# THE MECHANICAL AND DURABILITY PERFORMANCE OF WOVEN FIBERGLASS MESH REINFORCED LIGHTWEIGHT FOAMED CONCRETE

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# THE MECHANICAL AND DURABILITY PERFORMANCE OF WOVEN FIBERGLASS MESH REINFORCED LIGHTWEIGHT FOAMED CONCRETE

**by**

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# LIST OF SYMBOLS

| | |
|---|---|
| w/c | water to cement ratio |
| D | Target density |
| c | cement content |
| f | fine aggregate |
| W | Total mix water |
| $R^2$ | coefficient of determination |
| ºC | degree Celsius |
| % | percentage |
| $T_g$ | glass transition |
| V | Total volume of mixture |
| $m_2$ | Total weight of mixture |
| $m_1$ | Total weight of slurry mortar |
| Ø | diameter |
| $W_d$ | Oven-dried weight |
| $W_s$ | Saturated surface dry weight |
| $W_a$ | Water absorption capacity |
| $W_{dry}$ | weight of a saturated sample in air |
| $W_{s,a}$ | weight of oven-dried sample |
| $W_{s,w}$ | weight of the saturated sample in water |
| F | load of a given point on the load deflection curve |
| L | support span |
| b | width of test sample |
| d | depth / thickness of tested sample |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| LFC | Lightweight foamed concrete |
| TRC | Textile reinforced concrete |
| FRC | Fibre reinforced concrete |
| FRP | Fibre reinforced polymer |
| CFST | Concrete filled steel tube |
| CFRP | Carbon fibre reinforced polymer |
| GFRP | Glass fibre reinforced polymer |
| AFRP | Aramid fibre reinforced polymer |
| NAAC | Non-autoclaved aerated |
| AAC | Autoclaved aerated concrete |
| CIDB | Construction Industry Development Board |
| IBS | Industrialized Building System |
| BCA | British Concrete Association |
| EFB | Empty fruit bunch |
| OPC | Ordinary Portland Cement |
| ASTM | American Standard Testing Method |
| BS | British Standard |
| SEM | Scanning Electron Microscope |
| MIP | Mercury Intrusion Porosimetry |
| C-S-H | Calcium Silicate-Hydrate |
| $C_3S$ | Tricalcium silicates |
| $C_2S$ | Dicalcium silicate |
| MgO | Magnesium oxide |
| $SO_3$ | Sulphur oxide |
| $C_3A$ | Tricalcium aluminate |
| CaO | Calcium oxide |
| $SiO_2$ | Silica |
| $Al_2O_3$ | Alumina |
| $Fe_2O_3$ | Ferric oxide or Iron(III) oxide |
| $Na_2O$ | Sodium oxide |
| $SO_3$ | Sulphur trioxide |

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| NaOH | Sodium hydroxide |
| AR | Alkali-resistance |
| Kg | kilogram |
| g | gram |
| L | Litre |
| mm | millimetre |
| m | metre |
| g/L | gram per litre |
| $kg/m^3$ | kilogram per metre cube |
| $g/m^2$ | gram per metre square |
| N | Newton |
| kN | kilo Newton |
| $N/mm^2$ | Newton per millimetre square |
| N/sec | Newton per second |
| W | Watts |
| mK | metre-Kelvin |
| W/mK | Watts per metre-Kelvin |
| MPa | Megapascal |
| GPa | Gigapascal |

# PRESTASI MEKANIKAL DAN KETAHANAN GENTIAN KACA BERJEJALA MENGUATKAN KONKRIT RINGAN BERBUSA

## ABSTRAK

Konkrit ringan berbusa (LFC) terkenal sebagai konkrit berketumpatan rendah pelbagai kegunaan. Namun, kerana beratnya hampir separuh daripada konkrit konvensional, daya kekuatannya juga dianggarkan lebih rendah daripada konkrit biasa. Oleh itu, serat pendek (gentian sintetik dan semula jadi) digunakan oleh penyelidik terdahulu untuk meningkatkan prestasi LFC. Walaupun terdapat peningkatan pada sifat mekanikalnya, namun ia memberi kesan negatif terhadap daya ketahanan LFC untuk jangka masa panjang kerana kemerosotan serat. Pada masa kini, penggunaan fabrik tekstil sebagai elemen penguat telah mendapat perhatian. Oleh itu, tujuan penyelidikan ini adalah untuk menjalankan kajian eksperimental bagi menentukan prestasi mekanikal dan ketahana LFC yang diperkuatkan dengan gentian kaca berjejala. Dalam kajian ini, sampel LFC yang digunakan adalah berketumpatan 600 kg/m$^3$, 1100 kg/m$^3$, dan 1600 kg/m$^3$ dengan nisbah simen ke pasir dan simen ke air dimalarkan iaitu 1: 1.5, dan 1: 0.45 masing – masing. Fabrik tekstil yang dipilih untuk kajian ini adalah gentian kaca berjejala dengan berat per luas yang berbeza iaitu 110, 130, 145, dan 160 g/m$^2$. Bilangan lapisan membaluti LFC yang diperhatikan telah diperincikan akan pengaruhnya terhadap prestasi LFC. Prestasi mekanikal diuji melalui ujian kekautan mampatan, lenturan, dan ketegangan manakala ujian ketahan dilakukan melalui eksperimen keliangan, penyerapan air, dan pengecutan pengeringan. Secara keseluruhannya, pengukuhan dengan gentian kaca berjejala meningkatkan prestasi mekanikal dan ketahana LFC. Peningkatan yang

ketara dicapai apabila gentian kaca berjejala dengan berat per luas 160 g/m$^2$ digunakan. Selain itu, jumlah bilangan lapisan yang membaluti LFC juga mempengaruhi daya ketahanan dan prestasi mekanikal LFC. Hasil daripada dapatan ini, pengukuhan dengan gentian kaca berjejala mempertingkatkan prestasi mekanikal dan ketahan bagi LFC. Tambahan lagi, melalui kaedah pemerhatian terhadap mod kegagalan berdasarkan ujian mekanikal, LFC yang tidak diperkuatkan menunjukkan sifat yang rapuh, sementara LFC yang diperkuatkan menunjukkan prestasi mulur, yang mana balutan gentian kaca berjejala mencegah kegagalan mendadak dan menunda penyebaran retakan terhadap LFC di bawah beban paksi, lenturan, dan tegangan.

