MECHANICAL PROPERTIES OF 1200 kg/m^3 LIGHTWEIGHT FOAMED CONCRETE INCORPORATE WITH CALCIUM STEARATE

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

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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 **"MECHANICAL PROPERTIES OF 1200 kg/m^3 LIGHTWEIGHT FOAMED CONCRETE INCORPORATE WITH CALCIUM STEARATE"** was prepared by **LEONG KAR SING** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Lightweight foamed concrete (LFC) is gaining popularity in the construction industry due to its low self-weight and good thermal insulation. Hence, it is normally used on the exterior of buildings such as walls and roof slabs which causes it to be often exposed to natural weathering such as rain. Since water is an agent of deterioration towards the durability of LFC in long term, water repellent agent is introduced into LFC. Calcium stearate (CS) is a type of water repellent agent that reduces the penetration of water into LFC. The aim of this research is to investigate the effect of incorporating CS into LFC mix in terms of its mechanical strength. Four types of LFC containing different percentages of CS ranging from 0 % to 0.6 % of cement weight were casted and water cured for 7 days, 28 days and 56 days before being tested for its compressive, splitting tensile and flexural strength. Trial mixes were conducted to determine the workability and the optimum water to cement ratio of LFC with and without CS. Adding CS into the LFC does not affect the workability of fresh concrete. The optimum water to cement ratio of 0.60 for each of the LFC has been achieved. The major finding in this research is that CS only retards the strength development rate of LFC during the early ages of LFC instead of reducing its overall strength. Under continuous curing, LFC with CS are able to achieve strength similar to the strength obtained by the control mix. If the early strength of LFC is not a major concern, incorporating CS into LFC will have an added advantage of lower water absorption which improves the durability of LFC.

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LIST OF SYMBOLS / ABBREVIATIONS

A_c	cross sectional area of specimen on which the load is applied, mm^2
b	breadth of specimen, mm
B_d	density of base mix, kg/m^3
B_m	mass of base mix, kg
d	diameter of specimen, mm
D	depth of specimen, mm
E_f	flexural modulus, MPa
f_c	compressive strength, MPa
$f_{c,cube}$	cube compressive strength, MPa
$f_{c,cylinder}$	cylinder compressive strength, MPa
F_d	density of foam, kg/m^3
F_m	mass of foam required, kg
l	length of specimen, mm
P	maximum load at failure, N
R	flexural strength, MPa
T	splitting tensile strength, MPa
TD	targeted density, kg/m^3
U_T	flexural toughness, J/m^3
δ_y	vertical deflection, mm
ε	strain, mm/mm
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British Standards
CS	calcium stearate
C-S-H	calcium silicate hydrate
EN	European Standards
FM	fineness modulus
IS	Indian Standards
IUPAC	International Union of Pure and Applied Chemistry
LFC	lightweight foamed concrete

LFC-CS0.2	lightweight foamed concrete with 0.2 % calcium stearate
LFC-CS0.4	lightweight foamed concrete with 0.4 % calcium stearate
LFC-CS0.6	lightweight foamed concrete with 0.6 % calcium stearate
LFC-CTR	lightweight foamed concrete without calcium stearate
N	number of sieves
OPC	ordinary Portland cement
PI	performance index, MPa per 1000 kg/m^3
R^2	coefficient of determination
TPR	total percent retained
w/c	water to cement ratio

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The versatility and economic aspect of concrete have made concrete to be widely used in the construction industry and became the most abundant man made material. Concrete comprises of four main ingredients, namely cement, fine aggregate, coarse aggregate and water. By adding chemical admixtures or fibres, replacing part of cement with mineral admixtures or by changing the mix proportions of concrete materials, the properties of concrete can be enhanced. For example, steel reinforcements are embedded in concrete to resist the tensile stresses since concrete is poor in tension but good in compression. Various types of concrete have been developed by researchers as an alternative to conventional concrete which is able to suit the need of construction subject to different conditions.

The most common classification of concrete is based on its density. The density of normal weight concrete is between 2200 and 2600 kg/m^3 while the density of lightweight concrete ranges from 300 to 1850 kg/m^3 (Shetty, 2015). With a lower self-weight, construction using lightweight concrete can reduce the overall dead load of a structure and thus allowing the size of foundation supports and columns to be reduced without compromising the safety factor. Ultimately, construction is more economical in terms of design and production cost.

There are three kinds of lightweight concrete such as lightweight aggregate concrete, lightweight foamed concrete (LFC) and no fines concrete. A more technical term for LFC should be lightweight foamed mortar due to the absence of coarse aggregate in LFC. LFC is produced by introducing stable foam into mortar paste and the density of LFC can be reduced by adding foam to increase the air voids in the paste. LFC has the advantage of self-compacting properties and providing better fire resistance, sound absorbance and thermal insulation due to the presence of air voids in the concrete. LFC has numerous applications such as roof insulation, void filling, blocks and panels for walls and trench reinstatements (Yuvaraj, et al., 2015).

1.2 Background of the Study

LFC is a porous structure due to the presence of air voids introduced into the mortar paste via foam. The bursting of foam and the presence of free water that are not utilised for the hydration of cement will create interconnecting capillaries in the concrete. These capillaries are the main factors contributing to the absorption of water into the concrete. According to American Concrete Institute (ACI) Committee 515 (1985), waterproofing concrete is to prevent water from entering into the concrete as well as to prevent water from leaking out from the concrete. Different from damp proofing, waterproofing can resist the movement of water under hydrostatic pressure. In other words, waterproofing is the highest protection level of concrete against water. However, fully waterproof concrete can only be achieved by applying layers of membranes on the surface of concrete.

The main function of water repellent agent is to reduce the permeability of concrete. Concrete incorporated with water repellent agent can only repel water and resist the absorption of water up to a certain degree. It is poor in resisting the penetration of water under hydrostatic pressure (Kosmatka and Wilson, 2011). Therefore, the more technical term for this type of concrete is water resistant concrete or water repellent concrete. When water is poured onto concrete treated with water repellent agent, water droplets can be seen on the surface of concrete instead of spreading and subsequently absorbed into concrete since the concrete becomes hydrophobic.

1.3 Problem Statement

The usage of LFC in construction is limited to non-structural purposes due to its low compressive strength (Jones and McCarthy, 2005). Recognising the potential and advantages of LFC, research conducted with the purpose of enhancing the properties of LFC will be beneficial in the future.

Malaysia is situated near the equator with tropical rainforest climate. Therefore, it is hot and humid all year long. On average, Malaysia receives 2500 – 3500 mm of precipitation every year (Kot, et al., 2016). The high amount of rainfall and humidity increases the chance of water absorbed into concrete. Furthermore, LFC is commonly used at the exterior of a structure due to its good insulation properties, making it more susceptible to water penetration. Since the durability of concrete will be affected by the absorption of water into concrete, it is crucial to reduce the permeability of concrete for long term usage. Moreover, the maintenance or repair cost due to water penetration will be very high.

Besides, the usage of water repellent agent is not commonly adopted in the construction industry due to the availability of other waterproofing methods as well as lack of research in this aspect. Therefore, this study is designed to determine the effect of calcium stearate as the water repellent agent on the mechanical properties of LFC as well as to determine the viability of water repellent LFC in a specific density to be adopted in structures exposed to water or humid environment.

1.4 Objectives of the Study

The following are the objectives to be achieved in this study:

(i) To produce lightweight foamed concrete incorporate with calcium stearate with density of 1200 ± 50 kg/m^3.

(ii) To determine the optimum water to cement ratio of lightweight foamed concrete incorporate with calcium stearate.

(iii) To study the effect of calcium stearate towards the mechanical properties of lightweight foamed concrete incorporate with calcium stearate.

1.5 Scope and Limitation of the Study

The main focus of this study is to determine the effect of calcium stearate on the mechanical properties of LFC in terms of compressive, splitting tensile and flexural strengths. A total of four types of LFC with designated density of 1200 kg/m^3 and allowable variation of ± 50 kg/m^3 were produced, which are i) LFC with no calcium stearate as the control (LFC-CTR), ii) LFC with 0.2 % calcium stearate of cement weight (LFC-CS0.2), iii) LFC with 0.4 % calcium stearate of cement weight (LFC-CS0.4) and iv) LFC with 0.6 % calcium stearate of cement weight (LFC-CS0.6).

In order to find out the optimum w/c ratio for all the four types of LFC, trial mixes were conducted. The w/c ratios used in trial mixes were ranging from 0.47 to 0.55 with an increment of 0.02 intervals. The cement to sand ratio was fixed at 1:1 for all types of LFC. Sieve analysis of sand was carried out to determine the grade of the sand used. During the casting of LFC, flow table test and inverted slump test were conducted to determine the consistency and workability of fresh LFC. LFC cubes were water cured for a period of 7 days and 28 days before conducting the compressive strength test. Performance index of each type of LFC was calculated and used to determine the optimum w/c ratio for each mix proportion.

The optimum w/c ratio determined from the trial mix was used to cast other concrete specimens consist of cubes, cylinders and prisms. The water-cured concrete specimens were then tested for its mechanical properties stated when the concrete reached the age of 7, 28 and 56 days. Results obtained from these tests were then analysed and discussed.

1.6 Significance of the Study

Incorporating calcium stearate into LFC as a method to deal with the water absorption of LFC is the main significance of conducting this research. Through this study, it can be determined whether calcium stearate will cause a positive or adverse effect on the mechanical strength of LFC. This research also develops the optimum mix proportion to produce LFC incorporated with calcium stearate and studies its mechanical properties in terms of compressive strength, flexural strength and splitting tensile strength.

1.7 Contribution of the Study

This study contributes to the society by encouraging the application of LFC in the construction industry. With the reduced size of structural supports due to lower self-weight, the amount of cement required will be reduced. Since the production of cement is one of the major sources of carbon dioxide emission (Benhelal, et al., 2012), using lesser cement will cut down the production and thus reducing the emission of carbon dioxide into the atmosphere. This will reduce the impact of carbon dioxide such as global warming. Besides, incorporating calcium stearate into LFC produces a more durable LFC that can withstand harsh weathering conditions which prolongs the life cycle of LFC. Compared with other water repellent methods such as coating and laying membrane onto concrete, which require extra work and complicated procedures, using calcium stearate as water repellent agent can reduce the manpower required to produce water repellent LFC since calcium stearate is mixed together with the concrete slurry during casting. Therefore, if the results obtained are favourable, using calcium stearate as a water repellent agent can save the cost and time in construction.

1.8 Layout of the Report

A total of five chapters are included in this report. Chapter 1 briefs on the study introduction, background, problem statement, objectives, scope, significance and report layout.

Chapter 2 discusses the literature reviews and researches related to waterproof lightweight foamed concrete. This includes the advantages and disadvantages of LFC, application of LFC, effect of water towards the durability of concrete, various waterproofing methods, mechanical properties of LFC as well as the materials used in this study.

Chapter 3 outlines the research methodologies applied in this study. The material preparations, casting procedures and testing methods are elaborated as well.

Chapter 4 analyses and explains the trial mixes results and the data obtained from the compressive test, splitting tensile test and flexural test for the four types of LFC.

Chapter 5 concludes the whole study. Conclusions are drawn from the results collected and according to the respective objectives. The recommendations for further studies are also provided in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Also known as cellular concrete or aerated concrete, lightweight foamed concrete (LFC) achieves its lightweight property by introducing stable air bubbles within the concrete slurry and thus lowering the density of concrete. For LFC, at least 20 % by volume of concrete is filled with air voids (Kozlowski and Kaleda, 2017) to differentiate it from concrete with air entraining admixture. Through proper control of the foam quantity, the density of LFC between 400 and 1600 kg/m^3 can be achieved (Risdanareni, Sulton and Nastiti, 2016). This allows the density of LFC to be varied to suit different functions and purposes. In order to produce a good quality of LFC, several parameters such as the proportion of base mix, types of foaming agent used, mixing technique and distribution of air voids in concrete slurry must be taken into account. Nevertheless, the LFC is weaker than normal weight concrete in terms of strength.

The usage of LFC is gaining its popularity in the construction sector due to the advantages that it offers, mainly due to its lightweight properties. The properties of LFC can be enhanced by adding different types of admixtures. In this study, calcium stearate (CS) is used with the purpose to make the LFC repels water. Incorporating CS into concrete is not something new. Various researches have been conducted to determine the effects of CS on the performance of concrete.

2.2 Advantages of LFC

A list of advantages of LFC has been compiled by Yuvaraj, et al. (2015). One of the most obvious benefits is the reduction in weight. The density of normal weight concrete is in the range from 2200 to 2600 kg/m^3. When foam is incorporated into the concrete mix, the density of LFC can be reduced to 300 – 1850 kg/m^3 (Shetty, 2015). With the weight of non-structural members reduced by using LFC, the design of columns and foundations can be smaller.

Besides that, LFC has high workability and great flow property. LFC slurry can fill up small space or restricted region of a formwork. Since it is also a self-compacting concrete, compaction and vibration during casting are not required.

LFC can be self-levelling when sufficient workability and flowability are achieved. These can result in a shorter casting time and higher productivity.

Moreover, the presence of air voids enhances the thermal insulation of LFC. This is because the thermal conductivity of air is lower than in solid (Mydin, 2011). This also makes LFC to have excellent fire resistant properties. LFC is a good sound insulator. Porous structure helps in absorbing sound as the sound absorption area increases (Park, Seo and Lee, 2004). Normal weight concrete tends to deflect the sound instead of absorbing it. LFC is able to resist freeze-thaw cycles as the air voids in LFC act as an expansion chamber to allow the expansion of water without stressing the concrete.

2.3 Disadvantages of LFC

The strength of LFC is sacrificed in order to achieve a lower density. Because of this, LFC is normally used for non-load bearing members. LFC requires higher quality control during the foam production, addition of foam as well as the mixing process. Else, desired density and uniformity of concrete slurry might not be able to achieve. Therefore, longer mixing time is required to ensure the mix is homogeneous. The surface of hardened LFC is uneven due to the huge amount of pores present on the surface. This makes the finishing process of LFC to be more difficult than normal concrete.

2.4 Application of LFC in Construction

Barnes (2009) has discussed several applications of LFC in the construction sector. LFC is usually used to fill voids such as pipelines, old mines and tunnels. With a smaller amount of base mix, LFC can achieve higher volume output, making it a cost effective solution for void filling. Since LFC is a good thermal insulator, it is often used as a roof slab and walls of buildings. The walls can be either pre-cast or cast in-situ. With this, the indoor temperature will be lower than the outdoor due to a lower heat transfer through the walls and roofs.

Furthermore, LFC can be used for trench reinstatement. No compaction of LFC is necessary and LFC is able to provide sufficient strength required. LFC can also be used as floor screed to level the ground and raise floor levels. Other application of LFC includes road and pavement subbases, raft foundations, weak soil replacements and shock absorbing barriers.

2.5 Methods to Produce LFC

In order to produce LFC, foam must be introduced to the concrete mixes. The foam is mixed into the concrete either by pre-form method or inline method (Barnes, 2009).

In pre-foam method, foam and base mix slurry are prepared separately. In construction, pre-form foam is pumped into the back of the concrete mixer truck. The rotating action of the drum is responsible for the mixing process until the mix is homogeneous (Sari and Sani, 2017). The volume of LFC produced is governed by the size of the truck. Thus, the volume of base mix slurry delivered to site is usually reduced to make room for the foam.

The pre-form foam must be stable to resist the pressure exerted on it throughout the whole casting process until the setting of concrete. Foam is produced by a mixture of foaming agent, water and air. It can be manufactured through wet method and dry method. To produce wet foam, foaming agent solution is sprayed over a fine mesh, forming bubbles sized between 2 – 5 mm (Panesar, 2013). For dry foam, foaming agent solution, water and compressed air are forced into the mixing chamber of foam generator to produce bubbles with size smaller than 1 mm, which are more stable than wet foam (Barnes, 2009).

Inline method is conducted by putting base mix and dry foam into an inline static mixer to blend them together. Inline static mixer allows rapid mixing in a short span of length by converting the slurry flow into an axial and radial flow pattern in a turbulence condition. Inline method can be further classified into wet mix method and dry mix method (Barnes, 2009). The difference between the two methods is the preparation of the base mix slurry. For wet mix method, it is similar to pre-form method where the base mix slurry is produced off-site and delivered in concrete mixer truck. Normally, the base mix slurry contains higher water content than those for pre-form method (Sari and Sani, 2017). Since the mixing is not performed in the mixer truck, full load deliveries are possible and lead to larger volume production of LFC. For dry mix method, the production of base mix slurry is done on site where dry materials are delivered to site and are then mixed with water. A huge amount of water is needed on site for mixing purposes.

