IMPACT OF VARIOUS TYPES OF WATER REPELLENT AGENT TOWARDS CONCRETE ENGINEERING PERFORMANCE

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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 **"IMPACT OF VARIOUS TYPES OF WATER REPELLENT AGENT TOWARDS CONCRETE ENGINEERING PERFORMANCE"** was prepared by **TANG HOU JING** 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

Concrete can be categorised into three types such as heavyweight, normal-weight and lightweight. In this study, lightweight concrete was studied with the use of water repellent agent (WRA) due to the lightweight concrete have a more porous structure. Lightweight concrete is further classified into lightweight aggregate concrete (LAC), lightweight foamed concrete (LFC) and autoclaved aerated concrete. In this study, only the LAC and LFC were chosen to study with the incorporation of various WRA. Five types of WRA that used to study were calcium stearate (CS), zinc stearate (ZS), sodium oleate (SO), silane and siloxane. This study aims to apply these five types of WRA to investigate their impact on the LAC and LFC in terms of compressive strength and water absorption. Next objective of this study is to analyse the most effective WRA for respective LAC and LFC. The qualitative method had been adopted wherein an extensive review of research articles had been carried out. Keywords such as LAC and LFC with the use of WRA to search and filter. SWOT analysis was adopted to examine the most effective WRA for LAC and LFC. Results showed that these five types of WRA would reduce the compressive strength of LAC and LFC. Also, the water absorption of LAC and LFC would reduce with the incorporation of WRA. Results showed that ZS and CS were the optimal WRA for the respective LAC and LFC in terms of compressive strength and water absorption. Thus, ZS and CS can be widely used in the construction industry to produce water-resistant lightweight concrete.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

AAC	Autoclaved Aerated Concrete
COPS	Crushed Oil Palm Shell
CS	Calcium Stearate
EPP	Expanded Polypropylene
GGBFS	Ground Granulated Blast Furnace Slag
LAC	Lightweight Aggregate Concrete
LFC	Lightweight Foamed Concrete
SO	Sodium Oleate
W_A	Water Absorption
WRA	Water Repellent Agent
ZS	Zinc Stearate
w/c	water to cement ratio

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Concrete is the most used building material in every corner of the construction world because of its relatively abundant source of raw materials and controllable shape (Tian, et al., 2019). In the construction industry nowadays, there are various types of concrete available such as lightweight concrete with the density of 320 to 1920 kg/m^3 (ACI, 2001); normal weight concrete with density of 2200 to 2600 kg/m^3 and; heavyweight concrete with the density of 3000 to 3800 kg/m^3 (Neville, 2002). Heavyweight aggregates possess comparatively high density and are important where a high density concrete is required. Heavyweight concrete is produced by heavy self-weight manufactured aggregates such as iron, lead shot or heavy natural aggregates, for instance, magnetite and barites. Typically, the density of magnetite would be 3900 kg/m^3 which is 60 % larger than normal weight concrete, meanwhile, with barites, the density would be 3500 kg/m^3, or 45 % larger than normal weight concrete. Heavyweight concrete can be applied to prevent seepage from radioactive structures, for instance, hospitals, nuclear stations and laboratories. In normal practice, the water-to-cement ratio for heavyweight concrete is 0.40 to produce dense concrete with low permeability (Collins, 2019).

There are 3 categories of lightweight concrete such as structural lightweight concrete, moderate strength concrete and low-density concrete. For structural lightweight concrete with the density in the range of 1350 to 1950 kg/m^3, which has a minimum compressive strength of 17 MPa. The lightweight aggregates involved are typically clay, expanded slate or shale which have been burnt in the rotary kiln to develop the porous structure. Low-density concrete has a density in the range of 300 to 800 kg/m^3, and it is mainly implemented for thermal insulation purposes. As for the moderate strength concrete which is fall in between these two categories, and its compressive strength is in the range of 7 to 17 MPa (Neville, 2002). Besides, the significant characteristic of lightweight concrete is the highly porous structure. Therefore, the need for water repellent agents is indeed very essential to lightweight concrete due to the excessive capillary pores would absorb more water.

Water repellent agents can restrict the movement of water within the concrete and thus reduce the water absorption of concrete. Silane typically refers to siloxane-based and silane repellent agents which can repel hydroxyl in the cementitious compound, and make the concrete hydrophobic. Silane and siloxane are both derived from the family of silicone, but they still have significant differences in performance. Silane requires high pH value to catalyse, meanwhile siloxane is independent on the substrate of pH value. Because silane is generally made up of smaller molecules as compared to siloxane, therefore silane can achieve greater penetration in concrete.