# THE MECHANICAL AND DURABILITY PERFORMANCE OF WOVEN FIBERGLASS MESH REINFORCED LIGHTWEIGHT FOAMED CONCRETE

## ABSTRACT

Lightweight foamed concrete (LFC) is well known as a low-density concrete with a wide range of applications. However, since its weight is almost half that of conventional concrete, its strength can also be expected to be lower than that of normal concrete. Thus, short fibres (synthetic and natural fibres) were used by previous researchers to improve the performance of LFC. Even though there were improvements in its mechanical properties, yet these had a negative impact on its durability in the long term due to the deterioration of the fibres. Recently, the use of textile fabrics as a reinforcing element has gained considerable attention. Thus, the aim of this research was to perform an experimental investigation to establish the durability and mechanical performance of woven fibreglass mesh reinforced LFC. In this research, LFC samples were designed with densities of 600 kg/m$^3$, 1100 kg/m$^3$, and 1600 kg/m$^3$ with a constant cement-to-sand ratio of 1:1.5, and cement-to-water ratio of 0.45. The textile fabric selected for this research was woven fiberglass mesh with different weights per area of 110, 130, 145, and 160 g/m$^2$. The number of layer(s) for the observed confinement was detailed down to its effect on the performance of the LFC. As a result, reinforcement with woven fiberglass mesh enhanced the mechanical and durability performance of LFC. Moreover, through observations of the failure modes based on the mechanical tests, the unreinforced LFC showed a brittle behaviour, while the reinforced LFC showed a ductile performance, where the confinement with woven fiberglass mesh prevented sudden

failure and delayed the propagation of cracks in the LFC under axial, bending, and tension loading.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The construction industry, which began centuries ago, is one of the biggest contributors to the development of a country. The Pyramid of Khufu located at Giza, Egypt is an example of an ancient building that is still standing strong until today, and it is a historical building that has become a tourist attraction. The pyramid, which was built with 2,300,000 blocks, took 20 years to be completed using traditional methods throughout the construction period due to the limited technology at that time.

The construction sector is one of the main drivers for attaining rapid progress and expansion in developing countries like Malaysia. Generally, the construction methods utilized in Malaysia lean towards conventional or traditional methods of construction (Kumar, 2015). Structures take a longer time to be completed using these methods compared to non-conventional methods, and they are also not environmentally friendly since they normally employ timber as the raw material, where timber can only be used two to three times for the formwork and involves intensively huge transportation activities (Mokhtar, 2011). Prefabricated construction approaches are not regarded as new in a global context but their application in the construction industry of Malaysia is still uncommon due to numerous issues such as high overall costs, lack of expertise and familiarity among workers, environmental awareness, and scientific information compared to conventional construction methods.

Nevertheless, over the past decades, this country has started to switch from conventional methods of construction to the prefabricated approach to meet current needs owing to the high demand for new housing projects, high-rise commercial buildings, and other infrastructural development (Mydin et al., 2015). Besides, the construction industry worldwide has acknowledged that future construction materials need to be lighter, durable, simple to use, economic, and environmentally sustainable. In this regard, many factors need to be considered to satisfy all the demands and needs, namely, the scope (project requirements), time (duration for completing the project) and money (costs). Thus, the selection of building materials is one of the keys to ensuring that these three constraints of project management can be followed, aside from its importance in ensuring that buildings have a longer lifespan and safe occupancy.

Concrete is a building material that is being widely used in the construction industry due to its resistance to deterioration compared to wood, and it is also easier to build in several forms. It is produced by combining cement with water and coarse aggregates or sand to form a solid matrix through the hydration process. Its density ranges between 2240 kg/m$^3$ to 2400 kg/m$^3$, and its compressive strength ranges between 20 N/mm$^2$ to 40 N/mm$^2$ (Pulliattu & John, 2017). Despite that, there are some drawbacks to using normal concrete as a construction material. Raupit et al. (2017) reported that the heavy weight of normal concrete is inconvenient since it requires a larger volume of concrete to be cast over a structure with a long span. They also added that the transportation of a precast reinforced concrete plant is expensive since heavy machinery is required to handle it due to its high density, which is in the range of 2300 kg/m$^3$ to 2700 kg/m$^3$.

Comprehensive researches into concrete have been conducted over many years, and there is a growing interest among researchers to carry out investigations to improve the quality of concrete for use in the construction industry. Lightweight foamed concrete (LFC) is one of the innovative products that has been developed for lighter and more sustainable constructions (Raupit et al., 2017). Ramamurthy et al. (2009) defined LFC as a lightweight material that consists of cement paste with air-voids entrapped in the mortar following the introduction of a suitable foaming agent into the cement slurry. According to research conducted by Zaidi and Li (2009), the difference between LFC and normal concrete is that no coarse aggregates are used in LFC, but instead, homogeneous cells produced by air in the form of small bubbles are added to replace the traditional aggregates. Jalal et al. (2017) stated that LFC is only comprised of fine sand mixed with cement, water, and foam, and it is regarded as a homogenous material unlike normal concrete as it does not contain any coarse aggregates. In addition, Alwi (2009) reported that reducing the density of concrete will reduce the load that is applied to a building structure, and directly to the foundation of the building (Tan et al., 2017), and hence, this will enable smaller-sized foundations to be designed.

Besides, the growing development of precast concrete systems and components, referred to as an Industrialised Building System (IBS), has attracted the attention of the construction industry in Malaysia. As mentioned by Shah (2008) in his study, which highlighted the use of lightweight foamed concrete for non-load bearing wall systems, there are many construction components, one of which was used for a residential development project in Putrajaya. Apart from that, The Pantheon, which was built by the Romans in the second century, is the first recorded structure that used lightweight concrete (Siong, 2015; Zulkarnain, 2011). Thus, the implementation of LFC in the construction industry will not only offer an improved and lighter concrete-based material, but, at the same time, will also accelerate the construction process and increase the production rate of buildings and the development of infrastructure holistically.