2.6 Effect of Water on the Durability of Concrete

Durability of concrete is defined as the ability of concrete to maintain its quality throughout its service life. A durable concrete is able to resist harsh environment conditions without failing to perform its function (Kosmatka and Wilson, 2011). Other than the mechanical properties of concrete, the durability of concrete is considered as an important aspect of concrete in long term. The permeability of concrete is one of the major factors affecting the durability of concrete (Zhang and Zong, 2014).

Concrete requires water for the hydration of cement to form calcium silicate hydrate (C-S-H) gel, the main product that contributed to the strength of concrete. Although water is a necessity in the early age for the hydration of cement, the ingress of water into the concrete at later age will affect the quality of the concrete itself.

Water is a universal solvent since many chemicals are able to dissolve in it. When water containing chlorides or sulphates penetrate into concrete, it will slowly deteriorate the concrete. Chlorides will attack and corrode the steel reinforcements in the concrete which leads to a loss in strength. Ettringite is formed when there is sulphate in the concrete which will then cause the concrete to expand and crack (ACI Committee 201, 2001).

The freeze-thaw cycle of water in concrete will greatly affect the durability of concrete. When the free water in concrete and water absorbed by the capillaries freezes, it will expand and caused internal stress in the concrete (Tan, et al., 2013). This causes the concrete to crack when the internal stress exceeds its capacity.

Besides that, water also affects the appearance of concrete surface. Calthemite straws on concrete are similar to those stalactites that grow in caves. Calthemite straws are the deposition of calcium carbonate, $CaCO_3$ on concrete surfaces. It is formed through the reaction of calcium hydroxide, $Ca(OH)_2$ with carbon dioxide, CO_2 (Smith, 2016). When water travels through the concrete, it will dissolve free $Ca(OH)_2$ available in the concrete. Eventually, this solution will leak out of the concrete and reacts with CO_2 to form calthemite straws. Other than that, efflorescence of concrete occurs when water evaporates on the surface of concrete, leaving behind efflorescing salts (Brocken and Nijland, 2004). This creates a white thin layer of salts deposited on the surface of concrete. Although calthemite straws and efflorescence are usually not detrimental, its appearance not desirable and indicate the need for maintenance.

2.7 Waterproofing Method

The purpose of waterproofing a concrete is to reduce the water absorption of concrete as well as to resist penetration of water into concrete. There are several methods that can be applied to make the concrete more resistant to water. Concrete can be waterproof by method of external coating, integral mixing and using external membrane (Muhammad, et al., 2015).

External coating is done by spraying, brushing or dipping the concrete with agent such as polymers, epoxy, silicates, and siloxanes. This is by far the most popular approach in the current industry to waterproof concrete. Normally, two or more coatings are recommended to ensure the surface of concrete is fully protected and achieve desirable thickness (Jones, Dhir and Gill, 1995). Surface treatments can make the surface of concrete become hydrophobic, reduce concrete surface porosity by filling the pores or create a continuous layer along the concrete surface (Franzoni, Pigino and Pistolesi, 2013).

For integral mixing, waterproofing admixtures are mix together with the concrete slurry during casting (Ren and Kagi, 2012). This method makes the whole concrete to be hydrophobic, instead of just the surface of concrete. So, it is important to ensure the admixtures are dispersed throughout the mix. Waterproofing admixture includes nano silicon dioxide, silane, polymer modified with cement and conventional oil-based agent.

Waterproofing through the usage of external membrane is achieved by using polymer membrane as an overlay. Water adhesive layer such as atactic polypropylene and styrene-butadiene-styrene modified asphalt and is used on concrete bridge decks to prevent water penetration through cracks as well as to enhance the adhesion between concrete and asphalt (Xu, et al., 2009).

2.8 Mechanical Properties of LFC

2.8.1 Compressive Strength

Compressive strength is among the most crucial properties of concrete when it comes to the design of concrete structures. Compressive strength is required to sustain the load of building structures and transfer it to the ground. Hardened C-S-H gel is the main contributor to the compressive strength of concrete. Hydration of cement is a slow process. Concrete gains strength with a faster rate observed at the beginning and slows down as it ages (Abd elaty, 2013).

Grading of concrete is normally based on the compressive strength of standard concrete cubes or concrete cylinders at the age of 28 days. For normal weight concrete, the 150 mm cube strength is normally 1.25 times higher than the 150 mm diameter × 300 mm depth cylinder strength (Kumavat and Patel, 2014). However, this is not always true as there are many other factors that will affect the relationship such as specimen size, concrete strength level, quality of aggregate and casting procedure (Kumari, 2015). For LFC with dry density of 1250 kg/m^3, the compressive strength of 100 mm cube and 100 mm diameter × 200 mm depth cylinder is similar, with a difference of only 5 % (Sudin and Ramli, 2014).

The compressive strength of LFC is lower when compared with normal weight concrete due to the lack of coarse aggregate in LFC. LFC with density in the range of 800 kg/m^3 to 1000 kg/m^3 can normally achieve compressive strength between 1 MPa and 8 MPa (Lee et al., 2018). For LFC, the main factor that affects the compressive strength is density. It is reported that with a reduction of the density of LFC, the compressive strength decreases exponentially as shown in Figure 2.1 (Kearsley, 1996). Since density is related to porosity, the porosity of concrete also has an adverse impact on the compressive strength of LFC (Kearsley and Wainwright, 2001).

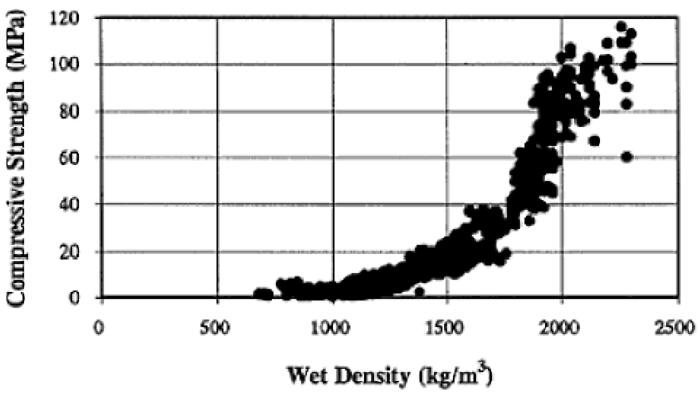

Figure 2.1: Exponential Relationship between Compressive Strength and Wet Density (Kearsley, 1996)

The w/c ratio is a crucial parameter when it comes to the design of concrete mixes. If the w/c ratio is too low, the concrete mix will be difficult to work with. The lack of free water as a lubricant will promote the bursting of foam and thus forming capillary pores within the concrete. When the w/c ratio is too high, segregation and bleeding will occur as the slurry is unable to hold the materials together (Nambiar and Ramamurthy, 2008). In contrast with normal weight concrete, an increase in w/c ratio within acceptable ranges can enhance the strength of LFC (Tam, et al., 1987). This is because the effect of w/c ratio towards the strength of LFC becomes less significant when the air to cement ratio is high. Liu, et al. (2016) reported that the optimum w/c ratios for LFC with a density of 400 and 800 kg/m^3 are 0.62 and 0.53 respectively. Hence, LFC with lower dry density will have higher optimum w/c ratio.

As the hydration of cement is the main contribution of strength development of LFC, the method of curing is important to provide moisture for the continuous hydration of cement paste. There are different ways to cure concrete such as fully immerse the concrete specimens into water, sprinkle water onto concrete, wrapping concrete with wet gunny bags and air curing. Concrete cured by fully submerging it into water shows the most favourable strength development and able to achieve the highest compressive strength when compared with other methods as there is no moisture loss, allowing more cement to be hydrated (James, et al., 2011). Studies conducted by James, et al. (2011) and Rahman, Islam and Abedin (2012) show that air curing concrete produced the lowest compressive strength, higher shrinkage and higher porosity. Thus, it is important to ensure the curing of concrete is adequate so that the hydration process is not affected.

Reviews on the compressive strength of various types of LFC have been conducted by Ramamurthy, Nambiar and Rajani (2009) and Amran, Farzadnia and Ali (2015). Based on the reviews, it is found that the curing temperature, replacement of cement with pozzolanic admixtures and fineness of sand used will affect the compressive strength. Besides, the type of foaming agent used and usage of superplasticizer will influence the compressive strength of LFC (Falliano, et al., 2017).

2.8.2 Splitting Tensile Strength

There are three tests to test the tensile strength of concrete, namely direct tensile test, splitting tensile test and flexural test. Splitting tensile strength is also called as indirect tensile strength. Concrete is known to be good in compression but poor in tension due to its brittle nature. Tensile force is one of the factors contributing to the cracking of concrete. Splitting tensile strength is a method used to evaluate the shear resistance of concrete (ASTM C496, 2011). Research has been conducted to test the validity of empirical equations and to estimate the splitting tensile strength based on the compressive strength of concrete (Yan, et al., 2013).

The splitting tensile to compressive strength ratio decreases when the compressive strength increases (Akinpelu, et al., 2017). At low strength, the splitting tensile to compressive strength ratio of LFC can achieve up to 0.4 while for normal weight concrete, the ratio ranges from 0.08 to 0.11 (Amran, Farzadnia and Ali, 2015). This means that splitting tensile strength increases at a decreasing rate when compressive strength increases. The splitting tensile strength of LFC can be improved by adding polypropylene fiber (Bing, Zhen and Ning, 2012).

2.8.3 Flexural Strength

Also known as modulus of rupture, flexural strength is the concrete ability to withstand the bending force without failure. Generally, flexural strength is the highest among the three tensile strengths. The flexural strength of LFC ranges between 22 % and 27 % of its compressive strength (Narayanan and Ramamurthy, 2000). The flexural strength increases at a decreasing rate when the density of LFC increases (Kozlowski and Kadela, 2017). The grade of concrete, presence of reinforcement in concrete and the age of concrete will affect the flexural strength (Ahmed, Mallick and Hasan, 2014). Moreover, the addition of polyolefin fibers in LFC can help in delaying the propagation of cracks (Ibrahim, et al., 2014).

2.9 Raw Material Description

2.9.1 Ordinary Portland Cement

According to ASTM C150 (2007), there are 8 types of Portland cement which are classified into Type I-V cement. Ordinary Portland cement (OPC) is a Type I cement commonly used when certain characteristics of other cement types are not needed. The usage of OPC should be limited to the condition where it is not exposed to sulphates in soil or in groundwater (Neville, 2011).

Portland cement has a specific gravity of 3.14 with particle size in the range of 2 to 80 μm (Domone and Illston, 2010). According to Indian Standard 12269 (2013), the minimum fineness for grade 53 OPC is 225 m^2/kg. The fineness of cement will affect the reactivity of cement as well as the amount of mixing water required during casting.

Cement is made up of argillaceous and calcareous materials. Different manufacturers use different raw materials and proportions to produce cement, causing the chemical composition to be varied. Calcium oxide, silica, alumina and iron oxide are the main chemical compositions that form the major compounds of Portland cement. Table 2.1 shows the range of chemical composition of Portland cement.

When all the raw materials are grounded and burnt in a rotary kiln under high temperature, reactions took place to form chemical compounds. The percentage of chemical compounds produced is presented in Table 2.2. If the chemical composition of raw material is known, the amount of each chemical compound formed can be estimated using Bogue's equations.

Table 2.1: Limits of Oxide Composition for OPC (Neville, 2011)

Oxide	**Chemical formula**	**Lower Limit (%)**	**Upper Limit (%)**
Calcium Oxide	CaO	60	67
Silicon Dioxide	SiO_2	17	25
Aluminium Oxide	Al_2O_3	3	8
Sulphur Trioxide	SO_3	2	3.5
Iron(III) Oxide	Fe_2O_3	0.5	6
Magnesium Oxide	MgO	0.5	4
Sodium Oxide	Na_2O	0.3	1.2

Table 2.2: Limits of Main Compounds for OPC (Neville, 2011)

Compound name	Common name	Chemical formula	CCN[1]	Lower Limit (%)	Upper Limit (%)
Tricalcium Silicate	Alite	$3CaO.SiO_2$	C_3S	42	67
Dicalcium Silicate	Belite	$2CaO.SiO_2$	C_2S	8	31
Tricalcium Aluminate	Celite	$3CaO.Al_2O_3$	C_3A	5	14
Tetracalcium Aluminoferrite	Ferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	6	12

Note: [1]CCN = Cement chemist notation

2.9.2 Sand

Sand plays an important role in the formation of concrete. One of the main objectives in using sand in concrete mix is to produce a more economical concrete, as sand is cheaper than cement (Hamidah, et al., 2005). However, the compressive strength of concrete decreased when the sand to cement ratio increased (Hamidah, et al., 2005). In LFC, the fineness of sand plays an important role as well. According to Lee, et al. (2018), using coarser sand in LFC affects the stability of the foam as coarser sand is usually rougher, thus promoting the bursting of foam. Besides, finer sand produces LFC with higher compressive strength due to higher surface area that improves the force transfer between sand particles (Lee, et al., 2018). Sand also reduces the shrinkage of LFC since the amount of cement in LFC reduces as well.

2.9.3 Foaming Agent

The function of foaming agent is to create tiny air bubbles by reducing the surface tension of the solution and improve the stability of foam by preventing the merging of bubbles (Panesar, 2013). Foaming agents are diluted in water with the ratio in accordance to the manufacturer’s specification to produce foam. The most common surfactants are synthetic-based and protein-based foaming agent. Synthetic foaming agent is amphoteric which can either donate or receive hydrogen ions based on the pH level of a solution. Air bubbles are produced when the hydrophilic heads are in contact with water and formed an enclosed sphere with the hydrophobic tails facing inwards. For protein-based foaming agents, the degradation of proteins into smaller hydrophobic molecules induced the formation of hydrogen bonds between molecules and thus air bubbles are formed (Panesar, 2013). The stability of foam is affected by the viscosity of solution, concentration of foaming agents, pH level and temperature.

Synthetic foaming agent is adopted in this study. It has the advantage of producing foam with greater overall stability when compared with protein-based foaming agent (Ghorbani, et al., 2019). Besides, LFC produced synthetic foaming agent is able to achieve higher compressive strength and lower initial sorptivity compared with protein-based foaming agent (Panesar, 2013). Synthetic foaming agent contains stabilizer components that reduce the chance of coalescence and bursting of air bubbles. By using a foam generator, the size of air bubbles produced is microscopic with consistent shape and size.

To produce pre-formed foam using dry method, the foaming agent is usually diluted with water. At a constant volume of foam added into the concrete, foam produced from higher foaming agent to water ratio will produce concrete with a lower density (Wan Ibrahim, et al., 2017).

2.9.4 Water Repellent Agent

There are various materials that can be used as water repellent agent such as calcium or sodium salts of stearates, liquid fatty acids, bitumen emulsions, wax emulsions and silicates (Ramachandran, 1995). Incorporating water repellent admixture into concrete mix can restrict the movement of water in the concrete.

The usage of waterproofing admixture does not block the capillary pores. Instead, a hydrophobic layer is coated on the walls of capillary pores and thus prevents capillary absorption (Zhang, et al., 2011). Hydrophobic property is achieved by increasing the contact angle between the walls of capillary and water above 90°, causing the water to be pushed out from the pores by surface tension forces (Ramachandran, 1995).

The water repellent admixture used for this study is calcium stearate (CS). The International Union of Pure and Applied Chemistry (IUPAC) name for CS is calcium octadecanoate with a chemical formula of $Ca(C_{18}H_{35}O_2)_2$, indicating two 18-carbon stearate chains bond with calcium ion. It is formed by heating of calcium oxide with stearic acid. CS is a white waxy powder which is insoluble in water and ethanol (Weast, 1979). Other applications of CS can be found in lubricants, surfactants and also food stabilizers.

Water repellent concrete in this study is produced by integral mixing of CS with concrete mix. However, CS merely deposited on the surface and capillary walls of the concrete instead of permanently bonded to the concrete in hardened stage (Ren and Kagi, 2012). When exposed to weathering conditions, CS tends to disintegrate. Thus, the effect of CS on the water repellency of concrete becomes weaker over time.