On the other hand, silane is comparatively volatile due to its smaller molecular size. As a result, the solids content of silane must be sufficiently large to compensate for those evaporated reactive materials during the curing process or application. A lesser rate of volatility for the siloxane typically provides good water repellent performance at a lower initial cost as compared to silane (Concrete Construction Staff, 1995). During the fabrication process, siloxane-based waterproofing admixtures can be added to the fresh concrete and produce cement-based integral water repellent concrete. With the silane-based repellent agent, the water capillary suction can be dwindled up to 90%. Nevertheless, another research has studied silicon resin (SR) which contains a high molecular weight for highly branched polysiloxanes. There are two types of concrete used for testing. The first type is surface impregnation that uses the surface SR treatment concrete (C-SSR). While, the second type is adding a different dosage of SR into the fresh concrete which produces the integral SR treatment concrete (C-ISR) (Tian, et al., 2019). Also, surface impregnation is an efficient way to prevent chloride ions from penetrating into the concrete. Thus, the service life of the reinforced concrete structure in the seashore area or aggressive environment can be prolonged noticeably. Furthermore, calcium stearate (CS) is a waterproofing admixture that can give a water repellent layer along with the capillary pores of the concrete, and thus reduce the concrete’s permeability under non-hydrostatic situation (Chari, Naseroleslami and Shekarchi, 2019). Among the available water repellent agents, CS has been widely adopted in recent researches to reduce the permeability of various kinds of concrete. Moreover, potassium trimethylsilanolate (PT) is also one of the water repellent agents, but this PT is rarely implemented in the construction industry. Therefore, this study will discuss the impact of various types of water repellent agent on concrete engineering performance.

1.2 Importance of the Study

Concrete is an inevitable material used in the construction industry that falls under the category of porous building materials. Thus, when concrete comes into contact with the fluid such as water, water is absorbed into the pores of concrete by capillary forces (Vries, 1997). Moreover, the penetration of chloride ions into the concrete through the capillary pores of concrete has affected the durability and compressive strength of concrete significantly. As a result, water repellent agent or also known as the water-resistant agent is developed to counter the water absorption and penetration of chloride ions through the pores.

There are various types of water repellent agents available in the construction industry since a very long time ago, for instance, calcium stearate, silane and siloxane. However, enormous attention is being paid in recent years to silicon resin (Tian, et al., 2019). According to Zhu, et al. (2020), a new water repellent additive called YREC was developed by mixing polydimethylsiloxane and silane coupling agent (KH550) with mica powder. Besides, concrete treated with four types of metal soaps will be discussed in detail as well. Concrete, no matter heavyweight, normal weight or lightweight, there definitely exist the pores on its surface. Out of the three types of concrete, lightweight concrete is considered to have the highest number of capillary pores due to the high porosity of lightweight aggregate, which leads to a low apparent specific gravity (Neville, 2002). It is not exaggerated to say that various types of water repellent agent can offer various types of concrete with good performance in terms of durability and permeability. In this contribution, it will provide future researchers regarding the knowledge of the summary of potential different types of water repellent agent towards the concrete in terms of durability, compressive strength, cracking resistance, sorptivity and hygroscopicity.

1.3 Problem Statement

Today, because of the aggressive environment is getting wider in the construction field, water repellent agent or damp-proofing admixture is getting more prominent throughout the construction sector. Water repellent agent is very essential for concrete due to the porous structure of concrete will attract unwanted water and aqueous salt solutions, for instance, water containing chloride or sulphate ions (Li, et al., 2012). In this study, the absorption of water and the penetration of chloride ions into the concrete will be discussed in detail.

In addition, there is a challenge encountered during the application of the water repellent agent. Firstly, it is confusing that researchers out there about what types of water repellent agents are best suited to the concrete used. Furthermore, water repellent agent is not merely good for reduction of water absorption and chloride penetration, but also improve the service life of the reinforced concrete structure, especially in the marine environment. By doing so, it will indirectly save lots of maintenance cost, such as repairing the cracking of concrete. Moreover, there are some disadvantages to applying the damp-proofing agent into the concrete. The disadvantages, for instance, reduce the compressive strength of hardened concrete and decrease the workability of fresh concrete regardless of the water-to-cement ratio. These disadvantages could be ignored for structures without high strength requirements (Chari, Naseroleslami and Shekarchi, 2019). Based on the researches, it is no specific research to state the summary of various types of water repellent agent towards the various types of concrete. In this study, therefore, findings stated that water repellent agent is very beneficial to adopt in concrete for enhancing the concrete engineering performance. Hence, the impacts of various types of water repellent agent on various types of lightweight concrete are studied.

1.4 Aim and Objectives

This study aims to investigate the impact of various types of water repellent agent on the various types of lightweight concrete in terms of engineering performance.

To attain the aim, there are several objectives need to be achieved and listed as follows:

1. To identify types of water repellent agent used in the current construction industry.
2. To investigate the performance of concrete attributed by the use of various types of water repellent agent.
3. To analyse the most effective water repellent agent towards the concrete engineering performance.

1.5 Scope and Limitation of the Study

This study is carried out to investigate the various types of water repellent agent towards the engineering performance of various types of lightweight concrete. The engineering performance includes compressive strength, flexural strength, thermal properties, durability, cracking resistance, sorptivity and hygroscopicity. Lightweight aggregate concrete, foamed concrete and autoclaved aerated concrete (AAC) belong to the category of lightweight concrete. The engineering performance of these three types of lightweight concrete with the use of various types of water repellent agent will be studied.