However, it should be pointed out that LFC has a low density (between 500 kg/m$^3$), which is good for compression but weak when it comes to tension. This disadvantage has limited its use in building construction, particularly for semi-structural and load-bearing components. This is due to the presence of numerous microcracks in the cement matrix (due to high porosity), which cause the material to have very poor tension and to be very brittle under compression. Despite that, LFC is not only being applied primarily for level correction in housing development and as fill-in material for load works (Kearsley, 1999), but is also being used as a semi-structural element in construction (Shah, 2008). Nevertheless, many researches have been conducted to improve the performance of LFC due to its potential use as a structural building material. There is a growing interest in LFC among researchers because of its characteristics such as its good thermal insulation (Kim et al., 2012; Yang et al., 2014) and acoustics shielding properties (Kim et al., 2012), especially when low densities of the material are applied.

Therefore, several studies have been conducted to improve the mechanical properties of LFC. As cited in Mohamad (2010) on the contribution of LFC to the strength of cross sections of composite members, it was found that LFC is not able perform satisfactorily when it comes to resisting the squash load and bending because of its brittle properties. According to Raupit et al. (2017), LFC that is unable to achieve a strength of at least 25 N/mm$^2$ cannot be considered as a structural component.

Consequently, the introduction of fibres into LFC has a positive impact on its mechanical properties. Over the last decades, reinforced lightweight concrete has been attracting attention in the construction industry (Islam et al., 2015). The use of fibres in lightweight concrete not only allows the cost of a structure to be reduced, but can also provide certain other improved properties (Alberti et al., 2014) such as a reduction in the drying shrinkage, porosity, water absorption, compressive strength, etc.

Basically, two types of fibres have been utilized to investigate the performance of LFC, namely, synthetic and natural fibres. Synthetic fibres are categorized as man-made fibres such as steel fibre, polypropylene fibre, carbon fibre, fibre mesh, etc., while natural fibres are extracted from organic materials (e.g. bamboo, coir, sisal, banana trunks) and are more environmentally friendly compared to synthetic fibres.

The inclusion of natural fibres in LFC has been widely investigated. The strength of LFC is significantly increased by the addition of natural fibres in the cement matrix. However, the fibres only enhance the strength of the concrete at an early age, and this strength will start to decrease at a later curing age. Wei and Meyer (2016) stated in their report that the main reason for this is the deterioration of the fibres in the concrete, where the fibres suffer degradation in the highly alkaline cement paste (Portland cement). Abdulameer (2015) also added that the high-alkaline environment dissolves the lining and hemicellulose phase of the fibres, thus weakening the natural structure of the fibres.

Nevertheless, many studies were also conducted previously using synthetic fibres. In 1996, Banthia and Sheng clarified that the addition of steel, polypropylene and carbon fibres can overcome the brittle properties of concrete. Kayali et al. (2003)

also stated in their study that the addition of 0.56% by volume of polypropylene fibres indirectly caused an increase of 90% in the tensile strength and 20% in the modulus of rupture of lightweight aggregate concrete. This was followed by a research conducted by Chen and Liu in 2005, in which they also verified that the addition of steel fibres not only increased the splitting tensile strength of expanded polystyrene concrete but also improved its resistance to shrinkage. Besides, Ibrahim et al. (2014) also mentioned that the compressive strength of LFC improved only slightly with the addition of polyolefin fibres, where the compressive strength of the control specimen was 7.4 N/mm$^2$ while the compressive strength of LFC was only 7.8 N/mm$^2$ on day-28 following the addition of 0.4% fibre.

Although all the mentioned studies were conducted to improve the durability and mechanical properties of LFC, there are still drawbacks to the use of these materials. In 2013, Olaoye et al. discovered that the major problem with using reinforcing elements like steel in concrete is the corrosion of the material, which clearly disrupts the lifespan and robustness of the concrete structure. Besides, Alberti et al. (2014) also found that although a good performance is obtained by the combination of steel in a concrete structure, its shortcomings range from corrosion to high purchase, storage and handling costs. Amran et al. (2015) also reported that the utilization of steel fibres in LFC is not appropriate due to their heavy weight, which causes them to settle at the bottom of the concrete mixture.

Hence, this research project was performed to explore the potential use of woven fiberglass mesh reinforced LFC as a construction material. Woven fiberglass mesh is a textile fabric that is widely used in normal concrete, also known as Textile

Reinforced Concrete (TRC). It is an alkali-resistant material that can be used to replace the reinforcing steel in LFC.

## 1.2 Problem Statement

The awareness of using lightweight, durable, economical, easy-to-construct, and yet eco-friendly construction materials is needed to fulfil the high demand for new housing, high-rise buildings, and other infrastructural development. One of the suggestions for accomplishing this requirement is the use of LFC as a construction material. LFC not only has a low weight density, but is also easy to cast because it is a self-compacting concrete and can be pumped directly from the mixer to the formwork. Moreover, the introduction of precast concrete systems has also accelerated the construction period, where the building components are ready-made in the factory and can be applied directly on-site.

In spite of that, LFC is good in compressive strength but weak in tension due to the formation of numerous microcracks caused by the combination of soft and brittle materials in the matrix. When a load is applied, the microcracks will begin to propagate in the matrix and lead to failure. LFC cannot sustain the development of tensile stress due to the zero applied force in the tensile zone. Besides, LFC also has a higher shrinkage, which is about two to three times greater than that of normal concrete (Kearsley, 1999), and this will cause changes to the dimensions and induce cracking in the structural components (Al-Haidary, 2010). Narayanan and Ramamurthy (2000) also reported that LFC has a high porosity due to the entrapment of air voids in the matrix.

The use of fibres such as natural fibres (jute, flax, kenaf, bamboo, hemp (Priyanka et al., 2017)) and synthetic fibres (aramid, glass, carbon, polyethylene

(Priyanka et al., 2017)) in LFC also has a negative impact on the long-term performance of LFC. The deterioration of natural fibres (Bentur & Mindess, 2007) and corrosion of reinforcing steel (Memon et al., 2018) will affect the lifespan and durability of LFC. Although the performance of LFC will improve with the addition of fibres, the excessive utilization of fibres may lead to a segregation effect in the cement matrix. Shah (2008) also stated in his study that fibres that are too long tend to "ball" in the mix and give rise to workability problems.