2.10 Effect of Calcium Stearate on the Strength of Concrete

The usage of CS as a water repellent admixture is not a new thing. Researches have been done in the past to study the effect of calcium stearate on the properties of concrete. However, those researches are mostly concern about normal weight concrete and cement mortar.

According to Suryavanshi and Swamy (2002), incorporating 1.25 % of CS by total mass of material into concrete mix resulted in a lower compressive and flexural strength of lightweight aggregate concrete when compared with control mix without CS. However, when CS is used together with foaming agent, it can be observed that it achieved a higher strength than concrete with foaming agent but without CS. Nevertheless, the strength is still lower when compared with the control mix due to the reduction of density by foaming agent.

Results from Maryoto, et al. (2018) showed that CS in any percentage decreases the compressive strength of normal weight concrete. For a concrete strength of 20 MPa, adding 0.25 %, 1.27 % and 2.53 % of CS into the concrete reduces the compressive strength by 7.0 %, 17.2 % and 36.4 % respectively. The effect of strength reduction when increasing the percentage of CS is less significant in concrete with a higher grade. Besides that, it is also found that incorporating CS in concrete reduces the corrosion of steel by inhibiting the infiltration of chloride ions. Maryoto, et al. (2018) recommends that not more than 0.25 % of CS should be added into the concrete to reduce the adverse effects of overdosing CS.

Maryoto, Buntara and Aylie (2017) also incorporated CS into normal weight concrete. The percentage of CS added ranges between 0 % and 1.9 %. The optimum amount of CS to be added is found to be 0.2 % which yields a compressive strength higher than the control specimen. Increasing the amount of CS after the optimum percentage reduces the compressive strength of concrete. This is because when the amount of CS is high, more wax-like substances are produced inside the concrete (Maryoto, Buntara and Aylie, 2017). As the wax is weaker than the C-S-H gel, having more wax will reduce the compressive strength of concrete.

Inconsistent with the results above, data presented by Maryoto (2015) indicate a slight increase in compressive strength of normal weight concrete at 28 days with the incorporation of CS, from 26.2 MPa for control mix to 27.3 MPa when CS is added up to 4 kg/m^3.

Quraishi, et al. (2011) stated that CS only retards the strength development rate of normal weight concrete instead of reducing the strength itself. A lesser strength difference is observed between concrete with 3 and 5 % of CS by cement weight and concrete without CS at 60 days when compared with the strength difference at 7 days and 28 days. As the hydrophobic property of water repellent agent comes into effect, the hydration of cement is delayed (Kumar, Singh and Singh, 2009).

LFC with a density of 550 kg/m^3 containing silica fume, polypropylene fiber, superplasticizer and CS were casted and tested by Ma and Chen (2016). Based on the report by Ma and Chen (2016), the compressive strength of LFC at 7 days and 28 days increased when the CS content increased up to 1 % of cement weight. At CS percentage of 1 %, the compressive strength at 7 days and 28 days is 53.1 % and 55.6 % higher than the strength for LFC without CS. When CS is added above 1 %, the compressive strength starts to reduce but it is still higher compared with the strength of control mix.

Izaguirre, Lanas and Álvarez (2009) analysed the effect of CS on the compressive strength of aerial lime-based mortars. The mortar was tested for its 7 days, 28 days, 91 days, 182 days and 365 days compressive strength. From the results, the strength obtained by mortar with CS is comparable to the strength of the control mortar. It was concluded that the incorporation of CS into mortar is not detrimental to the compressive strength and has a possibility of achieving strength higher than normal due to a better pore structure.

Falchi, et al. (2015) included CS into Portland limestone cement mortars. The compressive strength of mortar with CS is 10.4 MPa, which is about 6.3 % lower than the strength of control mortar. This is due to a higher cumulative pore volume which reduces the compressive strength of mortar.

Table 2.3 shows the summary of hardened properties test conducted for different types of concrete containing CS from previous researches. From Table 2.3, it can be observed that compressive test is the most common test conducted by researchers. This is followed by water absorption test and sorptivity test. Only two out of eleven researches tested the effect of CS in LFC. Moreover, none of the researches conduct splitting tensile test for concrete containing CS. The effect of CS in mortar is investigated by few researchers as well since mortar is normally used as exterior plastering and thus required protection against penetration of water.

Table 2.3: Summary of Hardened Properties Test Conducted for Different Types of Concrete Containing CS

Author(s) (year)	**Type of Concrete**				**Hardened Properties Test**									
	NWC[1]	**LFC[2]**	**LAC[3]**	**CM[4]**	**CT[5]**	**FT[6]**	**WAT[7]**	**ST[8]**	**WPT[9]**	**TCT[10]**	**DT[11]**	**CIT[12]**	**CRT[13]**	**HT[14]**
Falchi, et al. (2015)				✓	✓	✓		✓						
Izaguirre, Lanas and Álvarez (2009)				✓	✓			✓			✓			
Lanzón and García-Ruiz (2007)				✓				✓			✓			
Lanzón and García-Ruiz (2009)				✓			✓	✓						
Ma and Chen (2016)		✓			✓		✓			✓				✓
Maryoto (2015)	✓				✓				✓				✓	
Maryoto, Buntara and Aylie (2017)	✓				✓		✓					✓	✓	
Maryoto, et al. (2018)	✓				✓							✓		
Suryavanshi and Swamy (2002)		✓	✓		✓	✓	✓							
Quraishi, et al. (2011)	✓				✓								✓	
Ren and Kagi (2012)				✓							✓			

Note:
[1]NWC = Normal weight concrete, [2]LFC = Lightweight Foamed Concrete, [3]LAC = Lightweight Aggregate Concrete, [4]CM = Cement mortar, [5]CT = Compressive test, [6]FT = Flexural test, [7]WAT = Water absorption test, [8]ST = Sorptivity test, [9]WPT = Water penetration test, [10]TCT = Thermal conductivity test, [11]DT = Durability test, [12]CIT = Chloride ion infiltration test, [13]CRT = Corrosion test, [14]HT = Hygroscopicity test

2.11 Summary

LFC comprises of cement, fine aggregate, water and foaming agent which create a porous concrete. LFC has the advantages of being lightweight, high workability, good thermal and sound insulation, excellent fire resistant and more resistant to freeze-thaw cycles. Conversely, the strength of LFC is lower, production process of LFC requires high quality control and finishing process for LFC is troublesome. Various application of LFC includes void filling, thermal insulators, trench reinstatement and floor screed.

LFC can be produced either by pre-form method or inline method with the usage of wet foam and dry foam. Effects of water towards the durability of concrete such as chloride and sulphate attack, formation of calthemite straws and efflorescence on concrete surfaces have been studied. Identifying water as an agent of deterioration, there is a need to protect hardened concrete from exposing to water. So, various methods have been identified to make the concrete either waterproof or water repellent.

Besides, the mechanical properties of concrete are important for concrete to perform its function. Parameters such as compressive strength, splitting tensile strength and flexural strength are used to determine the quality and grade of concrete. However, due to the porous structure of LFC, it is weaker than normal weight concrete. Besides porosity, there are many other factors affecting the strength of LFC such as w/c ratio, curing regime, usage of admixtures and fibers and age of concrete.

CS is a non-toxic chemical that can cause the concrete to be hydrophobic. The effect of calcium stearate on the performance of concrete was investigated by other researchers in the past. The strength of concrete containing CS is expected to be lower than those without CS due to its hydrophobic properties that might retard the hydration process. However, most researches focus on the impact on normal weight concrete and mortars. Therefore, this research aims to fill in the gap by conducting an experiment using CS as a water repellent admixture in LFC.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In Chapter 3, the preparation of materials, casting procedures and tests performed on both fresh and hardened concrete were elaborated. This study consisted of two stages. The first stage was to determine the optimum w/c ratio of different types of lightweight foamed concrete (LFC) through trial mixes while the second stage was to study the mechanical properties of LFC based on different testing methods.

3.2 Raw Material Preparation

The raw materials for the production of water repellent LFC include cement, fine aggregates, water, foaming agent and water repellent agent. Preparation of these raw materials is necessary prior to the casting of LFC.

3.2.1 Ordinary Portland Cement

Ordinary Portland cement (OPC) used in this study as the binding material was manufactured by YTL Cement Bhd. with the brand of Orang Kuat as shown in Figure 3.1. The OPC is classified as CEM I with strength class of 52.5N and it is in compliance with requirements of Type I cement stated in ASTM C150 (2007). Since the concrete in this study does not expose to sulphate and requires no special properties, the usage of OPC was sufficient for the purpose of experiment. The OPC was sieved through a 300 μm sieve pan to separate clinkers from the cement particles. After sieving, the cement was stored in an airtight container to prevent partial hydration of cement as it will react with moisture in the air.

Figure 3.1: YTL Orang Kuat Ordinary Portland Cement

3.2.2 Sand

The fine aggregate that was utilized in this study is sand. The sand was used for two purposes, one for sieve analysis and the other for concrete casting. Sand was oven dried for 24 hours with a temperature of 105 ± 5 °C prior to sieving and casting in order to remove the moisture content in the sand particles. Oven dried condition was chosen because it is difficult to attain saturated surface dry condition for fine aggregates whereas sand in air dry condition has a high variation of saturation level due to the difference in temperature and humidity when drying. The sand used for concrete casting fulfilled the grading requirement set by ASTM C33 (2013). For the purpose of casting LFC, the sand particles were sieved through 600 μm sieve pan to maintain the fineness as coarser sand promotes the bursting of foam. After sieving, the sand was stored in a covered container.

3.2.3 Water

According to ASTM C1602 (2006), potable water can be used as mixing water without the need for testing. On the other hand, non-potable water must be tested to ensure the impurities are within the limit set by the standard. The source of water used in this study was tap water, which is considered as potable water. Tap water was used as mixing water as well as water for the curing of concrete.

3.2.4 Foam

Pre-form dry foam method was adopted to produce foam using a foam generator as shown in Figure 3.2. The base materials used to produce foam are synthetic foaming agent, water and compressed air. The foaming agent used was SikaAER®-50/50 produced by Sika Kimia Sdn. Bhd. which is in compliance with ASTM C869 (2011). It has a light straw colour with a density similar to water which is 1000 kg/m^3. The foaming agent was stored in a container as shown in Figure 3.3 The dilution ratio of foaming agent to water was 1 : 20 in volume. The solution was poured into the foam generator. Then, the valve was closed and compressed air was introduced into foam generator with a constant pressure of 0.5 MPa. A period of 5 minutes was waited before extracting the foam out from the foam generator. The foam generated has a density of 45 kg/m^3.

Figure 3.2: Foam Generator

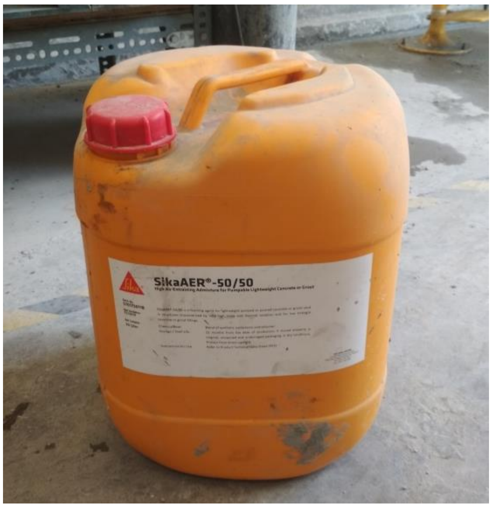

Figure 3.3: SikaAER®-50/50 in Its Packaging Container

3.2.5 Calcium Stearate

Calcium stearate (CS) was chosen as the water repellent agent in this study. It was produced by Sigma-Aldrich Corporation with an assay indicating 6.6 – 7.4 % calcium basis. CS is in a very fine white powder form with a density of 1080 kg/m^3. The CS produced has impurities which are lead and stearic acid with a concentration below 0.004 % and 0.3 % respectively. The loss on drying is less than 3 % under the temperature of 105 °C for 3 hours. Anion traces are also found in CS such as chloride and sulphate with concentration less than 200 mg/kg and 1000 mg/kg respectively. No special preparation was required for CS. It was kept in its packaging container as shown in Figure 3.4.

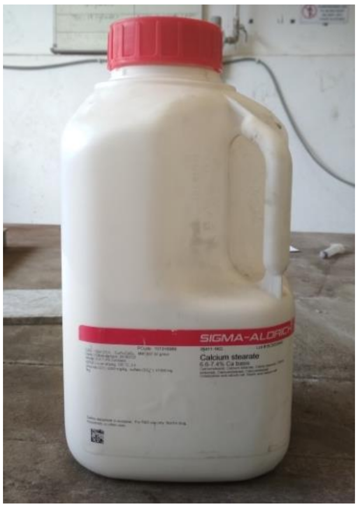

Figure 3.4: Calcium Stearate in Its Packaging Container

3.3 Sieve Analysis

Sieve analysis is a method used to determine the gradation of aggregates by assessing the particle size distribution. The sieve analysis was conducted in accordance to ASTM C136 (2014). The minimum sample size required after oven drying the sand is 300 g. In this study, a sample size of 500 g was adopted. The sieves were arranged with the largest size of 4.75 mm at the top and the smallest size of 75 µm at the bottom followed by a pan at the base. Then, the stack of sieves was placed on a mechanical shaker and fixed in place as presented in Figure 3.5. Next, the weighed sand was poured into the sieves. The top of the stack was covered using a sieve pan cover to avoid fine sand particles from dispersing to the air. The mechanical shaker was operated for 8 minutes to avoid excessive shaking which will degrade the sand. After the shaking process ended, the sand particles retained on each sieve were weighed and recorded. It was then used to calculate the total percentage of sand particles passing each sieve. A graph showing particle size distribution was plotted and the fineness modulus of the sand was calculated using Equation 3.1.

$$\mathrm{FM} = \frac{\sum \mathrm{TPR}}{100} \tag{3.1}$$

where

FM = fineness Modulus

$\sum$ TPR = summation of total percent retained from the biggest size observed to and including sieve size 150 µm

Figure 3.5: Stack of Sieves on Mechanical Shaker

According to ASTM C33 (2013), the fine aggregate shall has a fineness modulus in the range of 2.3 and 3.1. If the sand does not meet the grading requirements, it shall not be used for casting of concrete.

3.4 Mould Preparation

Three kinds of mould were used to cast LFC, which are cubical, cylindrical and prismatic moulds as shown in Figure 3.6. The cubical moulds used are made of plastic while cylindrical and prismatic moulds are made of steel. Table 3.1 shows the types and sizes of mould used for the testing of concrete in accordance to specifications set by ASTM and British Standards.

The moulds were prepared prior to casting. First, the inner surface of mould was scrapped using a scraper to remove any dried concrete from previous casting. For steel moulds, it is locked in place by tightening the screw or bolts and nuts of the mould to prevent leakage of concrete during placing. After locking, the dimension of the mould was measured to ensure the dimension is correct. Then, a thin layer of oil was applied on the inner surface of the mould for the ease of demoulding. Finally, the mould was placed on a flat surface free from vibration before placing the concrete into it.

(a)

(b)

(c)

Figure 3.6: Types Of Moulds; (a) Plastic Cubical Mould; (b) Steel Cylindrical Mould; (c) Steel Prismatic Mould

Table 3.1: Type of Mould Required for Different Testing Methods

Type of Mould	Dimension of Mould	Testing Method
Cubical	100 mm (*l*) × 100 mm (*b*) × 100 mm (*D*)	Compressive test
Cylindrical	100 mm (*d*) × 200 mm (*l*)	Compressive test, splitting tensile test
Prismatic	160 mm (*l*) × 40 mm (*b*) × 40 mm (*D*)	Flexural test

Note:

l = length, *b* = breadth, *D* = depth, *d* = diameter

3.5 Trial Mix

In this experiment, four types of lightweight foamed concrete with targeted density of 1200 ± 50 kg/m^3 were casted, namely i) LFC with no calcium stearate as control mix (LFC-CTR), ii) LFC with 0.2 % calcium stearate of cement weight (LFC-CS0.2), iii) LFC with 0.4 % calcium stearate of cement weight (LFC-CS0.4) and iv) LFC with 0.6 % calcium stearate of cement weight (LFC-CS0.6). The main purpose of conducting trial mix is to determine the optimum w/c ratio for all the four types of LFC. The w/c ratios chosen in this trial mix were 0.56, 0.58, 0.60, 0.62 and 0.64. The trial mix was divided into two parts. For the first part, six concrete cubes for both LFC-CTR and LFC-CS0.6 mixes and each w/c ratio were casted and tested for its 7 days and 28 days compressive strength. Flow table spread value, inverted slump value, consistency and stability for each w/c ratio were recorded for reference. The results obtained from compressive test were used to evaluate the optimum w/c ratio of LFC-CTR and LFC-CS0.6. The trial mix ended since it was found that the optimum w/c ratio for the two mixes was the same, which is 0.60. Therefore, the optimum w/c ratio for LFC-CS0.2 and LFC-CS0.4 mixes was taken to be the same as well since the percentage of CS added for the two types was in between the two limits. Else, the second part of trial mix has to be conducted for the remaining two mixes to obtain their respective optimum w/c ratio.

