presence of unusual elements, such as gold, molybdenum, and indium, suggests a need for careful sample preparation and contamination control.

Table 5.4: EDX Analysis Result for Actual Mix at 28 Days Curing Period.

	LFC-CTR		LFC-UF		LFC-TF 6HR		LFC-TF 9HR		LFC-TF 12HR	
Element	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
C	02.80	05.97	03.85	08.74	04.39	08.73	08.02	14.68	06.92	12.75
O	32.99	52.77	27.47	46.79	38.90	58.11	41.45	56.92	40.46	56.02
Mg	0	0	0	0	00.83	00.82	00.49	00.45	00.64	00.58
Al	01.76	01.67	01.36	01.37	02.45	02.17	02.11	01.72	02.63	02.16
Si	09.77	08.90	04.51	04.37	09.40	08.00	09.95	07.78	08.85	06.98
Au	0	0	0	0	05.27	00.64	03.33	00.37	0	0
Mo	0	0	0	0	02.59	00.65	01.75	00.40	02.74	00.63
In	0	0	0	0	01.74	00.36	00.97	00.19	0	0
Y	01.24	00.36	02.54	00.72	0	0	0	0	0	0
Nb	04.53	01.25	02.74	00.66	0	0	0	0	0	0
Pd	02.17	00.52	03.97	00.94	0	0	0	0	0	0
Ca	44.73	28.56	53.56	36.40	34.42	20.52	31.91	17.49	37.78	20.88

5.10 Summary

In summary, the inclusion of kenaf fibres in lightweight foamed concrete reduces workability, which decreases further as the fibre treatment duration increases due to greater surface roughness. However, the addition of treated kenaf fibres improves the compressive strength, residual compressive strength, splitting tensile strength, and flexural strength of the concrete after 7 and 28 days of curing. Kenaf fibres treated for 12 hours are the most effective for incorporation, as they exhibit higher tensile strength and better adhesion with the cement matrix due to the removal of impurities. This enhancement occurs because fibres with longer treatment durations provide greater tensile strength to hold the concrete together and bridge cracks during flexural testing, while reduced impurities allow for stronger bonding with the cement matrix. A strong bond between the matrix and fibres enables efficient stress transfer, allowing fibres to bridge cracks and prevent microcrack propagation, thereby enhancing structural integrity. These findings are further supported by SEM and EDX analysis.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study aimed to produce and evaluate the performance of 1200 kg/m³ lightweight foamed concrete incorporating 0.2% kenaf fibre treated for different durations with 6% sodium hydroxide (1.5 mol NaOH). The optimum water-to-cement (w/c) ratio was found to be 0.60, based on the compressive strength of LFC-TF 12HR. The mechanical properties of the concrete were assessed by analysing the compressive, flexural, and tensile strengths of the lightweight foamed concrete containing kenaf fibres treated for varying durations.

The results indicate that the inclusion of kenaf fibres significantly impacts both the fresh and hardened properties of lightweight foamed concrete. The addition of kenaf fibres generally reduces workability, with a more pronounced reduction observed as the fibre treatment duration increases, due to the greater surface roughness resulting from the removal of impurities during the treatment process. However, the inclusion of treated kenaf fibres enhances the mechanical properties, including compressive strength, residual compressive strength, splitting tensile strength, and flexural strength, after both 7 and 28 days of curing. Among the various treatment durations, kenaf fibres treated for 12 hours provided the most substantial benefits, optimising tensile strength and effective bonding with the cement matrix. This treatment duration effectively removes impurities, resulting in stronger fibre-matrix adhesion and improved performance in stress transfer and crack bridging, as supported by SEM analysis.

6.2 Recommendations

Based on the findings, it is recommended to use kenaf fibres treated with sodium hydroxide for 12 hours in lightweight foamed concrete to achieve optimal mechanical performance. This treatment duration effectively enhances the tensile strength of the fibres and promotes stronger bonding with the cement matrix, resulting in improved compressive, tensile, and flexural strength. Future research could explore the effects of different concentrations of the alkali treatment and varying treatment durations beyond 12 hours to determine whether further optimisation is possible. Additionally, it would be beneficial to investigate the long-term durability and environmental impact of using treated kenaf fibres in lightweight foamed concrete under various exposure conditions to better understand their performance in real-world applications.

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APPENDICES

Appendix A-1: Compressive Strength for Trial Mix of LFC-TF 12HR

W/C Ratio	Compressive Strength (MPa)					
	7 days			28 days		
	1	2	3	1	2	3
0.52	3.39	3.39	3.39	4.21	3.86	3.86
0.56	4.01	4.05	4.3	3.9	4.19	4.63
0.60	4.99	5.05	4.96	5.58	5.65	5.9
0.64	4.7	4.68	4.68	5.5	5.24	5.67

Appendix A-2: Compressive Strength for Actual Mix

Specimen	Compressive Strength (MPa)					
	7 days			28 days		
	1	2	3	1	2	3
LFC-CTR	3.24	3.17	3.29	4.64	4.82	4.88
LFC-UF	2.91	2.77	3.27	4.40	4.52	4.32
LFC-TF 6HR	3.95	4.52	4.28	5.69	5.09	4.87
LFC-TF 9HR	4.82	4.07	5.26	5.43	5.50	5.22
LFC-TF 12HR	4.99	5.05	4.96	5.58	5.65	5.90