To carry out the research, several limitations need to be justified. First of all, the water repellent agents adopted in this study are calcium stearate, zinc stearate, sodium oleate, silane emulsion and siloxane emulsion. Besides, there are two methods of applying the water repellent agent, which are the integral treatment of concrete and surface treatment of concrete. The integral treatment of concrete is prepared by adding the desired dosage of water repellent admixture into the fresh concrete. In contrast, surface treatment of concrete is made by surface impregnation with the desired dosage of water repellent admixture.

1.6 Contribution of the Study

The outcome of this research is to make use of an effective water repellent agent towards lightweight concrete and improve the durability of lightweight concrete by reducing the absorption amount of undesired water. Thus, the water repellent agent can contribute to the construction sector by maintaining the original compressive strength of lightweight concrete. This can help the construction sector to adopt lightweight concrete to build structures without high strength requirements at a safe margin throughout the design life.

1.7 Outline of the Report

This report includes a total number of 5 chapters.

Chapter 1 covers the general introduction, importance of the study, problem statement, aim and objectives, scope and limitation and contribution of the study.

Chapter 2 covers a series of literature reviews, which contains the previous researches on the applications of water repellent agent and their impact on lightweight concrete.

Chapter 3 is the methodology, which outlines the approach and process of analysis with the aid of a flowchart. The approach adopted, for instance, SWOT analysis was elaborated and discussed.

Chapter 4 is the results and discussion, which consists of the data analysis from concrete engineering properties. In this chapter, a thorough discussion was carried out by comparing how the water repellent agent affecting lightweight concrete properties. The properties include compressive strength and water absorption.

Chapter 5 concludes the whole study of this research. The conclusions were attained with the help of various information and according to the corresponding objectives. This chapter has also provided some recommendations for future exploration.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is said to be durable when the concrete structure unceasing to perform its intended functions. The functions include providing the required level of serviceability and safety for the design life of the strength in a given environment. Such an environment can be defined as the place where reinforced concrete (RC) is subjected to severe condition, that is the penetration of aggressive ions, especially chloride and sulphate ions. Therefore, with the aid of the water repellent agent used in RC, the ingression of aggressive ions can be diminished to a large scale (Xian, et al., 2007). All the penetration of liquids or gases into concrete can be related to the permeability of concrete. Permeability is in the sense of fluids flow through the porous medium in concrete. The transportation of fluids is highly dependent on the microstructure of the hydrated cement paste. The interface zone between cement paste and the aggregate contributes to the permeability of concrete. Despite the interface zone has a higher porosity, the permeability of concrete is still dominated by the bulk of hardened cement paste, which is the only continuous phase in concrete. The pores related to permeability have to be continuous with a diameter of at least 120 to 160 nm (Neville and Brooks, 2010).

Journals on lightweight concrete with the use of water repellent agents (WRA) are reviewed to investigate the characteristics of WRA toward the concrete engineering performance. Besides, reviewing other researchers' work is essential because it does serve as a benchmark on the results trend.

2.2 Lightweight Concrete

Lightweight concrete is manufactured with lightweight coarse aggregates, fine aggregates, cement, water, and sand. It can be categorised into two different types, either structural or non-structural lightweight concrete. It is also easy to classify the different types of lightweight concrete based on their different method of manufacturing. Lightweight aggregate concrete where it is produced by using lightweight porous aggregate with a specific gravity of less than 2.6 to replace the normal coarse aggregate in concrete. Aerated or foamed concrete is produced by introducing large voids within the mortar or concrete mix. These voids should be distinguished clearly against the very fine voids generated by air-entraining admixture. No-fines concrete where the fine aggregate from the mix is omitted. Thus, the concrete contains lots of interstitial voids due to only coarse aggregate is adopted. Besides, there are three various lightweight concrete type divisions in terms of strength and density range, which are low-density concrete, moderate-strength concrete, and structural concrete. First of all, low-density concrete is mainly used for insulation purposes. The thermal insulation is high with low unit weight that is smaller than 800 kg/m^3. Also, the compressive strength is low as in the range of 0.69 to 6.89 N/mm^2. Besides, the moderate-strength concrete is adopted with the compressive strength of 6.89 to 17.24 N/mm^2 which is fell about midway between the low density and structural concrete. Structural concrete is concrete with full structural efficiency which is typically manufactured with expanded shale, fly ash, slag, clay and slates. The minimum compressive strength is 17.24 N/mm^2. Nevertheless, most structural concrete can produce concrete with the compressive strength that is exceeding 34.47 N/mm^2. The thermal insulation efficiency is the lowest for structural concrete followed by moderate-strength concrete and low-density concrete (Mishra, 2018).

Furthermore, three types of lightweight concrete will be discussed explicitly with the use of the water repellent agent. First of all, is the lightweight aggregate concrete (LAC) followed by lightweight foamed concrete (LFC), and the last type is cement mortar. However, a brief introduction for autoclaved aerated concrete (AAC) due to hardly any journals are talking about the AAC incorporated with water repellent agent.