3.6 Mix Proportion

The mix proportion of base materials was calculated based on the ratio set for each base materials. The cement to sand ratio was set as 1 : 1 for all the four types of LFC. The w/c ratios used were in the range of 0.56 to 0.64 for trial mixes and 0.60 for actual mixes. The amount of foam to be added into the concrete mix was calculated using Equation 3.2. The amount calculated acted as a recommendation value to achieve a density of 1200 kg/m^3 since the actual amount of foam added depends on the fresh density measured during concrete casting.

$$F_m = B_m \cdot F_d \left(\frac{1}{TD} - \frac{1}{B_d} \right) \tag{3.2}$$

where

F_m = mass of foam required, kg

B_m = mass of base mix, kg

F_d = density of foam, kg/m^3

TD = targeted density, kg/m^3

B_d = density of base mix, kg/m^3

The density used for cement, CS, sand, water and foam are 3150 kg/m^3, 1080 kg/m^3, 2600 kg/m^3, 1000 kg/m^3 and 45 kg/m^3 respectively. Taking 1200 kg as the mass of all the base materials for 1 m^3 of LFC, the mass of each base material was then distributed according to its ratio. Table 3.2 tabulates the mass of materials required to produce 1 m^3 of LFC with a density of 1200 kg/m^3.

Table 3.2: Mix Proportions

Type of LFC	**w/c ratio**	**Mass of Base Materials (kg)**				
		Cement	**CS**	**Sand**	**Water**	**Foam**
LFC-CTR	0.56	468.75	0.00	468.75	262.50	18.38
	0.58	465.12	0.00	465.12	269.77	18.17
	0.60	461.54	0.00	461.54	276.92	17.96
	0.62	458.02	0.00	458.02	283.97	17.75
	0.64	454.55	0.00	454.55	290.91	17.55
LFC-CS0.2	0.60	461.18	0.92	461.18	276.71	17.98
LFC-CS0.4	0.60	460.83	1.84	460.83	276.50	18.00
LFC-CS0.6	0.56	467.65	2.81	467.65	261.89	18.44
	0.58	464.04	2.78	464.04	269.14	18.23
	0.60	460.48	2.76	460.48	276.29	18.02
	0.62	456.97	2.74	456.97	283.32	17.81
	0.64	453.52	2.72	453.52	290.25	17.61

The actual mass used for casting for one batch of LFC was calculated based on the total volume required multiply with the mass shown in Table 3.2. Total volume consists of the volume of specimens to be casted in that batch and including wastage of 0.002 m^3 or 20 % of the specimens' volume, whichever is larger. Wastage was added to compensate for the losses due to concrete slurry sticking on the equipment and also when conducting fresh property tests.

3.7 Mixing Procedure

The base materials for the casting of LFC such as OPC, sand, water and CS were weighed based on the mix proportion calculated. The w/c ratio used for actual casting was determined from the trial mix. All the dry materials were mixed together manually in a stainless steel mixing bowl that complies with ASTM C305 (2011). After the dry mix blended evenly, water was poured in gradually and mixed together until a consistent concrete slurry is produced. Fresh density test and flow table test were conducted before the addition of foam into the concrete slurry. The foam was weighed and added in stages to avoid oversupply of foam which will cause the LFC to have a density lower than its designated density and it is irreversible. Foam was mixed with concrete slurry until a homogeneous foamed mortar with a density of 1200 ± 50 kg/m^3 is achieved. Next, inverted slump test was conducted. After all the fresh concrete tests had been carried out, the concrete slurry was poured into the moulds using a scoop. During placing, no compaction was required and vibrations were avoided to prevent bursting of foam. The top layer of concrete slurry was struck off using a flat trowel after 15 minutes as the concrete slurry will settle at the beginning.

3.8 Concrete Curing

Hardened concrete specimens were demoulded after 24 hours of casting. Curing of concrete is important for concrete to gain strength. It prevents moisture loss and also to ensure continuous supply of moisture to concrete for further hydration process. Before curing, the concrete specimens were weighed to determine the hardened density. The curing method adopted in this study was the water curing method. Concrete specimens were placed in a water tank and fully submerged in water as shown in Figure 3.7. The water tank was covered and the temperature was maintained in a range of 25 °C to 30 °C. Concrete specimens were water cured for 7 days, 28 days and 56 days prior to testing.

Figure 3.7: Curing of Concrete in Water Tank

3.9 Fresh Concrete Test

During the mixing of fresh concrete slurry, various tests such as fresh density test, flow table test and inverted slump test were performed to find out the fresh properties of the concrete mix.

3.9.1 Fresh Density Test

Fresh density test was performed to obtain the fresh density of the concrete mixes. A container with a capacity of 1 litre was used for this test. First, the weighing scale was tare to zero with the container placed on top of it. Then, the container was overfilled with fresh concrete and was compacted by tapping the container gently to ensure all the space is filled with concrete. Excess fresh concrete on the top was struck off using a trowel and was made sure that it is flat. Any fresh concrete found on the surface of container was wiped off. The container filled with concrete was weighed to obtain the fresh density of concrete. This test was performed before and after the addition of foam into the concrete mix and also after the inverted slump test was conducted to obtain the final fresh density before proceeding to concrete placing. The final fresh density measured was used to determine the consistency of the concrete mix.

3.9.2 Flow Table Test

Flow table test is a procedure to investigate the consistency and flowability of fresh concrete. This test was conducted before the foam was added into the concrete mix. The specification of the apparatus used for flow table test is in compliance with ASTM C230 (2008). Figure 3.8 shows the experiment setup for flow table test. The apparatus was made sure that it is dry and level. A frustum mould was placed on the centre of a 250 mm diameter plate. The frustum mould was filled with fresh concrete mix until it is level with the top of the frustum. Then, the mould was lifted up and the table was dropped 25 times within 15 s (ASTM C1437, 2007). The test stopped after 25 drops or when the diameter of the spread exceeded the size of the plate. The number of drops and diameter of the spread in two directions perpendicular to each other were measured and recorded.

Figure 3.8: Setup for Flow Table Test

3.9.3 Inverted Slump Test

Inverted slump test was conducted after the foamed concrete slurry achieved a density of 1200 ± 50 kg/m^3. The purpose of conducting the inverted slump test is to determine the slump flow of concrete. Conventional slump test cannot be carried out due to the high flowability of LFC mix. The specification of the frustum of the cone mould is in compliance with ASTM C143 (2015). The procedure of the inverted slump test is following the guidelines provided in ASTM C1611 (2005). First, the frustum mould was damped, inverted and placed firmly on a flat and level surface as shown in Figure 3.9. The inverted mould was overfilled with the fresh concrete mix without the need for tamping. To level the top surface, excess concrete on the top was struck off. Next, the mould was lifted up vertically at a constant speed. The whole process from filling the fresh concrete into the mould to lifting up the mould was done within 2.5 minutes. The largest diameter of the spread and the diameter perpendicular to it were measured as shown in Figure 3.10. If the difference between the two diameters exceeds 50 mm, the test shall be repeated. The slump flow was taken as the average of the two diameters. The inner diameter formed in the middle of the spread was measured and recorded as well.

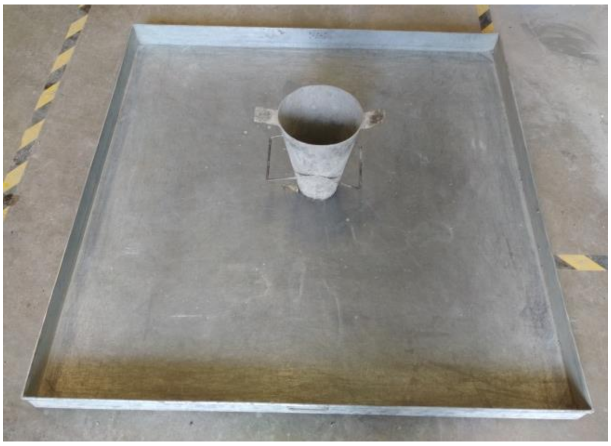

Figure 3.9: Setup for Inverted Slump Test

Figure 3.10: Inverted Slump Spread Diameter Being Measured

3.10 Hardened Concrete Test

The hardened concrete tests that were conducted in this study are destructive tests. The destructive tests consist of compressive test, splitting tensile test and flexural test. The hardened concrete tests were carried out after curing for 7 days, 28 days and 56 days, except for those in trial mixes where only 7 days and 28 days compressive tests were conducted. Three concrete specimens were used for each testing to obtain an average result. The shape and dimension of specimen used for each type of test are listed in Section 3.4. Prior to testing, the specimens were taken out and oven dried for 24 hours with a temperature of 105 ± 5 °C. Then, the dimensions of each specimen were measured and recorded. All the destructive tests were conducted using INSTRON 5582 Universal Testing Machine.

3.10.1 Compressive Test

The concrete compressive test was performed in accordance to BS EN 12390-3 (2002). Both cubical and cylindrical specimens were used to determine the compressive strength of LFC. For cube specimens, an even surface was chosen as the top and bottom surface to be subjected to axial load. Thus, the casting surface was facing the side since it was rougher. On the other hand, the top surface of cylindrical specimens was made sure to be even before the concrete hardened. Else, a thin piece of plywood is to be placed on top of the cylindrical specimen in order to create an even surface. The testing platform was cleaned and then the specimen was put on the centre of the testing platform as shown in Figure 3.11. A constant rate of axial compression load was set at 0.02 mm/s to avoid sudden failure of specimen. Once the machine settings were completed, the test was started until the specimen fails. The maximum load indicated by the machine was recorded and used to calculate the compressive strength of LFC using Equation 3.3. The average compressive strength from the three specimens was then calculated.

$$f_c = \frac{P}{A_c} \tag{3.3}$$

where

f_c = compressive strength, MPa

P = maximum load at failure, N

A_c = cross sectional area of specimen on which the load is applied, mm^2

(a) (b)

Figure 3.11: Setup for Compressive Test; (a) Cubical LFC; (b) Cylindrical LFC

3.10.2 Splitting Tensile Test

Splitting tensile test was conducted in accordance to ASTM C496 (2011). An alignment jig was used to fix the cylindrical specimen in place as shown in Figure 3.12. Two stripes of plywood were placed on the top and bottom of the cylindrical specimen to allow even distribution of loading along the length of specimen. Similar to compressive test, the axial compression loading rate was set to a constant of 0.02 mm/s. Then, the highest compression load achieved at failure was recorded. The splitting tensile strength of LFC was calculated using Equation 3.4.

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

where

T = splitting tensile strength, MPa

P = maximum load at failure, N

l = length of cylindrical specimen, mm

d = diameter of cylindrical specimen, mm

Figure 3.12: Setup for Splitting Tensile Test Using Alignment Jig

3.10.3 Flexural Test

Through this flexural test, three data can be determined, namely flexural strength, flexural toughness and flexural modulus. Centre point loading method was adopted in this test in accordance to ASTM C293 (2016). The prismatic specimen was marked to indicate the location of support and loading. As the span length is three times the depth of specimen, it means that the span length is 120 mm with a depth of

40 mm. The loading was located at the centre of the span length as shown in Figure 3.13. The INSTRON 5582 Universal Testing Machine can also record down the deflection of the specimen parallel to the loading direction. Thus, the loading point was ensured to be exactly on the specimen surface in order to obtain an accurate vertical deflection at the centre of specimen. A constant rate of axial compression load was set at 0.1 mm/min until the specimen cracks. The peak load and deflection at failure were recorded. Equation 3.5 was applied to compute the flexural strength.

$$R = \frac{3Pl}{2bD^2} \tag{3.5}$$

where

R = flexural strength, MPa

P = maximum load at failure, N

l = span length, mm

b = average breadth of specimen, mm

D = average depth of specimen, mm

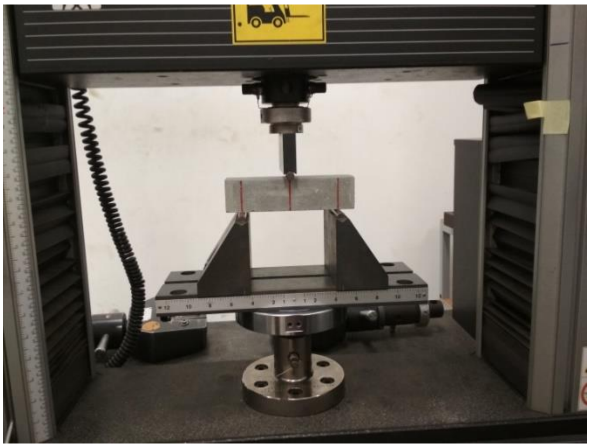

Figure 3.13: Setup for Centre Point Flexural Test

A graph of load against deflection was plotted continuously by the computer software during testing. The flexural toughness and flexural modulus of LFC can be determined from the stress-strain curve. In order to obtain a stress-strain curve, the load against deflection graph was converted to stress against strain graph using the raw data provided by the software. The stress is corresponding to the flexural strength, R. It was noted that the deflection recorded is in the vertical axis. Since the load caused an elongation at the horizontal axis, the strain is derived from the elongation at the bottom of the specimen. According to ASTM D790 (2015), the flexural strain can be calculated using Equation 3.6.

$$\varepsilon = \frac{6D\delta_y}{l^2} \tag{3.6}$$

where

ε = strain at the bottom of specimen, mm/mm

D = average depth of specimen, mm

δ_y = vertical deflection at the centre of the specimen, mm

l = span length, mm

With the stress-strain curve plotted, both flexural toughness and flexural modulus can be determined. Flexural toughness is the area under the stress-strain curve until failure. The area was approximated by using trapezoidal rule as shown in Equation 3.7.

$$U_T = \sum_{i=1}^{n} 0.5(\varepsilon_i - \varepsilon_{i-1})(R_{i-1} + R_i) \tag{3.7}$$

where

U_T = flexural toughness, J/m^3

R = flexural strength, N/m^2

ε = strain, mm/mm

n = total number of points recorded till failure

Flexural modulus or also known as bending modulus was used to estimate the Young's modulus of LFC. Flexural modulus is the gradient of the stress-strain curve which was calculated using Equation 3.8.

$$E_f = \frac{R_2 - R_1}{\varepsilon_2 - \varepsilon_1} \tag{3.8}$$

where

E_f = flexural modulus, MPa

R = flexural strength, MPa

ε = strain at the corresponding flexural strength, mm/mm

3.11 Consistency and Stability

The fresh density was measured before the placing of concrete slurry into the moulds while the hardened density was measured after demoulding. Both densities were used to check the consistency and stability of the concrete mix. When the fresh density of concrete mix is similar to the targeted density, the concrete mix is said to be consistent. The concrete mix is stable when the fresh density is similar to the hardened density. Therefore, the values of consistency and stability near to unity are preferred as it indicates good quality concrete. The consistency and stability of concrete mix were calculated using Equation 3.9 and Equation 3.10 respectively.

$$Consistency = \frac{Fresh\ Density}{Targeted\ Density} \tag{3.9}$$

$$Stability = \frac{Fresh\ Density}{Hardened\ Density} \tag{3.10}$$

3.12 Performance Index

As discussed in Chapter 2, the compressive strength is affected by the concrete density. Performance index (PI) was calculated in order to improve the consistency of the results obtained by taking into account the variation of density of LFC casted. With PI, the comparison between the compressive strength of each type of LFC is more accurate. Equation 3.11 was used to calculate the PI of concrete. PI for splitting tensile strength and flexural strength were also calculated by replacing the compressive strength in the equation

$$\mathrm{PI} = \frac{f_c}{Hardened\ Density/_{1000}} \tag{3.11}$$

where

PI = performance index, MPa per 1000 kg/m^3

f_c = compressive strength, MPa

3.13 Summary

LFC incorporated with CS with a density of 1200 ± 50 kg/m^3 was produced by pre-form method where dry foam is incorporated into the concrete mix. The base materials for the production of LFC such as OPC, sand, foam and CS were prepared accordingly. The mix proportions prepared in this study are LFC-CTR, LFC-CS0.2, LFC-CS0.4 and LFC-CS0.6. In trial mix, only LFC-CTR and LFC-CS0.6 for the five w/c ratios with six cubical specimens for each batch were casted and tested for 7 days and 28 days since the optimum w/c ratio obtained for both types of LFC are similar and thus eliminating the need of trial mix for LFC-CS0.2 and LFC-CS0.4. While in the real study, nine cubical specimens, eighteen cylindrical specimens and nine prismatic specimens were casted for each of the four types of LFC which were then divided for 7 days, 28 days and 56 days testing.