Appendix A-3: Residual Compressive Strength for Actual Mix

Specimen	Compressive Strength (MPa)					
	7 days			28 days		
	1	2	3	1	2	3
LFC-CTR	3.01	2.40	2.63	3.21	3.43	3.48
LFC-UF	2.54	2.16	2.58	3.08	3.17	3.04
LFC-TF 6HR	3.27	3.64	3.64	3.77	3.67	3.56
LFC-TF 9HR	3.36	3.72	3.60	3.74	3.97	3.55
LFC-TF 12HR	3.60	3.36	3.93	4.35	4.19	4.09

Appendix A-4: Splitting Tensile Strength for Actual Mix

Specimen	Splitting Tensile Strength (MPa)					
	7 days			28 days		
	1	2	3	1	2	3
LFC-CTR	0.48	0.54	0.55	0.63	0.60	0.59
LFC-UF	0.43	0.43	0.37	0.58	0.55	0.58
LFC-TF 6HR	0.52	0.50	0.54	0.71	0.79	0.75
LFC-TF 9HR	0.55	0.54	0.57	0.77	0.76	0.81
LFC-TF 12HR	0.60	0.60	0.55	0.84	0.81	0.84

Appendix A-5: Flexural Strength for Actual Mix

Specimen	Flexural Strength (MPa)					
	7 days			28 days		
	1	2	3	1	2	3
LFC-CTR	2.10	1.93	2.07	2.49	2.69	-
LFC-UF	2.09	2.27	-	2.42	3.22	2.58
LFC-TF 6HR	1.98	2.43	2.07	3.45	2.42	2.67
LFC-TF 9HR	2.33	2.29	-	3.25	3.06	3.00
LFC-TF 12HR	3.06	2.46	2.05	3.05	3.88	-

Appendix A-6: Tensile Strength for Kenaf Fibre Treated with 6 Hours

Specimen	Cross Sectional Area (mm^2)	Load (N)	Tensile Strength (MPa)
1	0.000452389	0.40337	891.6434638
2	0.001809557	0.92945	513.6338953
3	0.002123717	0.71585	337.0741598
4	0.001772055	0.93817	529.4249944
5	0.00090792	0.48877	538.3402182
6	0.000804248	0.33626	418.1050091
7	0.000706858	0.75668	1070.483221
8	0.00007.85398	0.1539	1959.515659
9	0.000593957	0.67361	1134.104978
10	0.000615752	0.68781	1117.024096
11	0.000490874	0.9748	1985.846253
12	0.000962113	0.69362	720.9342147
13	0.000804248	0.60022	746.3123433
14	0.000706858	0.24455	345.9674785
15	0.00090792	0.14442	159.0668296
16	0.000452389	0.36406	804.7492859
17	0.001134115	0.09674	85.29999554
18	0.00090792	0.75121	827.3964346
19	0.000201062	0.35558	1768.509833
20	0.000380133	0.37081	975.4751148
Average			846.445
Standard Deviation			547.315

Appendix A-7: Tensile Strength for Kenaf Fibre Treated with 9 Hours

Specimen	Cross Sectional Area (mm^2)	Load (N)	Tensile Strength (MPa)
1	0.002827433	1.32406	468.290431
2	0.001963495	2.19296	1116.865357
3	0.000962113	0.76795	798.1912721
4	0.002827433	2.17845	770.4690795
5	0.001710423	2.92298	1708.922629
6	0.002375829	1.12682	474.2848872
7	0.000706858	0.57876	818.7779099
8	0.001590431	1.03519	650.8863429
9	0.001590431	1.45542	915.1102707
10	0.001963495	1.16627	593.9764335
11	0.000962113	0.88855	923.5404061
12	0.002375829	1.00013	420.9603524
13	0.001256637	1.36866	1089.145022
14	0.000490874	0.868	1768.27508
15	0.001256637	0.43892	349.2814381
16	0.003150319	5.93729	1884.662929
17	0.001963495	1.32381	674.2108967
18	0.000490874	1.25862	2564.039609
19	0.001474803	0.77854	527.894156
20	0.002522001	3.05807	1212.557124
Average			986.517
Standard Deviation			582.991

Appendix A-8: Tensile Strength for Kenaf Fibre Treated with 12 Hours

Specimen	Cross Sectional Area (mm^2)	Load (N)	Tensile Strength (MPa)
1	0.000706858	0.57805	817.7734654
2	0.000314159	0.47683	1517.79703
3	0.000314159	0.36891	1174.277001
4	0.001256637	1.34246	1068.295725
5	0.000490874	0.62484	1272.913595
6	0.000706858	0.87422	1236.768305
7	0.001710423	2.56604	1500.237368
8	0.000314159	0.62955	2003.919888
9	0.000139626	0.21876	1566.753091
10	0.000490874	0.56139	1143.654317
11	0.001055924	0.56545	535.502455
12	0.001772055	1.07105	604.411397
13	0.002164754	3.70674	1712.314903
14	0.000872665	0.65628	752.0414836
15	0.002463009	1.30122	528.3050894
16	0.000314159	0.50972	1622.489152
17	0.001963495	2.05387	1046.027401
18	0.000452389	0.34235	756.7596495
19	0.000490874	0.57045	1162.111197
20	0.002596723	2.15116	828.413453
Average			1142.538
Standard Deviation			418.557