2.2.1 Lightweight Aggregate Concrete

The typical density for lightweight aggregate concrete (LAC) is 1400 to 1900 kg/m^3 (Neville, 2002). It can be produced by using a variety of lightweight aggregates. The lightweight aggregate is used to fully replaced the normal weight aggregate to have a low self-weight of concrete. The casting process of lightweight aggregate concrete remains unchanged as the casting of normal weight concrete. The only difference is the desired volume fraction of lightweight aggregates used. Lightweight aggregates can be obtained from various sources, whether it is natural or artificial, as shown in Figure 2.1. Figure 2.2 shows the spectrum of lightweight aggregates which categorised into three different classes based on the air-dry unit weight of the lightweight aggregate concrete.

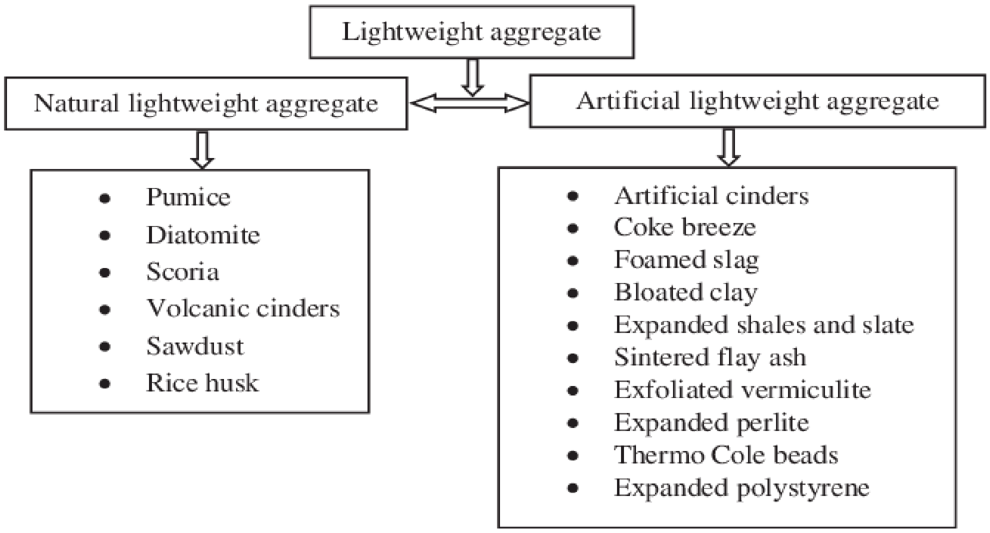


Figure 2.1: Natural and Artificial Lightweight Aggregates Used in Lightweight Concrete (Vakhshouri and Nejadi, 2017).

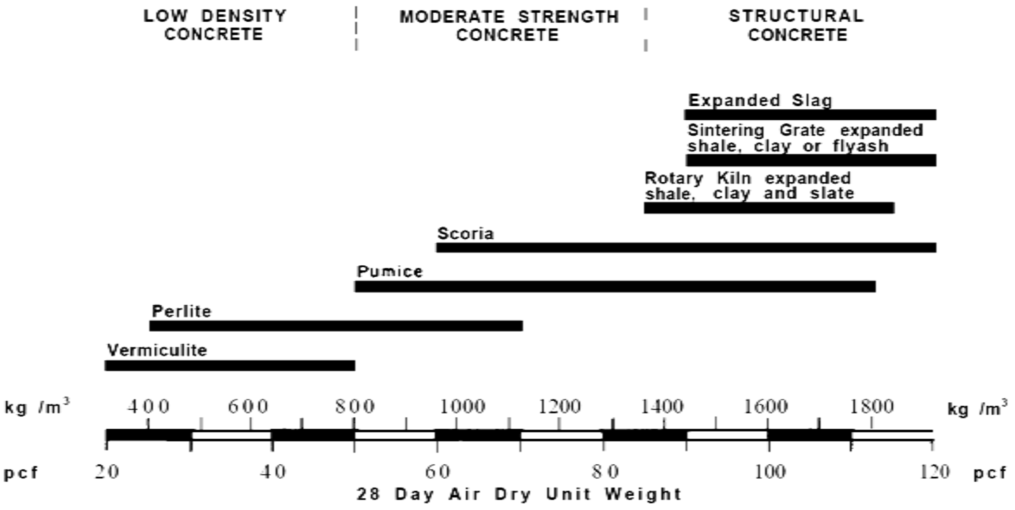


Figure 2.2: Spectrum of Lightweight Aggregates (ACI, 2001).

There are many advantages of using lightweight aggregate concrete. The utmost benefit is the reduction of overall dead loads, and thus cut down the foundation cost and steel reinforcement. Furthermore, it enhances the thermal properties as well as fire resistance of the reinforced concrete structure. In Malaysia, the common use of lightweight aggregate is the artificial type because the natural lightweight aggregate is generally derived from natural rocks, primarily those of volcanic origin. Therefore, the artificial lightweight aggregate is more suitable to be used in Malaysia due to Malaysia is not a volcanic oriented region. Several artificial lightweight aggregates, for instance, expanded clay, expanded shale, expanded slate, expanded polystyrene, sintered fly ash and foamed slag. Also, the Lightherm, which is a Singapore product and also certified by CIDB Malaysia. Lightherm is the superlight aggregates for the preparation of lightweight insulation aggregate concrete. There are three key features of Lightherm; first is the ultra-lightweight with density of 250 kg/m^3; second is the high thermal insulation with the value of 0.067 W/m K; the third feature is acoustic insulation with the capability of 14 dB reduction. For preparing the lightherm screed of 250 kg/m^3, no sand is required and it only involves the materials of Lightherm, cement and water. When applying Lightherm as aggregate for the building, the Lightherm lightweight building can sustain earthquake resistance and at least 25 % less piling works are needed as compared to conventional normal weight building (Vodapruf Pte Ltd, 2018).