Fresh density test, flow table test and inverted slump test were performed during the mixing process. Then, the concrete was casted into the moulds that were prepared before the commencement of the experiment. The concrete specimens were demoulded after 24 hours of casting and weighed for its hardened density. Then, it was cured in a water tank for 7 days, 28 days and 56 days prior to testing. Every test conducted on the hardened concrete were destructive tests consist of compressive test, splitting tensile test and flexural test. The procedures for casting and testing were followed based on the guidelines provided by ASTM and British Standards. The results obtained from the tests were analysed and discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the data obtained from sieve analysis, trial mix, fresh properties tests and hardened properties tests were presented and discussed. The screening of trial mix was done to find out the optimum w/c ratio for different types of LFC casted based on the cube compressive strength after water cured for 7 days and 28 days. Analyses were carried out to compare the different types of LFC and to find out the relationships between compressive strength, splitting tensile strength and flexural strength. The effects on the mechanical properties of LFC due to the addition of CS were studied and discussed with the results from 7 days, 28 days and 56 days tests.

4.2 Sieve Analysis

After conducting the sieve analysis, the weight of soil particles retained on each sieve was tabulated in Table 4.1. The total percent retained and total percent passing were based on the weight recorded.

Table 4.1: Sieve Analysis and Grading Requirements of Sand

Sieve Size	**Weight of Sand Retained (g)**	**Percent of Sand Retained (%)**	**Total Percent Retained (%)**	**Total Percent Passing (%)**	**Grading Requirements for Total Percent Passing by ASTM C33 (%)**
4.75 mm	5.5	1.1	1.1	98.9	95 to 100
2.36 mm	16.0	3.2	4.3	95.7	80 to 100
1.18 mm	82.3	16.5	20.8	79.2	50 to 85
600 μm	147.2	29.4	50.2	49.8	25 to 60
300 μm	153.4	30.7	80.9	19.1	5 to 30
150 μm	59.2	11.8	92.7	7.3	0 to 10
75 μm	22.3	4.5	97.2	2.8	0 to 3
Pan	14.1	2.8	100	0	-
Total	500.0	100			

From Table 4.1, the total percent passing of the sand for all sieve sizes is within the range set by ASTM C33 (2013) for fine aggregates. The limit for sand particles passing through 150 μm and 75 μm is low because very fine particles will absorb more water due to larger combined surface area which then affects the workability of fresh concrete. Fineness modulus is a value used to indicate the degree of fineness of aggregates. A higher value means that the aggregate is coarser and vice versa. ASTM C33 (2013) limits the fineness modulus of fine aggregates to be in the range from 2.3 to 3.1. The fineness modulus of the sand is calculated to be 2.5, which is acceptable. Therefore, the sand can be used for concrete casting. Figure 4.1 illustrates the particle size distribution curve plotted with logarithmic scale for the horizontal axis. It can be observed that the size of sand particles is well distributed with no excessive particles in a certain size. A well particle size distribution is important as finer particles can fill in the voids between coarser particles. About 50 % of sand passed through the sieve with an opening of 600 μm, which was then used for the casting of concrete.

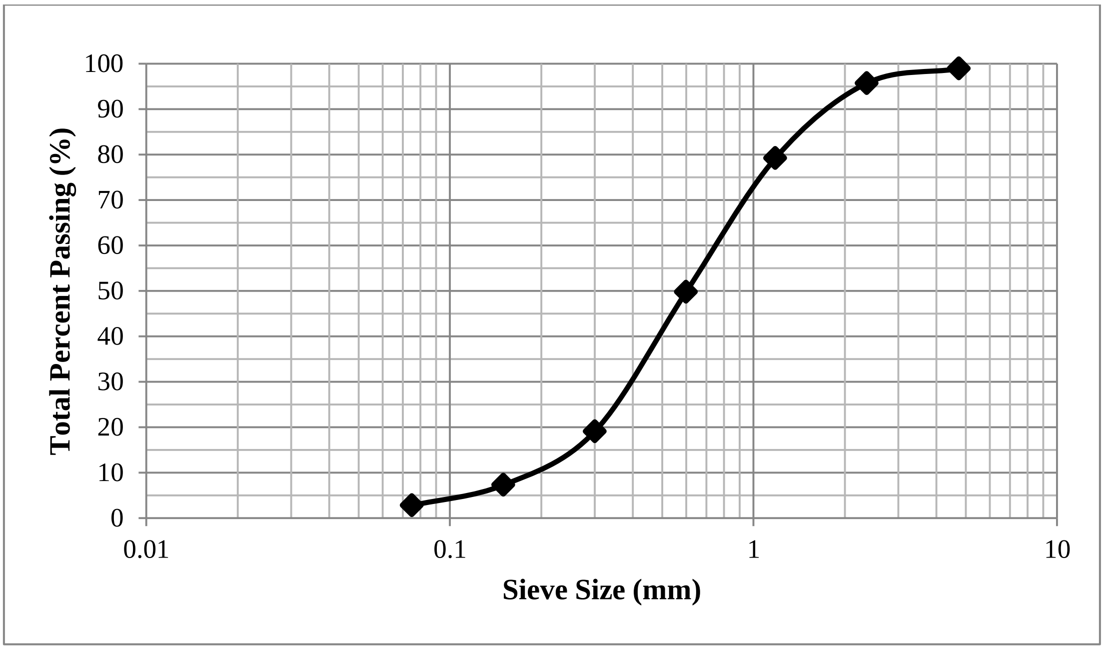

Figure 4.1: Particle Size Distribution of Sand

4.3 Trial Mix

Trial mix was conducted with the objective of obtaining w/c ratio that produces the highest strength with fixed cement to sand ratio. Five w/c ratios ranging from 0.56 to 0.64 were chosen for the trial mix. Performance indices calculated based on 7 days and 28 days compressive strength were used to evaluate the optimum w/c ratio. Table 4.2 shows the data recorded from flow table test and inverted slump test. As w/c ratio is one of the major parameters that affect the workability of concrete, the results from flow table test and inverted slump test were used to evaluate the effects of it. Higher the w/c ratio leads to higher free water content, which contributes to the workability of fresh concrete. By referring to Table 4.2, the number of drops required for the fresh concrete to spread to the diameter of 250 mm decreases and the inverted slump flow increases as the w/c ratio increases. Since higher w/c ratio leads to higher fluidity of fresh concrete, it is able to spread further at a lower force. It is noticed that the workability of concrete is not affected by the addition of CS into the concrete mix. Both LFC-CTR and LFC-CS0.6 have similar flow properties. Therefore, it can be concluded that CS neither increase the demand of water required nor improve the flowability.

Table 4.2: Flow Properties of Fresh Concrete

Type of LFC	**w/c ratio**	**Flow Table Spread Value (mm) / No. of Drop(s)**	**Inverted Slump Flow (mm)**	**Average Inverted Slump Inner Diameter (mm)**
LFC-CTR	0.56	>250 / 21	490	90
	0.58	>250 / 16	500	110
	0.60	>250 / 14	550	120
	0.62	>250 / 13	580	130
	0.64	>250 / 12	590	140
LFC-CS0.6	0.56	>250 / 21	480	100
	0.58	>250 / 17	490	110
	0.60	>250 / 14	550	120
	0.62	>250/ 13	570	130
	0.64	>250/ 12	590	140

The other results obtained from the trial mixes were the consistency and stability of LFC derived from the fresh and hardened density measured. The values calculated were tabulated in Table 4.3 together with the average cube compressive strength data obtained from 7 days and 28 days compressive test.

Table 4.3: Consistency, Stability and Compressive Strength of LFC

Type of LFC	w/c ratio	Fresh Density (kg/m^3)	Average Hardened Density (kg/m^3)	Consistency	Stability	Average Compressive Strength, f_c (MPa)	
						7 days	28 days
LFC-CTR	0.56	1184.0	1161.6	0.987	1.019	2.97	3.22
	0.58	1231.4	1213.2	1.026	1.015	3.41	3.73
	0.60	1210.8	1197.7	1.009	1.011	3.45	3.96
	0.62	1194.2	1175.4	0.995	1.016	3.30	3.68
	0.64	1212.8	1204.9	1.011	1.007	3.30	3.65
LFC-CS0.6	0.56	1229.0	1218.9	1.024	1.008	2.49	2.83
	0.58	1223.8	1202.3	1.020	1.018	2.77	3.14
	0.60	1228.8	1227.0	1.024	1.001	2.96	3.75
	0.62	1228.0	1213.2	1.023	1.012	2.86	3.55
	0.64	1225.2	1222.9	1.021	1.002	2.76	3.28

All the types of LFC casted have fresh densities and hardened density within the range of 1200 ± 50 kg/m^3. As the range of density is fixed, the minimum and maximum value for consistency are set to be 0.958 and 1.042 respectively. Consistency refers to the accuracy of fresh density when compared with the targeted density. It is dependent to the amount of foam added into the concrete mix where consistency with a value below one denotes that the foam added is in excess, resulting in a lower density and vice versa. The casting of LFC-CS0.6 with different w/c ratios is more precise compared to LFC-CTR as the densities are similar to each other. Overall, the LFCs casted are consistent as the values are near unity.

The stability is referring to the stability of foam in the concrete mix from fresh state to hardened state. Based on Table 4.3, the hardened density for each type of LFC is lower than its respective fresh density, making the stability value to be more than one. This might be due to the air being entrapped unintentionally during the placing of fresh concrete into the mould, further reducing the density of LFC. Nevertheless, the foam is stable with minimal bursting as the stability is close to one. The w/c ratio and the presence of CS in concrete mixes have no notable effects on the stability of foam.

From Chapter 2, it is learnt that the density of LFC has a great influence on the compressive strength. Since the determination of optimum w/c ratio is based on compressive strength, the variation of density of LFC casted cannot be ignored. Therefore, the performance index (PI) was calculated to estimate the compressive strength of LFC per 1000 kg/m^3. Figure 4.2 shows the compressive strength PI for LFC-CTR while Figure 4.3 shows the compressive strength PI for LFC-CS0.6 at different w/c ratios. The purpose of casting at different w/c ratios is to obtain a bell-shaped graph that can show an optimum point. The w/c ratios chosen were high compared to the typical range for normal weight concrete because the ratio of cement in the total mix proportion for LFC is higher than normal weight concrete as it lacks of coarse aggregate. Thus, more water is required for the hydration of cement.

Based on Figure 4.2 and Figure 4.3, both LFC-CTR and LFC-CS0.6 achieved the highest compressive strength PI of 3.31 MPa and 3.05 MPa respectively at 28 days with w/c ratio of 0.60. It is observed that the compressive strength for LFC-CTR increases from w/c ratio of 0.56 to 0.60 and then it starts to drop. LFC-CS0.6 has a similar trend with LFC-CTR. At low w/c ratio, insufficient water was provided to allow maximum hydration rate of cement and the workability of concrete mix was lower. Low workability might cause uneven distribution of cement particles in the concrete mix. The combined effects lead to a lower strength LFC when compared with the optimum strength. Although the workability of concrete is better at higher w/c ratio, the excess free water creates more pores in the concrete when the concrete hardens. Thus, the strength will decrease as well. At optimum w/c ratio, the water provided is sufficient for hydration purposes and to achieve favourable workability.

All LFC casted gained strength over a period of 7 days to 28 days. Besides achieving the highest compressive strength, LFC casted at w/c ratio of 0.6 shows the highest strength gaining rate. For LFC-CTR, there is a 15 % increase in strength from 2.88 MPa to 3.31 MPa during the period from 7 days to 28 days for w/c ratio of 0.60 while at w/c ratio of 0.56, there is only 9 % increase in strength. The increase in strength for LFC-CS0.6 at w/c ratio of 0.60 is higher, which is 27 % from 2.41 MPa to 3.31 MPa.

It can be concluded that the optimum w/c ratio for LFC-CTR and LFC-CS0.6 is 0.60. This is because the w/c ratio of 0.60 achieves the highest compressive strength compared with other w/c ratios. Moreover, w/c ratio of 0.6 is more favourable in terms of the strength gaining rate. Since the addition of highest percentage of CS in this experiment yields similar flowability characteristics and similar trend for the strength at different w/c ratios when compared with the control mix, it is deduced that for LFC-CS0.2 and LFC-CS0.4, where the addition of CS is in between the two limits, the optimum w/c ratio is 0.6 as well.

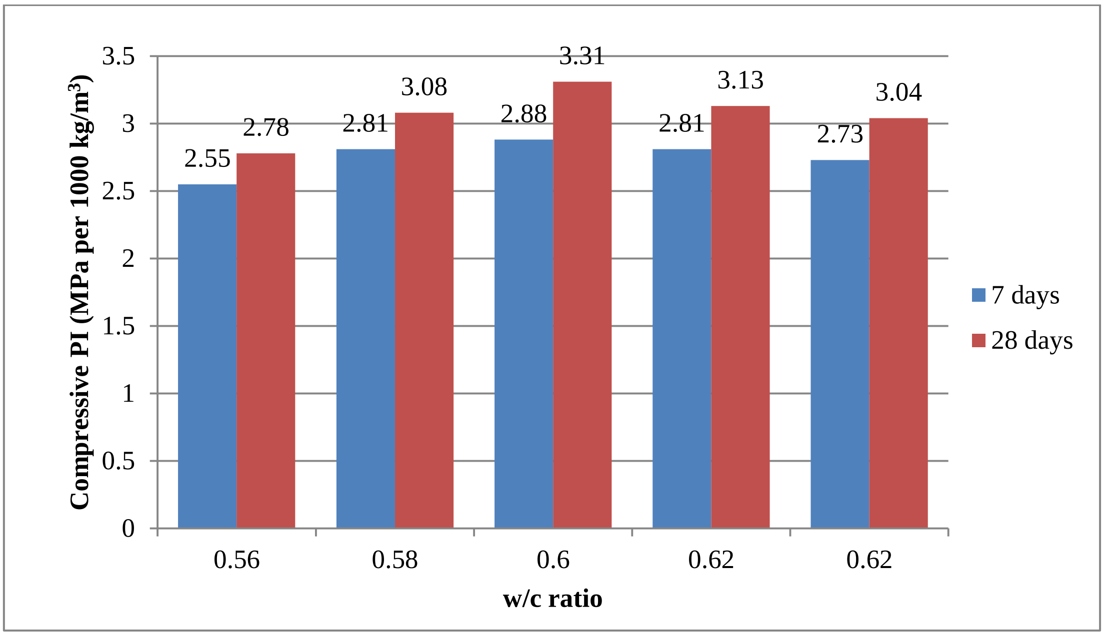

Figure 4.2: 7 Days and 28 Days Compressive Strength PI of LFC-CTR at Different w/c Ratios

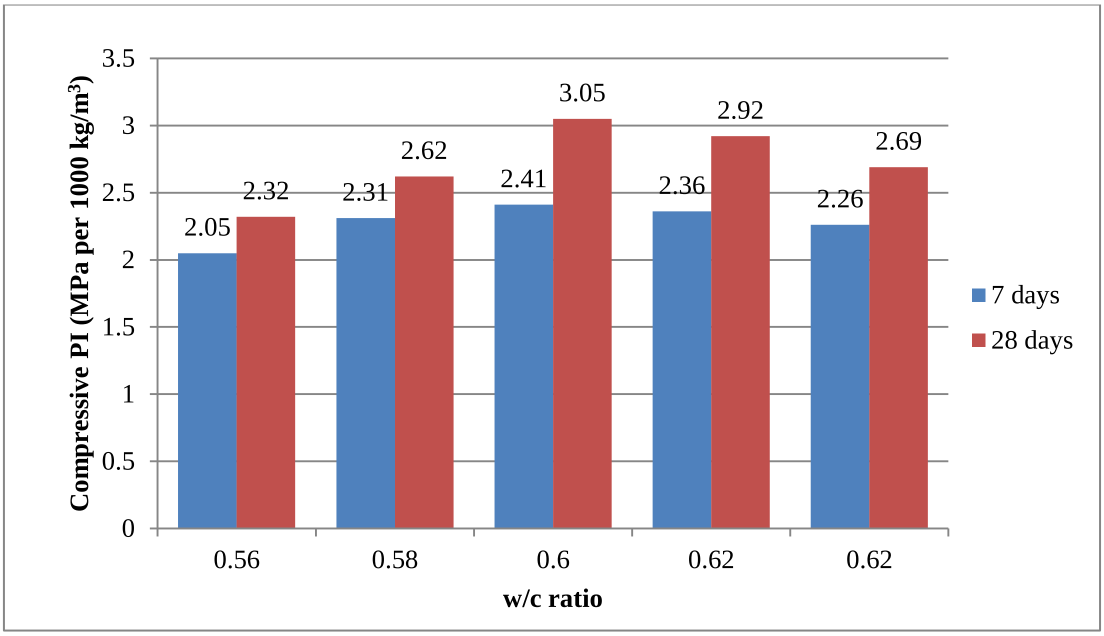

Figure 4.3: 7 Days and 28 Days Compressive Strength PI of LFC-CS0.6 at Different w/c Ratios

4.4 Compressive Strength

In the construction industry, compressive strength test is the most common test to determine the grading and quality of concrete casted. In this research, 100 mm concrete cubes and 100 mm diameter concrete cylinders with a height of 200 mm were casted and tested for its compressive strength to determine the relationship between cube and cylinder compressive strength. Due to the variability of the density of LFC casted, all results from the compressive test are expressed in terms of PI.