Therefore, due to the abovementioned problems, the introduction of textile fabric reinforcements is expected to address all the stated drawbacks. Woven fiberglass mesh is one such textile fabric material. This textile fabric, which has continuous multi-filaments with a weft knitting weave, could be a suitable alternative for use as a reinforcing element in LFC as it is expected to increase the toughness and tensile properties of the basic matrix. Moreover, it has the capability to control the high drying shrinkage in low-density LFC.

## 1.3 Study Objectives

The main aim of this research was to investigate the mechanical and durability performance of woven fiberglass mesh reinforced lightweight foamed concrete. The specific objectives of the current research were as follows:

1. To investigate the mechanical properties of woven fiberglass mesh reinforced lightweight foamed concrete.

2. To determine the durability of woven fiberglass mesh reinforced lightweight foamed concrete.

3. To examine the failure modes of woven fiberglass mesh reinforced lightweight foamed concrete.

## 1.4 Scope of the Study

This research was conducted to investigate the potential use of woven fiberglass mesh in LFC. The study was also designed to improve the mechanical and durability performance of LFC. Woven fiberglass mesh was utilized as an enclosure for LFC. Besides, the failure modes in the use of this textile fabric were also determined.

In the case of this study, several parameters had to be highlighted, namely, the density of the LFC, weight of the woven fiberglass mesh (weight per area), number of textile fabric layers, and the age of the specimens. These four parameters were expected to influence the overall mechanical and durability properties of the LFC.

Thus, three different densities of LFC, namely, 600 kg/m$^3$, 1100 kg/m$^3$, and 1600 kg/m$^3$, were selected for a comparative study to gain a better understanding of how a small variation in the density can cause a reduction in the properties. Moreover, the LFC with a density of 600 kg/m$^3$ represented non-structural elements, while the LFC with densities of 1100 kg/m$^3$ and 1600 kg/m$^3$ represented semi-structural and structural elements, respectively. In addition, this study was also carried out to examine the enhancement in the strength of low-density and high-density LFC through the use of woven fiberglass mesh. Apart from that, four different weights of woven fiberglass mesh (110g, 130g, 145g, and 160g) per area, and 1, 2 and 3 layers of textile fabric were applied to the respective densities to investigate their effect on the durability and mechanical properties of LFC aside from the observation of its failure modes. The test results of the samples were taken at day-7, day-28, day-56, and day-

180. The purpose of studying the samples up to 56 and 180 days was to investigate and monitor the long-term reaction of the woven fiberglass mesh in LFC to ensure that it is really resistant to alkali and can withstand changes to the environment.

The woven fiberglass mesh was cut and prepared according to the dimensions of the LFC mould. Then, it was placed differently depending on the test that was to be performed. This will be explained more fully in CHAPTER 3.

## 1.5 Significance of the Study

Energy consumption is currently a global issue and substantial efforts have been made to enhance the efficient use of energy in most fields of engineering, including building construction. LFC can be efficiently utilized as a building material while fulfilling the requirement for energy efficiency in the construction industry.

Many researches have been carried out with regard to LFC. However, these previous studies focused more on the inclusion of fibres based on the volume aspect ratio of concrete, which was not conceivable since a balling effect can occur during the mixing of the materials. However, no further studies were done on the effects of using textile fabric reinforcements in LFC.

Hence, the present study was conducted to explore the potential use of woven fiberglass mesh, which is an example of a textile fabric, as a reinforcing element in LFC. An experimental research was conducted to investigate the mechanical and durability performance of this textile fabric when applied in LFC. It is essential that an LFC be developed that is durable and contributes to the higher strength of a product. Additionally, a microstructural analysis was used to justify the behaviour of LFC in terms of its mechanical and durability characteristics. The final finding from this research will provide future researchers with a better view of the effect of using various densities of LFC enclosed with 110, 130, 145, and 160 g/m$^2$ of woven fiberglass mesh. Besides, the effect of applying different number of layers of woven fiberglass mesh in LFC was also examined to provide accurate data for future use.

## 1.6 Thesis Organization

This thesis is divided into five chapters, including the introduction to the research, literature review, research methodology, data collection and analysis, and the conclusion and recommendations for future research. It has been designed in such a way that the objectives of the research can be fulfilled through the discussions that are presented chapter by chapter.

***Chapter One*** presents the introduction to the thesis, an overview, and the objectives of the current study. The problems faced by plain LFC are also highlighted in this chapter in the explanation on the problem statement. Besides, the potential use of woven fiberglass mesh reinforced LFC is also emphasized in this chapter. On top of that, the significance and the scope of the study are also defined.

***Chapter Two*** discusses more about the previous studies conducted by other researchers. The fundamental development of LFC is explained in more detail in this chapter. Additionally, the properties, advantages, and application of LFC are emphasized in this chapter, while the potential use of textile fabric is also featured. Finally, this chapter concludes with a summary of the findings of previous studies and sets the framework for the current study.

***Chapter Three*** explains the research methodology, and provides details of the constituents and the proportions of the LFC mix. Moreover, this chapter also demonstrates the preparation and production of the specimens as well as the types of methods that were applied to determine the mechanical and durability performance of the LFC enclosed with woven fiberglass mesh.

***Chapter Four*** focuses mainly on the findings obtained in this study. The results of the experimental work on the mechanical properties (axial compressive strength, flexural strength, and splitting tensile strength tests) and durability (water absorption, porosity, and drying shrinkage tests) are presented. Besides, the failure modes of LFC are also discussed further in this chapter. All the data are analysed based on comparisons of the plain specimens with the reinforced specimens. The different densities, weights per area of woven fiberglass mesh (gram per square metre), numbers of textile fabric layers, and curing ages of the samples are the parameters that are examined in this chapter.