Besides, there are some applications of lightweight aggregate concrete. First of all, LAC is easy to be used for screeding and thickening when the slab or floor needs smoothing or thickening. LAC can be adopted for casting structural steel to have a better anti-corrosion and fire-resistant. Furthermore, LAC can be adopted for insulating the water pipes. LAC can also be used for installing partition and panel walls in the frame structures. Also, LAC can be used for obtaining surface rendered for external walls of small houses. If LAC panels are installed throughout the house, the room inside will not get too hot due to LAC has good thermal insulation characteristics.

Based on the research from Maghfouri, et al. (2017) showed that crushed oil palm shell (COPS) used as a lightweight aggregate in the concrete mix would provide higher compressive strength, which can be used as structural concrete. However, incorporating COPS in concrete mix will result in high water absorption of concrete due to a more porous structure of COPS are used. Therefore, the water absorption test is required to assess the quality of concrete. Results showed that COPS concrete had a high initial and final water absorption rate, hence it is not categorised as functional and durable concrete.

2.2.2 Lightweight Foamed Concrete

Lightweight foamed concrete (LFC) is manufactured from cement, sand, water and foam. LFC can be defined as a cementitious material where a minimum of 20% of foam (per volume) has to be entrained into the plastic mortar. LFC has the dry density in the range of 400 to 1600 kg/m^3 and compressive strength tested at 28 days may vary from 1 MPa to 15 MPa. Moreover, LFC can be placed easily by pumping through the pumping hose due to its highly flowable trait (The Concrete Institute, 2016).

On top of that, Yuvaraj, et al. (2015) had compiled a list of advantages of LFC. It is well known that the most apparent benefit of LFC is the reduction of overall building weight. Therefore, it saves the total cost for less building materials. Furthermore, LFC has high workability and high flowability. LFC slurry can fill up the confined space of formwork, which can indirectly enhance the compressive strength of that casted structural member. Also, LFC is known as self-compacting or self-consolidating concrete (SCC); therefore, compaction and vibration of LFC during casting are not required.

Besides, the presence of air voids in the LFC will improve the thermal insulation of the LFC. Therefore, air voids make the LFC possess the utmost fire resistance properties, among other types of concrete. This is mainly because the thermal conductivity of air is lower than liquid and then followed by solid (Mydin, 2011). According to Park, Seo and Lee (2005), these researchers claimed that the porous structure of concrete at the void ratio of 25 % was best for sound absorption, and thus, LFC is a good sound insulator. Lastly, the porous nature of LFC functions as an expansion room for allowing the expansion of water to resist the freeze-thaw cycles during cold weather applications.

2.2.3 Cement Mortar

Cement mortar is generally referred to Portland cement mortar. The cement mortar is produced by mixing Portland cement with sand and water. Falchi, et al. (2015) incorporated calcium stearate (CS) into Portland limestone cement mortars. The compressive strength of control mortar and mortar incorporated with CS was respective 11.1 MPa and 10.4 MPa. The results indicated that the compressive strength of CS mortar was about 6.3 % lower than that of control mortar. This may be attributed to a higher cumulative pore volume which will cause the compressive strength of CS mortar to decrease to a certain extent.

Moreover, in the water absorption test carried out by Falchi, et al. (2015), CS had proven that it was good in reducing the water absorption of cement mortar. The results showed the capillary water absorption coefficient for control mortar and CS mortar was 1.77 $kg/m^2h^{0.5}$ and 0.48 $kg/m^2h^{0.5}$, respectively. This provides clear evidence that CS can reduce the water absorption of cement mortar by about 72.8 %. Furthermore, more review for the impact of WRA on cement mortar would be discussed in section 2.7.

2.2.4 Autoclaved Aerated Concrete

Autoclaved aerated concrete (AAC) or also known as autoclaved cellular concrete is a typical lightweight precast building material. AAC is manufactured by mixing raw materials such as cement, pulverised fuel ash or sand, anhydrite, lime, aluminium powder and water (Wehrhahn, 1892). With one single wall panel of AAC, it provides structural characteristics, thermal insulation and fire resistance. The properties of AAC rely on its microstructure of the void-paste system and composition. Besides, one of the AAC benefits in the construction site is easy and quick installation work. This is mainly because the material can be cut to the desired size on-site by using the standard carbon steel band saws (Neville, 2002).