Figure 4.4 shows the growth trend of cube compressive strength, $f_{c,cube}$ for different types of LFC. From Figure 4.4, it can be observed that $f_{c,cube}$ of all types of LFC increases when the curing duration increases. The growth trend for the four types of LFC is similar as well, with a higher increment of $f_{c,cube}$ from 7 days to 28 days compared with the increment from 28 days to 56 days. This is consistent with the theory that compressive strength increases with time, with a higher rate during early ages and slows down at later ages (Abd elaty, 2013). LFC-CS0.6 shows the highest increase of $f_{c,cube}$ of 0.90 MPa per 1000 kg/m^3 from 7 days to 28 days while LFC-CTR shows the lowest increase of $f_{c,cube}$ of 0.26 MPa per 1000 kg/m^3 from 28 days to 56 days.

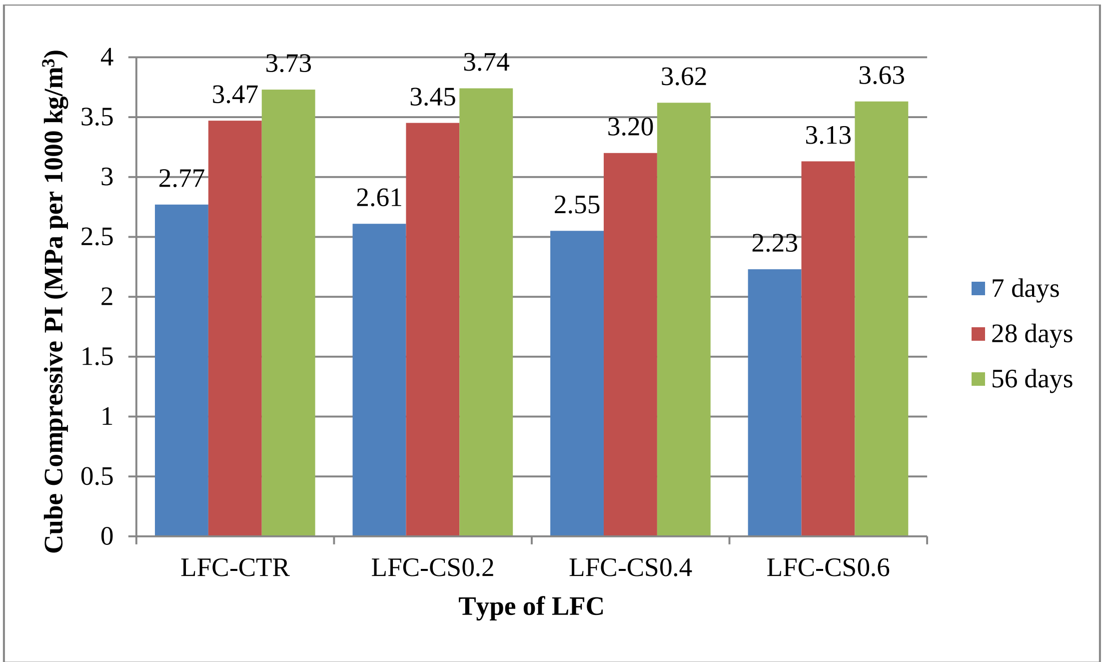

Figure 4.4: Cube Compressive Strength Growth for Different Types of LFC

Figure 4.5 compares the $f_{c,cube}$ of LFC at different curing ages. The highest $f_{c,cube}$ is achieved by LFC-CS0.2 at 56 days with a value of 3.74 MPa per 1000 kg/m^3. At 7 days and 28 days, $f_{c,cube}$ of LFC decreases as the percentage of CS increases. At 56 days, $f_{c,cube}$ of all types of LFC is similar to each other, with the largest difference of only 0.12 MPa per 1000 kg/m^3 compared to a difference of 0..54 MPa per 1000 kg/m^3 at 7 days.

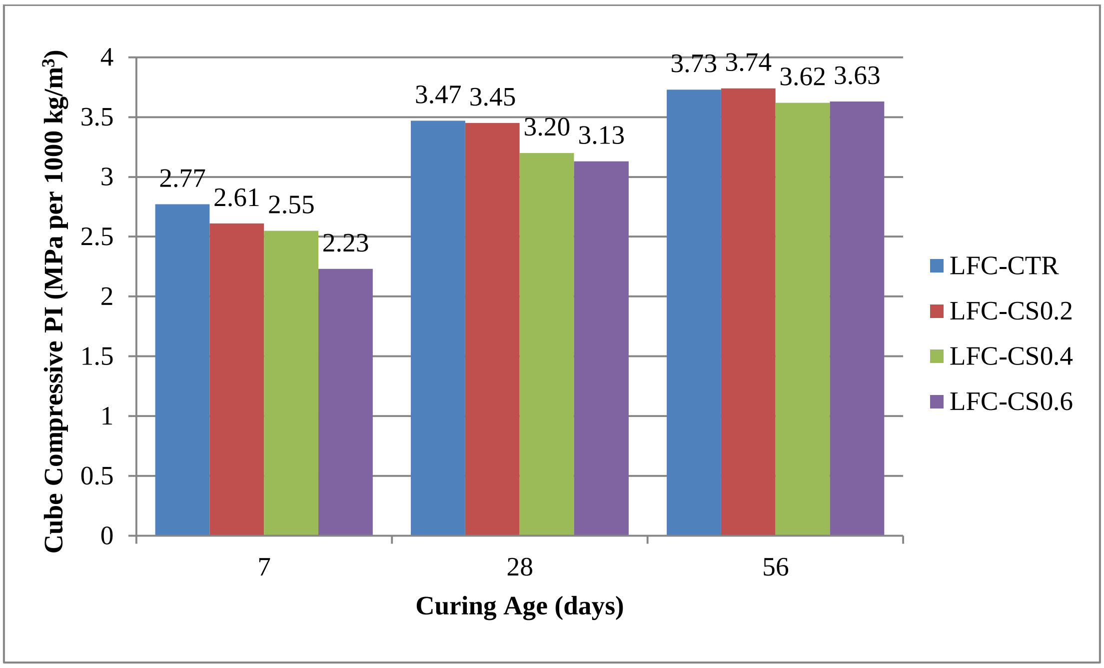

Figure 4.5: Cube Compressive Strength of LFC at Different Curing Ages

To study the effect of incorporating CS into LFC, $f_{c,cube}$ of LFC with CS is expressed as a percentage of control mix at different curing ages and then tabulated in Table 4.4. Together with Figure 4.5, it can be seen that when the curing age increases, the compressive strength achieved by LFC with CS is getting closer to that of the control mix. Research done by Quraishi, et al. (2011) produced similar findings. It is deduced that incorporating CS into LFC only retards the compressive strength development of LFC at early age. Due to the hydrophobic effect of CS, the hydration process of cement is delayed, forming lesser C-S-H gel and thus reduced the compressive strength. LFC with the highest percentage of CS, LFC-CS0.6 shows the highest retardation rate with 7 days $f_{c,cube}$ of only 80.5 % when compared with LFC-CTR. After 7 days, the compressive strength development for LFC with CS is no longer retarded. At later ages such as at 56 days, $f_{c,cube}$ of LFC-CS0.6 is 97.3 % of

LFC-CTR while LFC-CS0.2 is able to achieve $f_{c,cube}$ higher than LFC-CTR. This means that adding CS into LFC will not affect the overall compressive strength of LFC. In order to gain similar compressive strength of LFC-CTR at later ages, the compressive strength development after 7 days increased, resulting in the highest compressive strength increment from 7 days to 28 days for LFC-CS0.6. Besides, CS can be decomposed due to biological deterioration (Ren and Kagi, 2012). Moreover, the LFC specimens were fully submerged in water for curing purposes. The effectiveness of CS as water repellent agent reduces since it is poor in resisting the penetration of water under hydrostatic pressure (Kosmatka and Wilson, 2011). The penetration of water into concrete will take some time and this allows the hydration process of cement at later ages under continuous water curing condition.

Table 4.4: Effect of Incorporating CS into LFC on Its Cube Compressive Strength Development

Type of LFC	**Cube Compressive Strength Development as Percentage of LFC-CTR at Different Curing Ages (%)**		
	7 Days	**28 Days**	**56 Days**
LFC-CTR	100.0	100.0	100.0
LFC-CS0.2	94.2	99.4	100.3
LFC-CS0.4	92.1	92.2	97.1
LFC-CS0.6	80.5	90.2	97.3

The compressive strength of LFC for cylindrical specimens is illustrated in Figure 4.6. At 7 days, cylinder compressive strength, $f_{c,cylinder}$ of LFC-CS0.2 is a little bit higher than the control. After analysing $f_{c,cylinder}$ at 7 days and 28 days and comparing with $f_{c,cube}$, it is deduced that the $f_{c,cylinder}$ of LFC-CTR at 7 days is lower than it should be. Thus, the retardation on the growth rate for LFC-CS0.2 at 7 days is still valid. Other than that, the $f_{c,cylinder}$ shows a similar trend with $f_{c,cube}$. It is also noted that $f_{c,cylinder}$ is generally lower than $f_{c,cube}$. This is due to the higher length to depth ratio of cylinder which causes the compressive strength to be lower. The highest $f_{c,cylinder}$ obtained is 3.27 MPa per 1000 kg/m^3 at 56 days by LFC-CTR. The largest $f_{c,cylinder}$ difference between the types of LFC at certain curing age is 0.52 MPa per 1000 kg/m^3, which occurs at 28 days instead of 7 days. At 56 days, the $f_{c,cylinder}$ difference is the lowest which is 0.18 MPa per 1000 kg/m^3.

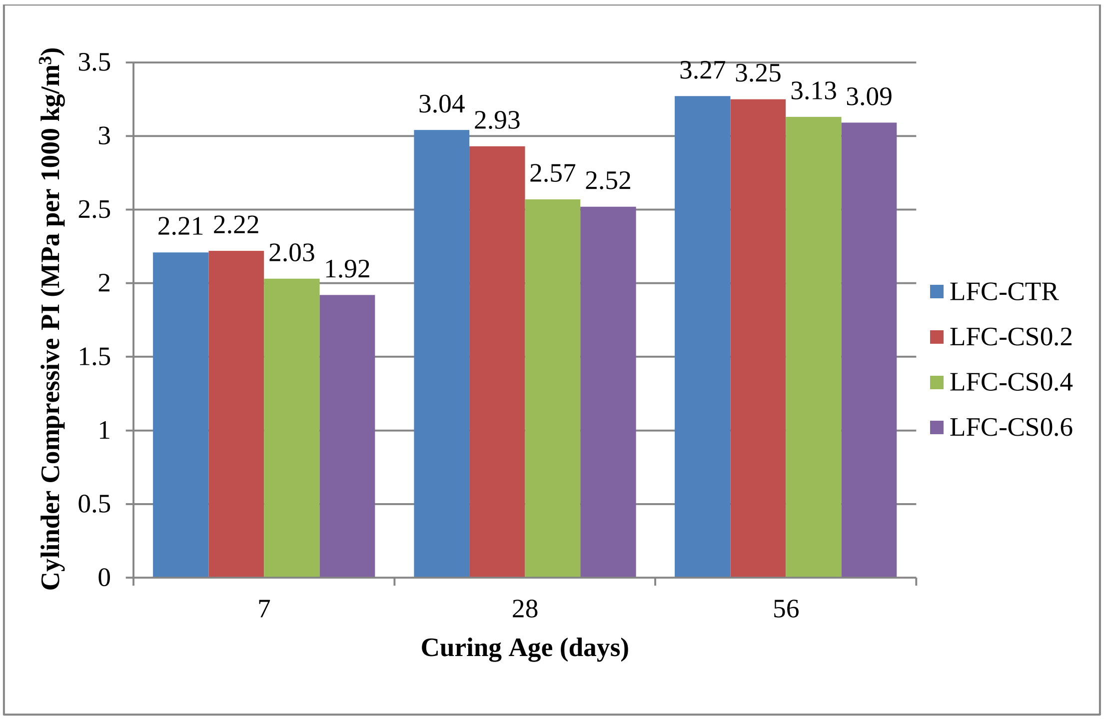

Figure 4.6: Cylinder Compressive Strength of LFC at Different Curing Ages

The relationship between $f_{c,cylinder}$ and $f_{c,cube}$ is plotted in Figure 4.7 while Table 4.5 shows the ratio and the coefficient of determination, R^2 of the two compressive strengths. R^2 represents the closeness of the data to the linear trend line plotted in the graph with value closer to one indicating a stronger linear relationship between the two variables. From Figure 4.7, it is observed that $f_{c,cylinder}$ increases linearly with $f_{c,cube}$. Based on the R^2 calculated, the relationship between $f_{c,cylinder}$ and $f_{c,cube}$ is better explained as linear instead of directly proportional since the R^2 for linear relationship for all types of LFC is closer to one compared to the R^2 for directly proportional. Directly proportional relationship is also a linear relationship but the y-intercept is equalled to zero. The lowest $f_{c,cylinder}$ / $f_{c,cube}$ ratio is 0.796 by LFC-CS0.4 at 7 days while the highest ratio is 0.877 by LFC-CTR at 56 days. The ratio obtained from the experiment is quite close to the typical $f_{c,cylinder}$ / $f_{c,cube}$ ratio, which is 0.80 (Kumavat and Patel, 2014). LFC-CTR has the largest range of $f_{c,cylinder}$ / $f_{c,cube}$ ratio of 0.079 throughout the three curing ages while LFC-CS0.2 has the smallest range of 0.020. This is due to higher variation of the density of LFC-CTR casted. There is no significant effect of CS on the $f_{c,cylinder}$ / $f_{c,cube}$ ratio as the average ratio of all the types of LFC is close to each other. As the number of specimens casted is not enough to make a solid relationship, it is concluded that the ratio of

$f_{c,cylinder}$ / $f_{c,cube}$ for water repellent LFC with density of 1200 ± 50 kg/m^3 is in the range of 0.796 to 0.877.