Last but not least, ***Chapter Five*** presents the main conclusion and recommendations for future works. This chapter gives a summary of the results (mechanical and durability properties) obtained and suggests improvements that can be made in future researches.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The main aim of this research was to experimentally examine the properties of lightweight foamed concrete (LFC) confined with woven fiberglass mesh. This investigation is expected to fill the gaps of knowledge with regard to the mechanical and durability performance of LFC-based systems. Hence, this chapter will examine and consider previous researches that investigated the mechanical and durability properties of LFC holistically. Furthermore, this chapter will also discover the potential utilization of textile fabrics in LFC, as with other cement-based materials.

## 2.2 Lightweight Foamed Concrete (LFC)

### 2.2.1 Overview of Lightweight Concrete

Nowadays, construction industries in many countries around the world are using concrete as their main element for structural designs. Mehta and Monteiro (2013) highlighted that concrete is being utilized as an engineering material due to its excellent resistance to water compared to wood and ordinary steel, where it can withstand the action of water without serious deterioration. They also added that freshly-made concrete can be formed into various shapes and sizes due to its plastic consistency, which enables it to flow freely into prefabricated formworks.

According to Sulaiman (2011), concrete can be divided into 3 major categories based on its unit weight (density), namely, heavyweight concrete, where the density of the concrete is more than 3600 kg/m$^3$, normal concrete with a density of 2400 kg/m$^3$, and lightweight concrete with a density of 2000 kg/m$^3$ or less (Neville, 1995), while its practical density range is within 300 kg/m$^3$ – 1800 kg/m$^3$. Mehta and Monteiro (2013) also stated that heavyweight concrete, which is usually used for radiation shielding, is produced from high-density aggregates, while normal weight concrete is a type of concrete that is commonly utilized as structural elements, and lightweight concrete is used for applications where a higher strength-to-weight ratio is desired.

In 1978, Short and Kinniburgh reported that there are three types of lightweight concrete, namely, lightweight aggregate concrete, no-fines concrete, and aerated concrete (refer to Figure 2.1). Lightweight aggregate concrete can be produced using various types of lightweight aggregates, which are natural materials (volcanic pumice), thermally-treated natural raw materials (clay, state or shale), those manufactured from industrial by-products (fly ash) and the processing of industrial by-products (furnace bottom ash or slag) (Shah, 2008). Shah (2008) also stated that no-fines concrete can be produced by omitting the finer-sized aggregates. Aerated concrete is also known as cellular concrete (Neville & Brooks, 1987). Table 2.1 gives a summary of the characteristics of the various types of lightweight concrete.

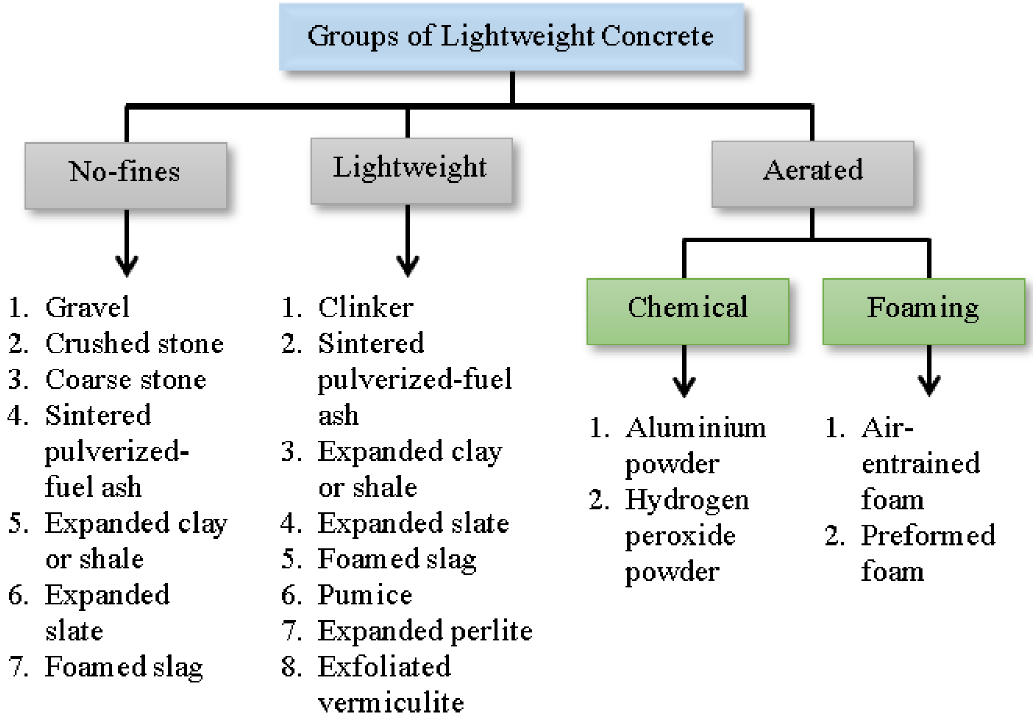


Figure 2.1 Groups of lightweight concrete (Short & Kinniburgh, 1978)

Table 2.1 Summary of characteristic of lightweight concrete based on its type (Raupit et al., 2017).

| No. | Type of lightweight concrete material | Description |
|---|---|---|
| 1 | Lightweight aggregate concrete | Produced by using lightweight aggregates with a low apparent specific gravity. |
| 2 | No-fines concrete | Composed of cement and coarse aggregates with a diameter of 9 – 19 mm. |
| 3 | Aerated concrete | Concrete with entrapped air. |

Hamad (2014) stated in his study that aerated concrete can be classified into two different types based on its method of production (refer to Figure 2.2); (1) foamed concrete, also known as non-autoclaved aerated concrete (NAAC), and (2) autoclaved aerated concrete (AAC). Foamed concrete is produced by injecting stable foam (pre-foamed) into the base mix of cement paste (cement + water) or mortar (cement + sand + water), while ACC is formed by adding a predetermined amount of aluminium powder and other additives into a slurry of ground high silica sand, cement or lime, and water (Yen, 2006). Yen (2006) also mentioned that the density of ACC typically ranges between 400 kg/m$^3$ to 700 kg/m$^3$, and it has strength of 2-8 N/mm$^2$. The disadvantages of AAC products are that they have a high production cost, their size is limited by the size of the autoclaving facilities at the factory, and it is not always possible for them to be cast on-site. Thus, the production of foamed concrete is more beneficial compared to AAC because there is no size restriction and the moist-cured foamed concrete can be produced in large quantities with a minimum capital outlay compared to AAC. In addition, its high shrinkage volume can still be controlled by the addition of other additives such as super plasticizers, fibres, etc. Figure 2.3 shows the cross-sectional view of AAC and foamed concrete.