However, there is hardly any research on AAC incorporated with water repellent agents. This might be due to the manufacturing process of AAC requires strict guidance with fixed mix proportion recommended by Wehrhahn, a German technology. Therefore, no trial mix with the water repellent agent is implemented due to the high cost of producing one AAC (BFT International, 2011). AAC production is a high-cost process because it is a full automation process, where it requires Wehrhahn technicians, IT specialists and automation engineers to connect all the machines to operate. A programmable logic controller is adopted in the Wehrhahn technique for ensuring the compliance of the highest standards of efficiency, functionality and safety (Wehrhahn, 1892). Furthermore, AAC nowadays is only installed as an interior wall, but not an exterior wall due to the highly porous structure of AAC.

2.3 Waterproofing Method

The aim of waterproofing a concrete is to reduce the water absorption rate of concrete. Besides, waterproofing is also used for inhibiting the penetration of water that contains aggressive ions such as chloride. Several methods can be adopted to make the damp-proofing concrete, for instance, the surface impregnation and the integral mixing of concrete (Muhammad, et al., 2015).

Surface impregnation of concrete is referred to as the external surface coating. This coating can be done by brushing, spraying or soaking the concrete with water repellent agents, for instance, calcium stearate, zinc stearate, sodium oleate, silane, siloxane, ethyl silicate and silicon-resin. For the concrete to be thoroughly protected from the ingress of water or chloride ions, at least two layers of coating are recommended to attain the average thickness of 0.2 mm per coat (Jones, Dhir and Gill, 1995). The surface impregnation method can reduce the surface porosity, with nearly total pores filling effect as well as generate a continuous protective film on the surface of concrete, which makes the concrete surface hydrophobic (Franzoni, Pigino and Pistolesi, 2013).

In addition, the integral mixing of concrete is to mix the water repellent agent with the fresh concrete. It is essential to ensure the waterproofing admixtures are dispersed throughout the concrete mix. Thus, this mixing will make the concrete become hydrophobic no matter internal or external concrete. Typical water repellent agents used are silicon, stearates and oleates (Kebao and Douglas, 2012).

2.4 Water Repellent Agent

Various types of construction materials can be adopted as water repellent agents (WRA), for instance, calcium stearate, zinc stearate, sodium oleate, silane emulsion and siloxane emulsion. Water repellent admixture is incorporated into the concrete mix to restrict the mobility of water in the hardened concrete (Ramachandran, 1995).

Besides, the application of waterproofing admixture will not block the capillary pores from taking up the water for hydration of the cement process. On the contrary, a hydrophobic layer formed on the walls of capillary pores and hence prevents capillary absorption of fluids. A piece of goniometer equipment is adopted to measure the degree of hydrophobicity of treated hardened concrete. This method is carried out by dropping water onto the concrete surface and then measure the sessile drop contact angle (θ). In general, the concrete surface with a contact angle greater than 90° is considered hydrophobic concrete. If the contact angle larger than 150°, the concrete is said to be superhydrophobic (Anderson and Carroll, 2011).

2.4.1 Calcium Stearate

Calcium stearate (CS) is one of the chosen water repellent agents that will be used in this study. It is manufactured by Sigma-Aldrich Corporation with an assay indicating 6.6 % to 7.4 % calcium basis. The density of CS is 1080 kg/m^3 with a very fine white powder form. The CS generated contains some impurities which are lead and stearic acid with a respective concentration below 0.004 % and 0.3 %. Furthermore, the loss on drying is less than 3 % under the temperature of 105 °C for 3 hours. Anion traces such as chloride and sulphate are also found in CS with the respective concentration of less than 200 mg/kg and 1000 mg/kg. Besides, there is no additional preparation required for the CS because it is kept inside its packaging container (Leong, 2019).

2.4.2 Zinc Stearate

Zinc stearate is a white, hydrophobic powder that is insoluble in water. In contrast, zinc stearate is soluble in hot ethyl alcohol, benzene, turpentine and other organic solvents. The molecular weight and density of zinc stearate are 632.33 g/mol and 1100 kg/m^3 respectively (PubChem, 2005). The particle size of zinc stearate is very small in which the diameter can be smaller than 1 µm. Thus, it has a high specific surface area of 25000 cm^2/g (Lower, 1982). Furthermore, the characteristics of prepared zinc stearate is shown in Table 2.1.

Table 2.1: Characteristics of Zinc Stearate (Helaly, et al., 2011).

Appearance	Soft, white powder
Moisture, %	0.2
Ash, %	14.2
Free Fatty Acid, %	0.87
Melting point, °C	125
Solubility:	
In water	Insoluble
In alcohol, ether	Insoluble
In benzene	Slightly soluble

2.4.3 Sodium Oleate

Sodium oleate has a density of 900 kg/m^3. Sodium oleate is a reactive hydrophobic agent. Because the sodium oleate contains too much of unsaturated fatty acids, thus it shows no gelling effect. Therefore, sodium oleate is easy to be soluble in cold water. As compared to the metal stearates such as calcium stearate, sodium oleate exhibits a higher bulk density and can be manufactured in a coarse structure. Furthermore, the main important part to obtain a good quality of sodium oleate is the carbon-chain (C-chain) distribution. The neat oleic acid contains a high amount of monounsaturated C18 acid. Moreover, the polyunsaturated acid shows the long-term stability is less as well as less hydrophobicity. Therefore, the C-chain distribution must have high consistency (Stolz, 2009).