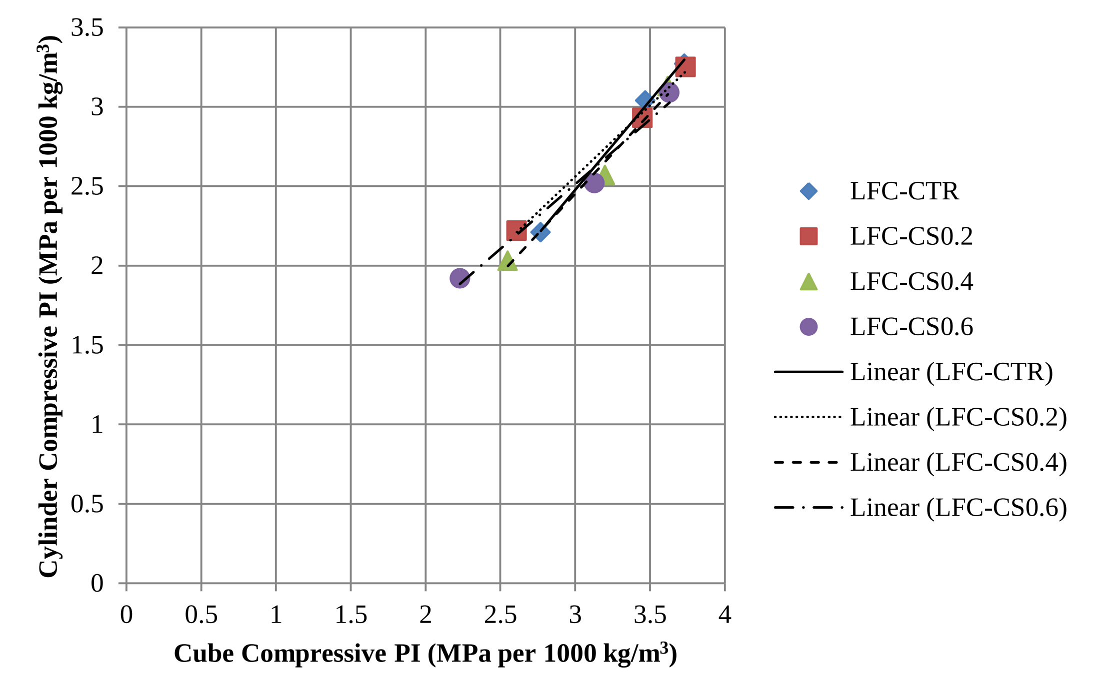

Figure 4.7: Linear Relationship between Cylinder and Cube Compressive Strength

Table 4.5: Ratio of Cylinder to Cube Compressive Strength

Type of LFC	**$f_{c,cylinder}$ / $f_{c,cube}$ Ratio**					**R^2**	
	7 Days	**28 Days**	**56 Days**	**Mean**	**Range**	**Linear**	**Directly Proportional**
LFC-CTR	0.798	0.876	0.877	0.850	0.079	0.9967	0.9412
LFC-CS0.2	0.851	0.849	0.869	0.856	0.020	0.9966	0.9947
LFC-CS0.4	0.796	0.803	0.865	0.821	0.069	0.9822	0.9495
LFC-CS0.6	0.861	0.805	0.851	0.839	0.056	0.9781	0.9774

4.5 Splitting Tensile Strength

The next mechanical property of water repellent LFC studied is the splitting tensile strength. Although the testing machine is operated under compression load, the cylindrical specimen experienced elongation at the direction perpendicular to the load. This results in an indirect tension force along the vertical diameter of cylinder where the load is applied. Thus, the LFC fails in tension instead of compression. Figure 4.8 depicts the cracking of cylindrical specimens after splitting tensile test.

(a) (b)

Figure 4.8: Splitting Tensile Failure; (a) Cracking at Centre; (b) Splitting of Cylindrical Specimen into Halves

The splitting tensile strength, *T* is converted to PI for a more accurate comparison between the results obtained. Figure 4.9 shows the splitting tensile strength of different types of LFC at curing age of 7 days, 28 days and 56 days. For all the types of LFC, *T* increases with time because of the hydration process of cement that takes place with time. The highest *T* of 0.58 MPa per 1000 kg/m^3 is attained by LFC-CTR at 56 days. The trend for *T* is consistent with the compressive strength. It is observed that *T* decreases when the amount of CS added into LFC increases. The difference between the highest *T* and lowest *T* for 7, 28 and 56 days is 0.15, 0.08 and 0.05 MPa per 1000 kg/m^3 respectively. Similar to the compressive strength, *T* achieved by LFC with CS is comparable to the *T* of control mix at 56 days as shown in Table 4.6. At 7 days, *T* of LFC-CS0.6 is only 64.3 % of *T* of LFC-CTR. Then, it increases to 85.5 % at 28 days and 91.4 % at 56 days. As the curing age increases, the effect of CS in LFC decreases. Therefore, it is concluded that the presence of CS in LFC is not detrimental to the splitting tensile strength as CS only retards the development of splitting tensile strength at early age but not at later age.

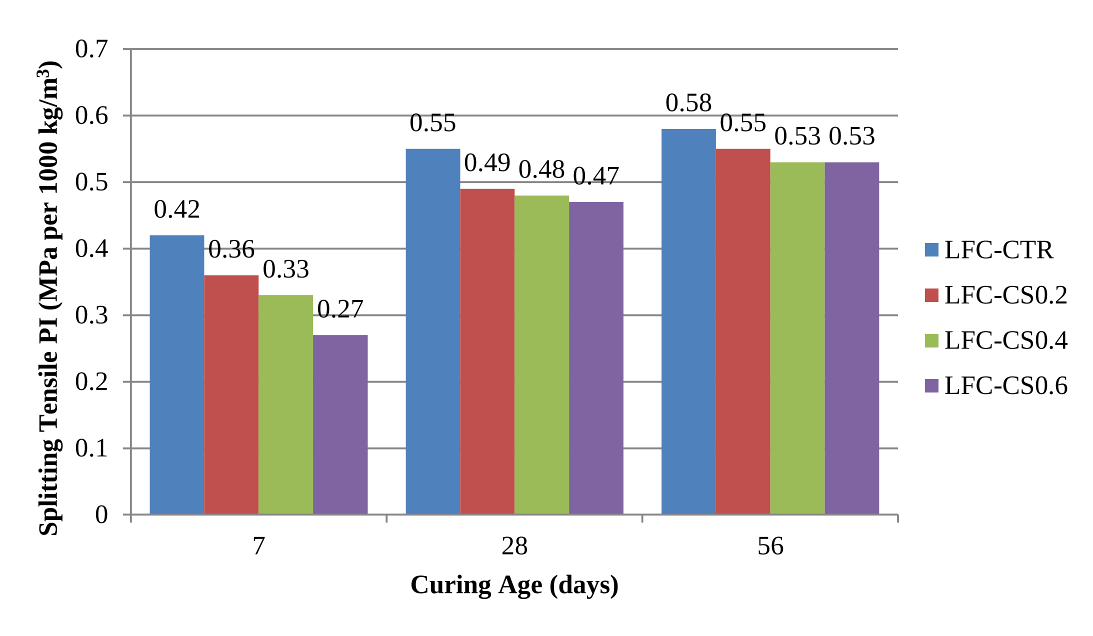

Figure 4.9: Splitting Tensile Strength of LFC at Different Curing Ages

Table 4.6: Effect of Incorporating CS into LFC on Its Splitting Tensile Strength Development

Type of LFC	**Splitting Tensile Strength Development as Percentage of LFC-CTR at Different Curing Age (%)**		
	7 Days	**28 Days**	**56 Days**
LFC-CTR	100.0	100.0	100.0
LFC-CS0.2	85.7	89.1	94.8
LFC-CS0.4	78.6	87.3	91.4
LFC-CS0.6	64.3	85.5	91.4

The relationship between T and $f_{c,cube}$ is plotted in Figure 4.10 and the ratio is tabulated in Table 4.7. Generally, T is lower than $f_{c,cube}$ as concrete is poor in tension. Based on the R^2 calculated, T has a strong linear relationship with $f_{c,cube}$ compared to directly proportional. From Figure 4.10, polynomial trend line is drawn instead of linear trend line. This is because T increases at a decreasing rate when compressive strength increases, resulting in a concave curve (Akinpelu, et al., 2017). It is seen that all types of LFC have concave curve except for LFC-CS0.2. This is due to the lower T recorded at 28 days, resulting in a convex curve. LFC-CS0.4 and LFC-CS0.6 have a larger range of ratios compared to LFC-CTR and LFC-CS0.2. This might be because the retardation rate is different for splitting tensile strength and compressive strength, especially at higher percentage of CS. Incorporating CS into LFC also decreases the T / $f_{c,cube}$ ratio as the mean ratio decreases when the amount of CS increases. As the T / $f_{c,cube}$ ratio for lower strength concrete is higher, the LFC casted with density of 1200 kg/m^3 has T / $f_{c,cube}$ ratio of 0.121 to 0.159, which is slightly higher than normal weight concrete with the range of 0.08 to 0.11 (Amran, Farzadnia and Ali, 2015). It is concluded that for water repellent LFC with density of 1200 ± 50 kg/m^3, T is about 12.1 % to 15.9 % of $f_{c,cube}$.

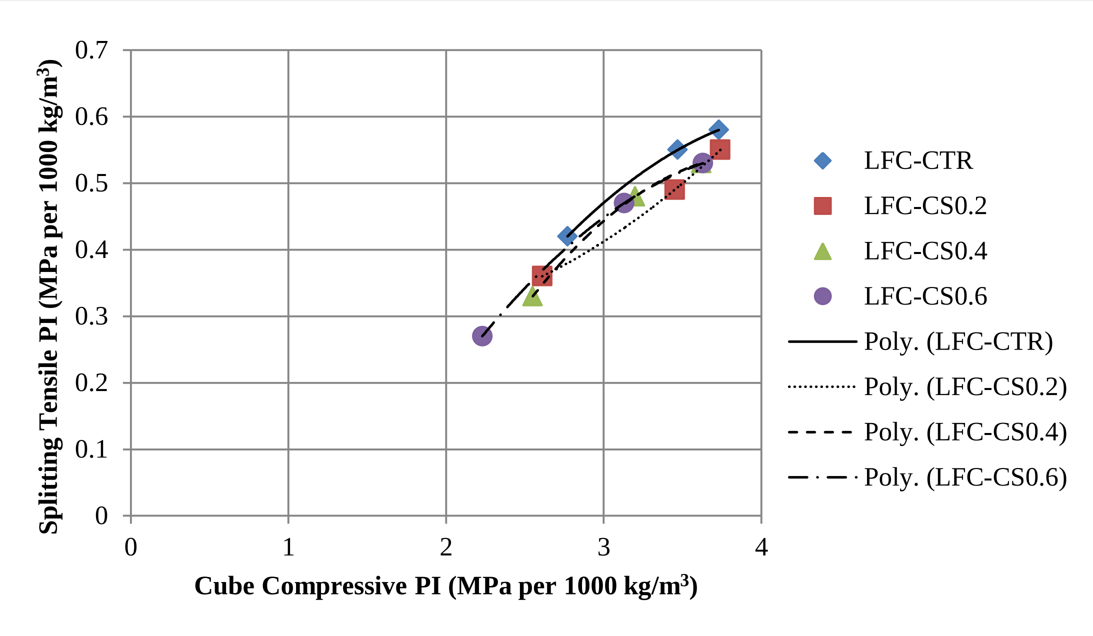

Figure 4.10: Polynomial Relationship between Splitting Tensile and Cube Compressive Strength

Table 4.7: Ratio of Splitting Tensile to Cube Compressive Strength

Type of LFC	***T* / *f*** $T / f_{c,cube}$ **Ratio**					R^2	
	7 Days	**28 Days**	**56 Days**	**Mean**	**Range**	**Linear**	**Directly Proportional**
LFC-CTR	0.152	0.159	0.155	0.155	0.007	0.9923	0.9846
LFC-CS0.2	0.138	0.142	0.147	0.142	0.009	0.9959	0.9781
LFC-CS0.4	0.129	0.150	0.146	0.142	0.021	0.9754	0.9156
LFC-CS0.6	0.121	0.150	0.146	0.139	0.029	0.9811	0.9188

4.6 Flexural Strength

Flexural test is another test that determines the tensile properties of concrete. As the load is applied at the centre of prism, the prism experienced compression at the top and tension at the bottom. The prism fails when it can no longer sustain the tension due to the elongation caused by bending, resulting in cracking from the bottom as depicted in Figure 4.11. The load versus deflection curve produced by the machine and computer software is converted to stress-strain curve as plotted in Figure 4.12. The maximum flexural strength, *R* achieved by the LFC is represented by the peak of the curve. Then, the area under the graph until the maximum *R* is the flexural toughness of LFC and the gradient of the curve is the flexural modulus.

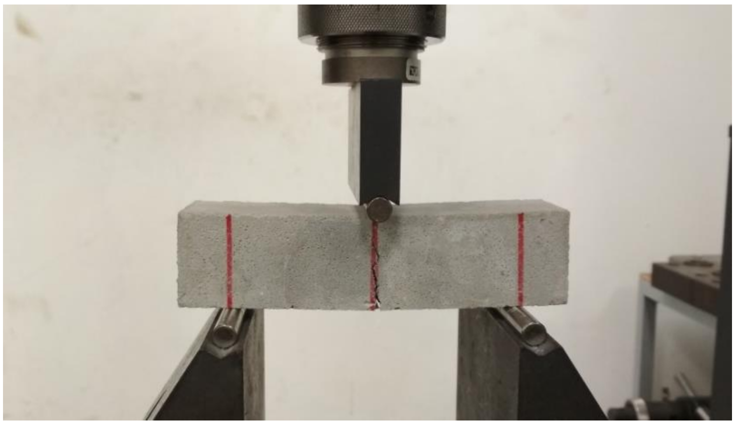

Figure 4.11: Cracking of Prism during Flexural Failure

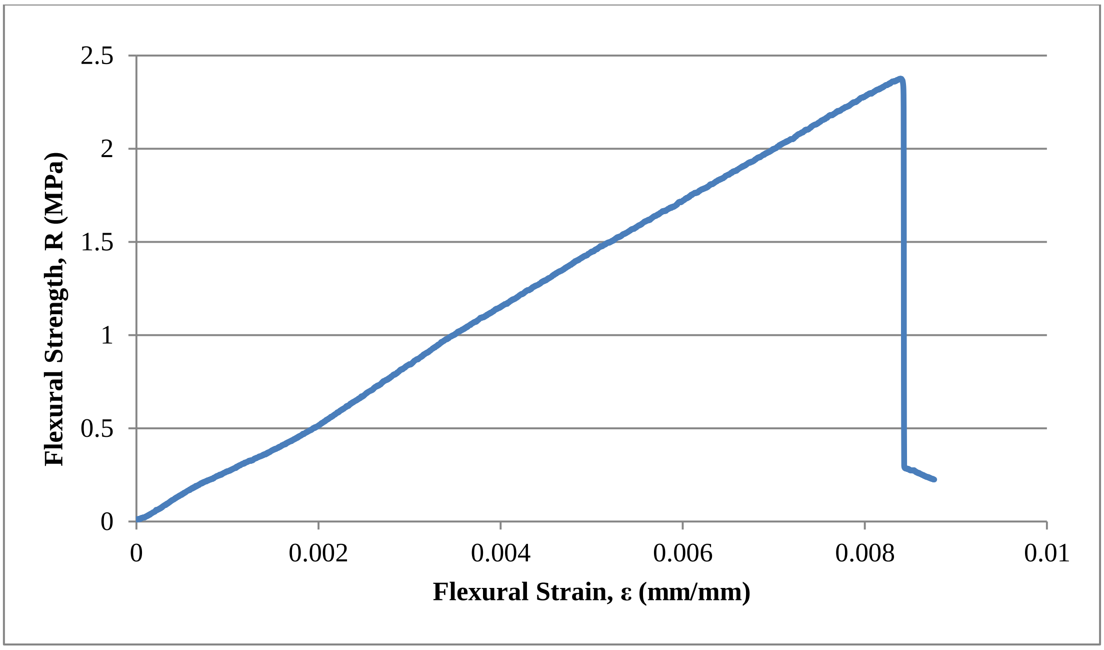

Figure 4.12: Stress-Strain Curve for a Sample from LFC-CTR at 7 Days

Figure 4.13 shows the *R* of LFC expressed in terms of PI to take into account the variation of density of LFC casted. The *R* of each LFC increases as the LFC ages. Continuous curing of LFC allows continuous formation of C-S-H gel which contributes to *R*. LFC-CTR achieved the highest *R* of 2.17 MPa per 1000 kg/m^3 at 56 days. Similar to the two previous strengths discussed earlier, *R* decreases when the percentage of CS increases. The difference between the highest *R* and lowest *R* for 7, 28 and 56 days is 0.38, 0.25 and 0.05 MPa per 1000 kg/m^3 respectively. Based on Table 4.8, *R* of LFC containing CS is approaching the *R* of control mix as the LFC ages. However, there is a slight decrease in percentage for LFC-CS0.2 at 28 days from 93.8 % to 90.9 %. The specimen for splitting tensile test for LFC-CS0.2 at 28 days which is casted in the same batch also has splitting tensile strength lower than expected. This might be due to the error in casting, causing the quality of LFC to be poorer. Consistent with compressive and splitting tensile strength, it is concluded that CS retards the growth of *R* at early ages and the strength development of LFC containing CS improves at later ages.