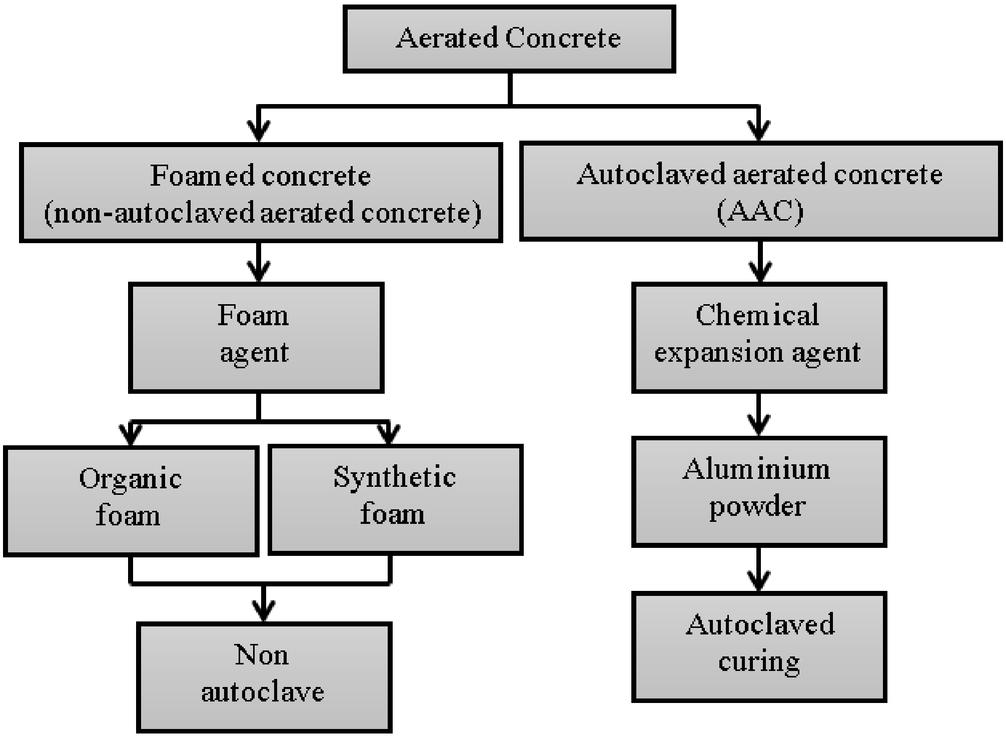
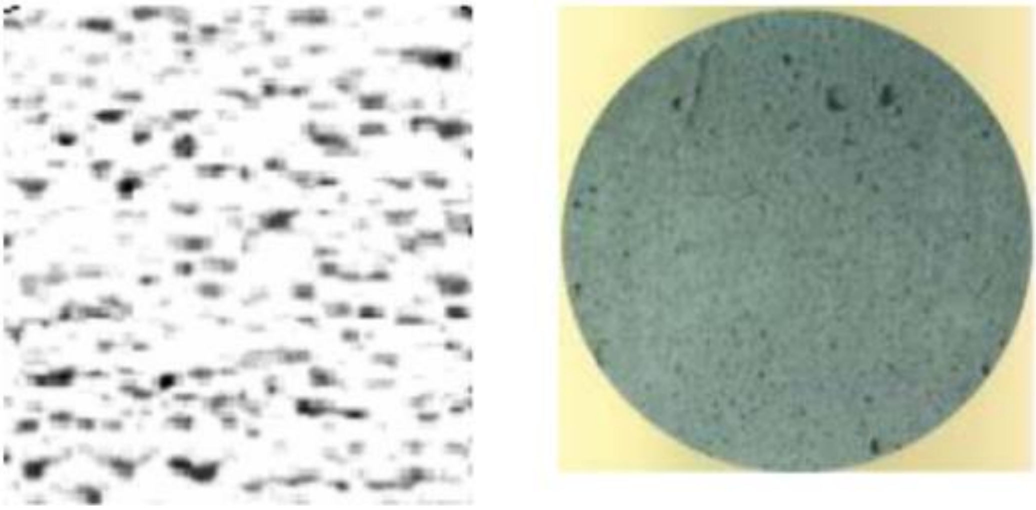


Figure 2.2 Classification of lightweight aerated concrete (Hamad, 2014)



(a) AAC (b) Foamed concrete

Figure 2.3 Cross-sectional view of AAC and foamed concrete (Yen, 2006).

### 2.2.2 Introduction of Lightweight Foamed Concrete (LFC)

Generally, LFC is produced using four main materials, which are cement, sand, water, and stable foam or foaming agent. The air voids entrapped in the matrix cause its unit weight (density) to be lower (i.e. two times lighter) than that of normal concrete. The Draft International Standard Model Code for concrete construction classifies lightweight concrete as having a density of between 1200 kg/m$^3$ to 2000 kg/m$^3$ (Shah, 2008).

Deijik (1991) defined LFC as a cementitious material with a minimum of 20 per cent (by volume) of mechanically entrained foam in the mortar mix, where air voids are entrapped in the matrix by utilizing a suitable foaming agent. Nambiar and Ramamurthy (2007) stated that LFC is a lightweight material consisting of a Portland cement paste or cement filler matrix (mortar) with a homogeneous void or pore structure created by introducing air in the form of small bubbles. Besides, Jalal et al. (2017) also clarified that LFC is generally concrete that is extremely light in weight and contains no large aggregates, only fine sand mixed with cement, water, and foam.