2.4.4 Silane

Silane requires a high pH to catalyse. Silane is made up of smaller molecules as compared to siloxane. Therefore, silane performs well under the situation of weathering and abrasion because silane can penetrate deeper as compared to siloxane. However, the disadvantage of using silane is relatively volatile due to its smaller molecular size. As a result, the content of silane should be sufficiently large during the application process to compensate for the loss of reactive materials by evaporation. Silane is very essential for the concrete surfaces that are subjected to abrasive wear, for instance, pavement and deck, which can prolong their service life. Furthermore, silane is a covalently bonded compound that contains silicon and hydrogen only. The silane is structurally unstable which consists of saturated hydrocarbons. Therefore, the unstable silane is readily replaced by other atoms, such as tetrachlorosilane, $SiCl_4$ (Concrete Construction Staff, 1995).

2.4.5 Siloxane

Siloxane is independent of the substrate pH. Siloxane is suitable for treating the brick, stone and stucco. Also, siloxane is less volatile and generally provides a good water repellent performance as compared to silane. Siloxane has a lower initial cost than silane. Siloxane usually darkens the treated surface. Furthermore, siloxane molecules rotate freely around the Si-O bond. The siloxane can still manage to rotate randomly with methyl, phenyl or vinyl groups attached to the silicon atoms. Thus, the molecule is said to be flexible. Besides, the Si-O bond is good in resistance to heat and hence, the bond is not easily attacked by oxygen. Therefore, siloxane is extremely stable and has a lower glass-transition temperature (the temperature where the molecules are fixed in a glassy and rigid state). Also, siloxane possesses higher permeability relative to other polymers. In summary, siloxane is suitable to be adopted in concrete due to its high permeability and other relevant factors (Concrete Construction Staff, 1995).

2.5 Effect of Various Types of Water Repellent Agent on the Lightweight Aggregate Concrete

Yu, Spiesz and Brouwers (2013) reported that the lightweight aggregate concrete (LAC) mix with the expanded glass would reach the final strength at seven days. The expanded glass is a lightweight aggregate that is produced from recycled glass. Due to the weakness of expanded glass, the 28 days compressive strength was similar to the 7 days of compressive strength even though the hydration process still ongoing after 7 days. Furthermore, the elastic modulus of the matrix, the effective water-to-binder ratio, the type of aggregates used and the cement volume would affect the elastic modulus of the lightweight aggregate concrete. Figure 2.3 shows the relationship between elastic modulus and the 28 days compressive strength of the concrete mixes by adopting various aggregates (Chandra and Berntsson, 2002).

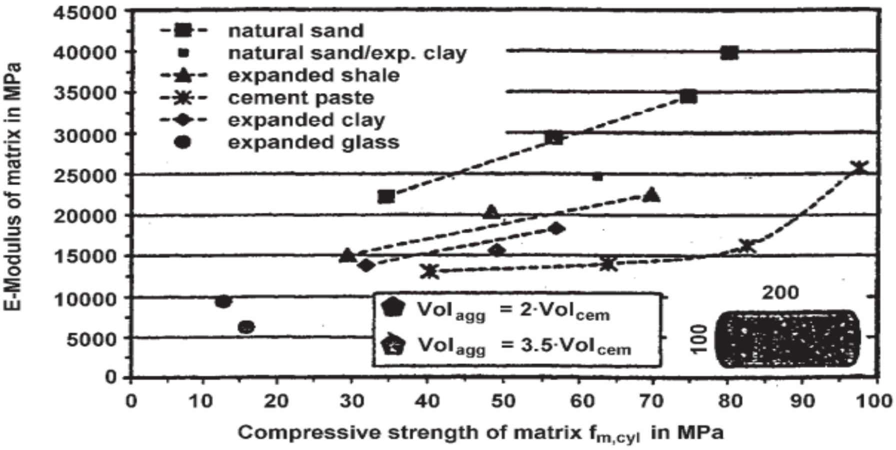


Figure 2.3: Relationship between E-modulus and compressive strength of different lightweight aggregates (Chandra and Berntsson, 2002).

Yu, Glas and Brouwers (2020) adopted the naturally expanded silicate (NES) materials as lightweight aggregate incorporated in the concrete. NES aggregates were treated with silane emulsion (hydrophobic agent) before use. These researchers did several tests such as fresh behaviour, microstructure pattern, mechanical properties, water penetration under pressure, freeze-thaw resistance and drying shrinkage. Some parts are only highlighted in this context. First of all, the 28 days compressive strength for 1000 kg/m^3, 1150 kg/m^3 and 1400 kg/m^3 concrete mixes are 23 MPa, 28 MPa and 43 MPa respectively. Besides water penetration under 5 bars of water pressure, a concrete mix of 1150 kg/m^3 had the highest permeability of water, with an average of 5.5 mm of water penetration. However, 1400 kg/m^3 concrete mix exhibited the lowest average penetration of water depth of 2.1 mm, while for the 1000 kg/m^3 concrete mix showed the penetration depth of 4.1 mm. According to Brouwers and Radix (2005), smaller than 50 mm depth of water penetration is considered impermeable concrete. Therefore, all the mixes developed by Yu, Glas and Brouwers (2020) were waterproof concrete.