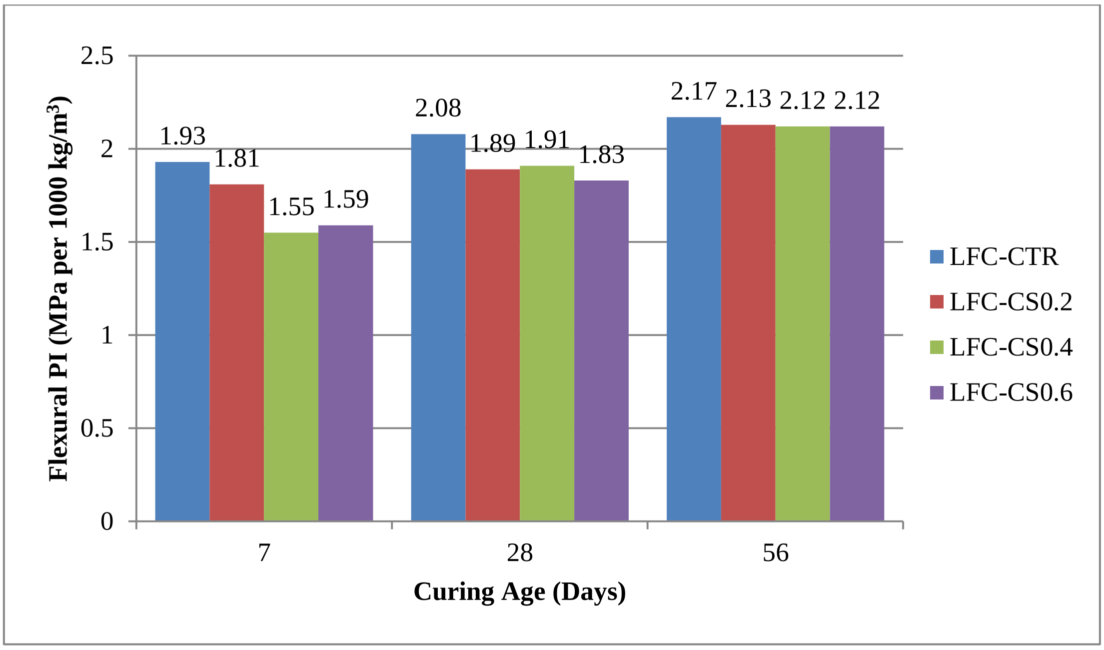

Figure 4.13: Flexural Strength of LFC at Different Curing Ages

Table 4.8: Effect of Incorporating CS into LFC on Its Flexural Strength Development

Type of LFC	**Flexural Strength Development as Percentage of LFC-CTR at Different Curing Ages (%)**		
	7 Days	**28 Days**	**56 Days**
LFC-CTR	100.0	100.0	100.0
LFC-CS0.2	93.8	90.9	98.2
LFC-CS0.4	80.3	91.8	97.7
LFC-CS0.6	82.4	88.0	97.7

Figure 4.14 shows the relationship between R and $f_{c,cube}$. Generally, R is lower than compressive strength but higher than splitting tensile strength. However, the ratio of R / $f_{c,cube}$ obtained is higher than the typical values of 0.22 to 0.27 (Narayanan and Ramamurthy, 2000). This might be due to the low loading rate during flexural test, allowing the propagation of stress throughout the span and thus yielding a higher R. From Figure 4.14, it is observed that R increases linearly with $f_{c,cube}$. The R^2 calculated and tabulated in Table 4.9 shows that the data has a good fit with the linear trend line except for LFC-CS0.2 due to the lower R at 28 days as discussed earlier. The directly proportional R^2 values for LFC-CTR and LFC-CS0.2 are not stated as it is in negative. This indicates that data does not fit when the y-intercept is equalled to zero. Unlike splitting tensile strength, polynomial trend line is not chosen since it does not produce a consistent trend. The range of R / $f_{c,cube}$ ratio is bigger compared to the other ratio discussed previously. This means that the development rate for R and $f_{c,cube}$ is not the same. There is no notable effect caused by CS on the R / $f_{c,cube}$ ratio as the average ratio of all the types of LFC is close to each other. With the results obtained, it is concluded that the R / $f_{c,cube}$ ratio for water repellent LFC with density of 1200 ± 50 kg/m^3 is between 0.548 and 0.713.

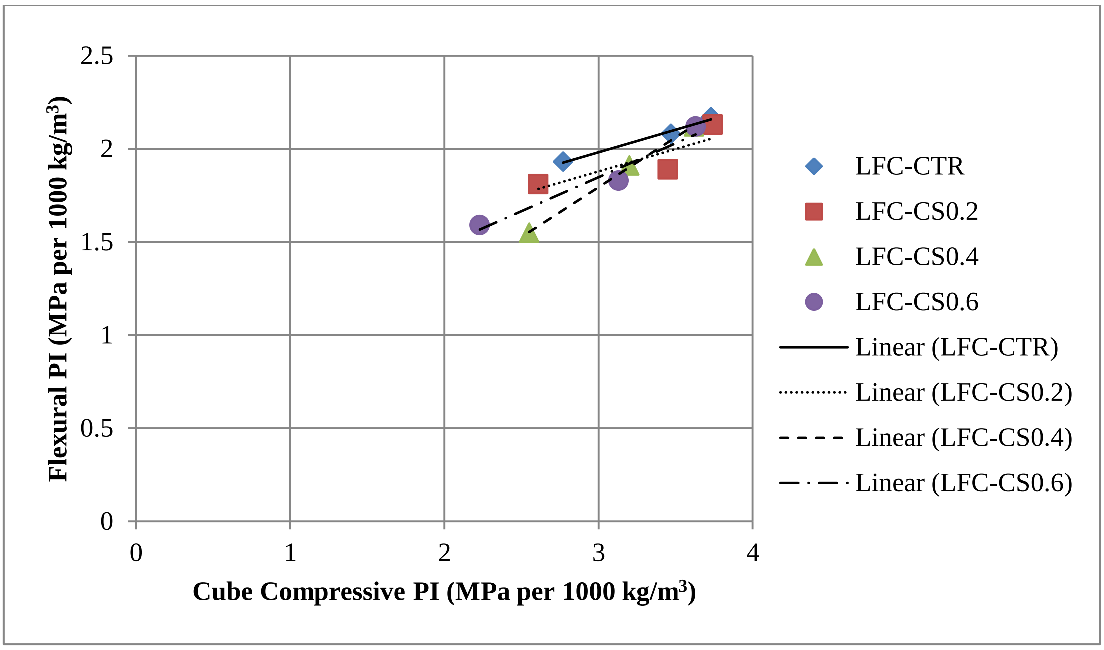

Figure 4.14: Linear Relationship between Flexural and Cube Compressive Strength

Table 4.9: Ratio of Flexural to Cube Compressive Strength

Type of LFC	$R / f_{c,cube}$ Ratio					R^2	
	7 Days	28 Days	56 Days	Mean	Range	Linear	Directly Proportional
LFC-CTR	0.697	0.599	0.582	0.626	0.115	0.9868	-
LFC-CS0.2	0.693	0.548	0.570	0.604	0.145	0.7223	-
LFC-CS0.4	0.608	0.597	0.586	0.597	0.022	0.9993	0.9865
LFC-CS0.6	0.713	0.585	0.584	0.627	0.129	0.9533	0.5192

The flexural toughness and flexural modulus of LFC are shown in Table 4.10. Flexural toughness represents the energy a material can absorb before it fractures while flexural modulus represents the stiffness of the material to resist the change in length under compression or tension load. Based on Table 4.10, there is a large variation of flexural toughness and flexural modulus for each LFC at different days with no specific trend observed. This is because LFC is a heterogeneous material made up of cement, sand, water and foam. Different composition and distribution of base materials will affect the flexural toughness and flexural modulus of LFC. Besides, the area under the graph is approximated using trapezoidal rule and some of the stress-strain curves produced do not have a single straight gradient. Generally, when the strain of LFC at failure is higher at similar flexural strength, the flexural toughness is higher as well since the area under the graph is larger. On the other hand, flexural modulus will be lower as the amount of load required to elongate the LFC decreases. LFC-CS0.6 has the highest flexural toughness of 9874.1 J/m^3 at 56 days while LFC-CS0.4 has the lowest flexural toughness 0f 6323.1 J/m^3 at 56 days. The highest flexural modulus of 518.8 MPa is achieved by LFC-CTR at 28 days and the lowest is LFC-CS0.4 at 7 days with a value of 220.7 MPa.

Table 4.10: Flexural Toughness and Flexural Modulus of LFC

Type of LFC	**Average Flexural Toughness, U_T (J/m^3)**			**Average Flexural Modulus, E_f (MPa)**		
	7 Days	**28 Days**	**56 Days**	**7 Days**	**28 Days**	**56 Days**
LFC-CTR	9383.3	6770.8	7224.1	284.6	518.8	477.4
LFC-CS0.2	7400.5	8423.9	7621.4	319.4	299.0	411.2
LFC-CS0.4	7568.5	7022.5	6323.1	220.7	426.0	505.9
LFC-CS0.6	6849.1	7253.8	9874.1	265.0	340.3	370.4

4.7 Summary

The results obtained from various tests conducted in this research were analysed and discussed on the effect of incorporating CS into LFC. Through sieve analysis, it is confirmed that the sand used for the casting of LFC meets the requirements set by ASTM C33. The usage of the sand will not cause adverse effect on the workability and strength of the LFC.

The optimum w/c ratio for each of the LFC is determined to be 0.60 after taking into consideration the workability, compressive strength and strength development of LFC with different w/c ratios. Incorporating CS into LFC does not affect the workability of fresh concrete.

Mechanical properties of LFC such as compressive strength, splitting tensile strength and flexural strength show similar trends on the strength development. All the LFCs gain strength at a decreasing rate with respect to time as the formation of C-S-H gel that contributes to the strength is higher at early ages. Adding CS into LFC only retards the strength development of LFC at early ages instead of reducing the overall strength of LFC. This is proven as the strength of LFC containing CS is lower compared to LFC-CTR at early ages but as time passes, the strength of LFC containing CS is similar to the strength of LFC-CTR. This is due to the hydrophobic effects of CS that delayed the hydration process of cement at early ages. Higher percentage of CS in LFC results in higher retardation rate at early ages. At later ages, the hydration process is back to normal provided that it is under continuous water curing condition.

The cylinder compressive strength has a strong positive linear relationship with the cube compressive strength. The cylinder compressive strength is lower than the cube compressive strength, with a ratio between 0.796 and 0.877. There is no significant effect of CS on the cylinder to cube compressive strength ratio as the average ratio for each type of LFC is similar.

The splitting tensile strength increases at a decreasing rate with the increase of cube compressive strength, forming a concave curve trend line. The splitting tensile strength is much lower than the cube compressive strength, which is about 12.1 % to 15.9 % of cube compressive strength. It is noted that the average splitting tensile to cube compressive strength ratio decreases when the amount of CS added increases.

The flexural strength also has a strong positive linear relationship with the cube compressive strength. The flexural strength is lower than cube compressive strength but higher than splitting tensile strength. The flexural to cube compressive strength ratio is in the range of 0.548 to 0.713. The ratio is higher than the typical ratio due to a low loading rate which allows the propagation of stress throughout the span. Incorporating CS has no notable effect on the flexural to cube compressive strength ratio since the mean ratio for each type of LFC is close to each other.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

After analysing the results collected from laboratory testing, the following conclusions can be drawn based on the objectives set for this research.

The first objective was to produce LFC incorporate with CS with density of 1200 ± 50 kg/m^3. This was accomplished as all the LFCs casted were within the range of the desired density.

The second objective was to obtain the optimum w/c ratio of LFC incorporate with CS. This was achieved by conducting trial mixes. The optimum w/c ratio of LFC-CTR, LFC-CS0.2, LFC-CS0.4 and LFC-CS0.6 are similar, which is 0.60.

The third objective was to study the effect of CS towards the mechanical properties of LFC containing CS. By incorporating CS into LFC, the development of compressive strength, splitting tensile strength and flexural strength is retarded at early ages but at later ages, the strength development is back to normal.

5.2 Recommendations

In order to further improve and confirm the reliability of results obtained from this study, the following suggestions can be taken into consideration for future research.

(i) Investigate the effect of CS on other engineering properties such as water absorption, sorptivity, sound and thermal insulation.

(ii) Increase the percentage of CS incorporate into LFC to determine the impact of overdosing on the engineering properties.

(iii) Increase the curing duration to study the long term effects of CS on the engineering properties of LFC.

(iv) Adopt different curing methods such as air curing or stream curing to analyse the impact on the hydration of cement with the presence of CS.

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APPENDICES

APPENDIX A: Compressive Strength for Various Types of LFC at Different Curing Age

Table A.1: Cube Compressive Test Data

Type of LFC	Curing Age (Days)	Average Hardened Density (kg/m^3)	Average Compressive Strength (MPa)	Average Performance Index (MPa per 1000 kg/m^3)
LFC-CTR	7	1191.09	3.30	2.77
	28	1234.71	4.28	3.47
	56	1195.84	4.46	3.73
LFC-CS0.2	7	1210.70	3.16	2.61
	28	1214.65	4.19	3.45
	56	1199.04	4.49	3.64
LFC-CS0.4	7	1206.89	3.08	2.55
	28	1190.29	3.80	3.19
	56	1202.61	4.35	3.62
LFC-CS0.6	7	1189.04	2.66	2.23
	28	1196.55	3.74	3.13
	56	1208.62	4.39	3.63

Table A.2: Cylinder Compressive Test Data

Type of LFC	Curing Age (Days)	Average Hardened Density (kg/m^3)	Average Compressive Strength (MPa)	Average Performance Index (MPa per 1000 kg/m^3)
LFC-CTR	7	1014.84	2.64	2.21
	28	1216.53	3.70	3.04
	56	1194.24	3.90	3.27
LFC-CS0.2	7	1021.36	2.70	2.22
	28	1213.91	3.55	2.93
	56	1208.17	3.92	3.25
LFC-CS0.4	7	1026.75	2.44	2.03
	28	1187.29	3.05	2.57
	56	1200.92	3.76	3.13
LFC-CS0.6	7	1010.43	2.28	1.92
	28	1190.25	2.99	2.52
	56	1216.86	3.76	3.09

APPENDIX B: Splitting Tensile Strength for Various Types of LFC at Different Curing Age

Table B.1: Splitting Tensile Test Data

Type of LFC	**Curing Age (Days)**	**Average Hardened Density (kg/m^3)**	**Average Splitting Tensile Strength (MPa)**	**Average Performance Index (MPa per 1000 kg/m^3)**
LFC-CTR	7	1212.73	0.50	0.42
	28	1207.12	0.66	0.55
	56	1182.83	0.69	0.58
LFC-CS0.2	7	1222.06	0.44	0.36
	28	1190.41	0.58	0.49
	56	1192.15	0.66	0.55
LFC-CS0.4	7	1195.95	0.39	0.33
	28	1191.10	0.57	0.48
	56	1186.18	0.63	0.53
LFC-CS0.6	7	1194.94	0.33	0.27
	28	1204.27	0.57	0.47
	56	1193.12	0.64	0.53

APPENDIX C: Flexural Strength for Various Types of LFC at Different Curing Age

Table C.1: Flexural Test Data

Type of LFC	**Curing Age (Days)**	**Average Hardened Density (kg/m^3)**	**Average Flexural Strength (MPa)**	**Average Performance Index (MPa per 1000 kg/m^3)**
LFC-CTR	7	1220.31	2.35	1.93
	28	1209.19	2.52	2.08
	56	1166.99	2.53	2.17
LFC-CS0.2	7	1211.72	2.19	1.81
	28	1212.23	2.30	1.89
	56	1182.83	2.52	2.13
LFC-CS0.4	7	1188.02	1.84	1.55
	28	1185.87	2.26	1.91
	56	1173.93	2.49	2.12
LFC-CS0.6	7	1207.81	1.92	1.59
	28	1204.39	2.20	1.83
	56	1185.44	2.52	2.12