They also stated that LFC should be considered as being relatively homogeneous in comparison to normal concrete as it does not contain a coarse aggregate phase. Ahmad (2015) also explained that LFC can be defined as a type of concrete that uses an expanding agent to increase the volume of the mixture, while raising the quality of the lightweight concrete and cutting back on the dead load.

Neville (1995) claimed that the first recorded date of LFC, known as aerated and cellular concrete, was in the early 1920s. It was initially used mainly for roof and floor units, and wall panels in Scandinavia, where it was patented in 1931. Therefore, LFC was not considered as an innovation in worldwide construction, but its applications were only limited to non-structural and semi-structural elements. However, due to its versatile characteristics, LFC gained interest among researchers. The main advantages of using LFC are its low weight, high flowability, low cost, and fast completion time (Falliano et al., 2019; Ghorbani et al., 2019; Rai & Kumar, 2017). A comprehensive review of LFC was reported by Valore in 1954, while a detailed study was done by Rudnai (1963) and Short and Kinniburg (1963), who summarized the composition, properties and utilization of cellular concrete, irrespective of the method by which the cell structure was formed. In late 1975, the application of LFC in construction work was finally recognised (Hamad, 2014).

Even though the application of LFC began a long time ago, the utilization of this concrete for construction work is still new in Malaysia. The acceptance of LFC blocks and panels by the Construction Industry Development Board (CIDB) of Malaysia as components of the Industrialized Building System (IBS) has promoted its commercial application (Sulaiman, 2011). Kuik Wall, with a density that varies between 1000 kg/m$^3$ to 1500 kg/m$^3$, is one example of a precast composite wall system in Malaysia. According to Shah (2008), many construction projects have been completed using a precast concrete system and precast concrete components, one of which is a residential development project in Putrajaya.

### 2.2.3 Characteristics of Lightweight Foamed Concrete (LFC)

Zaidi and Li (2009) clarified that the difference between LFC and normal concrete is in the use of aggregates, where in LFC, which utilizes a stable air structure rather than traditional aggregates, the coarse aggregates are eliminated and replaced by homogeneous cells created by air in the form of small bubbles. According to Hedjazi (2019), structural LFC has a density that ranges between 300 kg/m$^3$ to 1840 kg/m$^3$, where it is 87% or 23 times lighter than normal concrete, which has a density that ranges between 2240 kg/m$^3$ to 2400 kg/m$^3$. LFC is created by the uniform distribution of air bubbles throughout a mass of concrete, where the discrete air bubbles range in size between 0.1 – 1.0 mm in diameter (Jalal et al., 2017).

LFC has also been classified as a self-compaction concrete due to its high workability (Sipple, 2009). Jalal et al. (2017) also explained that LFC is a free-flowing concrete, and it can be placed without compaction. As reported by Rahman et al. (2010), LFC is a cellular material made up of an interconnected network of solid structures that form the edges and faces of cells. They also added that the introduction of bubbles into the cement slurry allows the bubbles to grow, and to stabilize and solidify the whole structure by cross-linking.

Besides, the growing interest in LFC among civil engineers is due to its varied density. The main characteristics of LFC is its low density, which is economical for the walls of lower floors and the foundation (Puttappa et al., 2008). Besides, Shah

(2008) also stated that LFC has a wide array of applications, ranging from wall blocks and panels, architectural decorative components, landscaping components, roof screeds, trench reinstatements, road foundations, bridge abutments, and void fills.

### 2.2.4 Properties of Lightweight Foamed Concrete (LFC)

#### 2.2.4(a) Compressive Strength of LFC

The most apparent characteristic of LFC is its range of densities. Even though low-density LFC has many advantages such as the reduction of dead load, a faster building rate, and lower haulage and handling costs, this type of concrete has also been reported to have many drawbacks. Based on a study by Yasser (1997) into the contribution of LFC to the cross-sectional strength of a composite, it was discovered that LFC is not able to satisfactorily resist a bending load because of the brittle properties of the material. According to Zhu (1999), LFC is a combination of soft and brittle materials, and as such, it contains many microcracks. Thus, when it is compressed, these microcracks will propagate and cause failure.

Amran et al. (2015) highlighted that the compressive strength of LFC is directly related to its density, where a reduction in unit weight affects the compressive strength both exponentially and adversely. As reported by Deijik (1991), the compressive strength is influenced by many factors such as the foaming agent, proportions of the mix, size of the sand particles, curing method, characteristics of the additives and their distribution in the matrix. According to Thakrele (2014), the compressive strength of LFC will continue to increase indefinitely due to the reaction with the existing carbon dioxide ($CO_2$) in the surrounding air, but the increasing strength with age is essentially linear over the first 12 months.

Jalal et al. (2017) explained that the high strength of LFC can be achieved at an early age by the utilization of rapid hardening cement. They also suggested that LFC with a higher density and thus, a higher strength, can be achieved by increasing the amount of sand and cement, and reducing the volume of foam. Figure 2.4 shows the relationship between the compressive strength and the cast density of LFC.

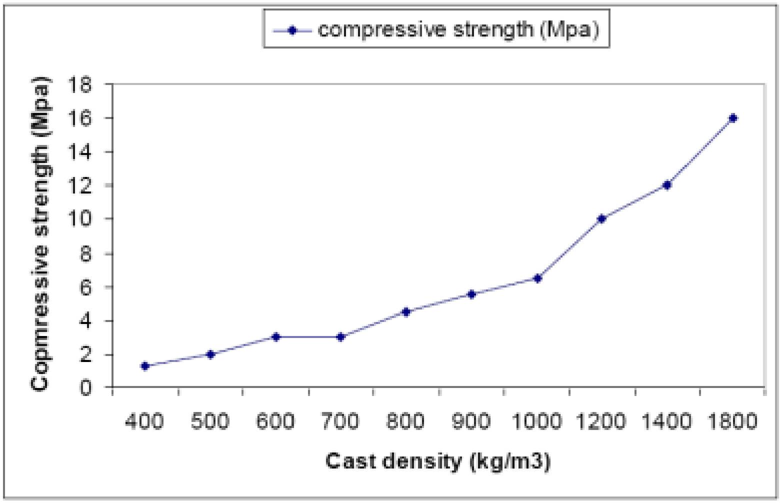


Figure 2.4 Relationship between compressive strength and cast density (Jalal et al., 2017)

As mentioned earlier, Zamzani (2019) verified that the compressive strength of LFC is significantly affected by its density due to its porosity. The higher amount of foam in LFC with a lower density will reduce its strength due to the development of air voids caused by the higher volume of foaming agent. Moreover, the pores, air voids, and matrix, which typically determine the quality of the microstructure, will influence the compressive strength in relation to the density.

Nevertheless, Coker et al. (2016) indicated that the longer the curing time of the LFC, the higher will be the gain in strength. They clarified that when foam is added to the concrete, it not only creates air voids or pore spaces, but also increases the total quantity of water present in the pore spaces within the concrete mass or the water-to-binder ratio. As reported by Coker et al. (2016), the hydration of cement increases the alkalinity of the water to pH 13 or even higher due to the reaction of tricalcium silicate ($C_3S$) and dicalcium silicate ($C_2S$) to form calcium silicate hydrate (C-S-H), which is largely responsible for the development of strength.

### 2.2.4(b) Flexural Strength of LFC

Based on a study by Dawood and Hamad (2015), plain concrete is a brittle material which has poor fracture toughness, weak resistance to crack propagation, and low impact strength. These characteristics, which cannot sustain the tensile stress due to the zero applied force in the tensile zone, tend to restrict its applications. However, Jones and McCarthy (2005b) explained that LFC can still be used as a structural material. According to the research conducted by Narayanan and Ramamurthy (2000), the flexural strength of LFC ranges between 15% to 35% of its axial compressive strength. Besides, Kozłowski and Kadela (2018) discovered that the flexural strength of LFC can be increased by increasing its density as the apparent density of hardened LFC is strongly associated with the foam content in the mix.

### 2.2.4(c) Splitting Tensile Strength of LFC

According to Neville (2011), the tensile strength is correlated to the compressive strength, although this relationship depends on multiple factors such as the aggregate type and particle size distribution, the age of the concrete, the curing process, and the air content. Besides, Thakrele (2014) reported that the tensile strength of LFC can be as high as 0.24 times its compressive strength, with an ultimate strain of about 0.1%. Parra and Gomez (2011) mentioned that the splitting tensile strength for self-compacting concrete is lower than normal vibrated concrete due to the absence of aggregate-paste bonds in the matrix. Moreover, Amran et al. (2015) posited that the factors influencing compressive strength will equally affect the tensile strength and vice versa. Additionally, the proportion of flexural strength to axial compressive strength is around zero when LFC is designed with a density that is below 300 kg/m$^3$. Table 2.2 shows the splitting tensile strength results from a lower to a higher density, as examined by Jalal et al. (2017).

Table 2.2 Results of splitting tensile strength from a lower to a higher density (Jalal et al., 2017).

| Density (kg/m$^3$) | Splitting tensile strength (N/mm$^2$) |
|---|---|
| 400 | 0.10 |
| 500 | 0.20 |
| 600 | 0.30 |
| 700 | 0.35 |
| 800 | 0.45 |
| 900 | 0.55 |
| 1000 | 0.65 |
| 1200 | 1.10 |
| 1400 | 1.20 |
| 1800 | 1.60 |

#### 2.2.4(d) Porosity of LFC

Shabbar et al. (2018) defined porosity as the sum of the entrained air pores and voids within a paste, measured by vacuum saturation, which is approximately four times that which is measured by the water absorption method. The entrained air voids create an increasingly tortuous path for capillary flow in proportion to the foam volume, and dampens or lessens the transport phenomenon (Tada & Nakano, 1983). A study by Kearsley and Wainwright (2001) into the porosity of LFC proved that it is mainly dependent on the dry density of LFC rather than the content or types of fly ash. Based on the results presented by Narayanan and Ramamurthy (2000), the larger pores in LFC can be considered as zero-density aggregates, and a transmission zone exists in the void-paste interface.

Ramamurthy et al. (2009) found that LFC with a uniform distribution of air voids has good mechanical properties. Furthermore, according to Visagie and Kearsley (2002), at higher densities of LFC, the distribution of air voids does not seem to influence the compressive strength, which is related more to the uniform distribution of air voids at higher densities. Luping (1986) also mentioned that bigger pores have an effect on the concrete strength rather than smaller pores, where for materials with the same matrix and porosity, the strength is lower for those that contain larger-sized pores. Figure 2.5 shows the results of the porosity test performed by Hilal et al. (2014), where a higher percentage of porosity was obtained at a lower density of LFC. According to Kurpińska and Ferenc (2017), the high percentage of porosity in LFC is due to the higher content of voids (pores) in the composition and the lower fulfilment of the voids.

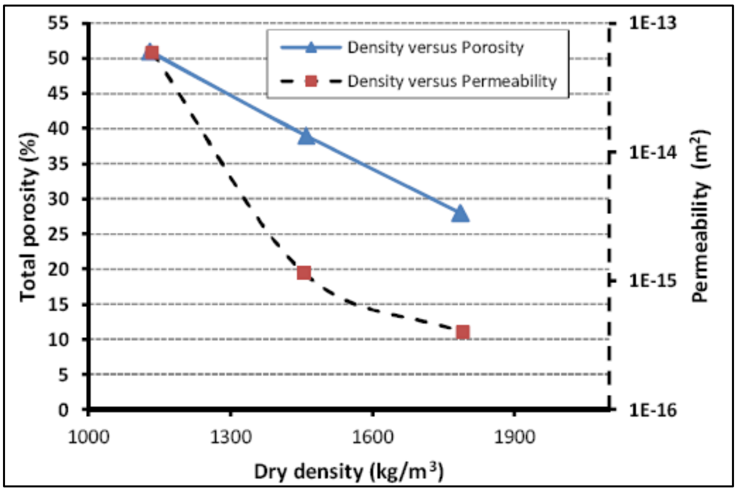


Figure 2.5 Porosity and permeability as functions of dry density (Hilal et al., 2014)