Záleská, et al. (2019) paved the way for the waste plastic aggregate mix with water repellent additive. In their research, crushed waste expanded polypropylene (EPP) aggregates were thoroughly used to replace the natural silica sand in producing the lightweight magnesium oxychloride (MOC) cement. Several tests had been conducted, such as structural properties, strength parameters, water transport properties, thermal conductivity and volumetric heat capacity. Moreover, EPP was incorporated in MOC cement composite and then treated with surface impregnation method as well as integral hydrophobic treatment. Also, the water repellent admixtures used by Záleská, et al. (2019) were calcium stearate and sodium oleate. Both admixtures were added into the magnesium oxychloride cement that contains expanded polypropylene (EPP-MOC) as lightweight aggregate. Furthermore, 100 g of MgO powder required the amount of 1 gram of calcium stearate and 2 grams of sodium oleate. In general, various incorporated additives in the MOC cement would lead to compressive strength to decrease (Zgueb, Brichni and Yacoubi, 2018). Results showed that the compressive strength of EPP-MOC treated with the integral mixing of the hydrophobic agent (EPP-MOC-IH) and EPP-MOC was 7.6 MPa and 6.3 MPa respectively. As for the water absorption test, it showed that the EPP-MOC treated with surface impregnation of the hydrophobic agent (EPP-MOC-LO) was $0.0007 \pm 2 \times 10^{-5}$ $kg/m^2s^{1/2}$, while EPP-MOC-IH was $0.0014 \pm 3 \times 10^{-5}$ $kg/m^2s^{1/2}$. Moreover, thermal conductivity for EPP-MOC and EPP-MOC-IH was respective 0.34 W/mK and 0.35 W/mK. While the MOC incorporated with natural silica sand sample (R-MOC) was 2.09 W/mK. Therefore, the substantial reduction in the thermal conductivity for EPP-MOC and EPP-MOC-IH were respective 83.7% and 83.3% as compared to R-MOC.

Zhu, et al. (2013) analysed the effect of siloxane emulsion on the compressive strength, water absorption, chloride penetration and carbonation of lightweight recycled aggregate concrete. The recycled aggregates are derived from demolition and construction wastes. Several tests were conducted by Zhu, et al. (2013) such as compressive strength, capillary water absorption, chloride penetration and carbonation. For the compressive strength, 100 % recycled aggregate concrete (RAC) as a control mix had greater compressive strength. When the amount of siloxane in RAC increases, the 28 days compressive strength will reduce noticeably. For RAC incorporated with 0.5 % silane by cement weight (RAC-0.5) and RAC-1.0, the respective compressive strength was 38 % and 20 % lower than the control mix. This might be due to the reaction of silanol groups that could bind to the aggregates and made the surface become hydrophobic (Spaeth, Delplancke-Ogletree and Lecomte, 2008).

Furthermore, the capillary water absorption of concrete was measured at 96 hours of immersion in water. The results showed surface siloxane treatment with 100 g/m^2 and 200 g/m^2 of siloxane paste were reduced by 95 % and 96 % respectively as compared with the control mix. Besides, the water absorption coefficient for RAC-0.5 and RAC-1.0 was decreased by 61 % and 72 % respectively. This capillary water absorption trend same goes for the chloride penetration test. Therefore, it is noted that the surface siloxane treatment is more effective than integral siloxane treatment in repelling the water (Wittmann, et al., 2008). This is due to the porosity of RAC was larger, which led to the silane could penetrate deeper into the RAC. Thus, the protection of concrete against the water and chloride usually increases as the impregnation agent can penetrate deeper (Hankvist and Karlsson, 2001).

According to Qu and Yu (2018), a method of ball milling is adopted to prepare the hydrophobic ground granulated blast furnace slag (H-GGBFS) powder. This method is done by milling the alumina balls with the addition of stearic acid and GGBFS. Furthermore, four different sizes of naturally expanded silicate are served as lightweight aggregates that range from 0.09 mm to 4 mm. H-GGBFS is then added to the lightweight concrete mix to produce hydrophobic concrete. Based on the results from Qu and Yu (2018), the optimum stearic acid required is 1% based on the total weight of the concrete mix. With the optimum amount of 15 %, superhydrophobic GGBFS is added, showing a water contact angle of 92°. This contact angle showed that the designed lightweight aggregate concrete possesses excellent hydrophobic characteristics. Besides, the addition of 15 % of superhydrophobic slag also contributes to improved durability. This optimum amount also reduces the capillary water absorption rate and chloride penetration up to 90%.

Based on the research from Dai, et al. (2008), cracked reinforced concrete was investigated for chloride penetration. When treating existing cracks on the concrete surface, the silane-based gel was proven to be superior to liquid silane as a water repellent agent. Because it is found that silane-based gel can penetrate into concrete up to 25 mm, while liquid silane is only 4 mm.

Therefore, only the silane-based gel was chosen for the chloride penetration test. After treating the silane-based gel onto the concrete, the results showed that the depth of chloride ingress into the concrete was only 8 mm when the crack width was 0.13 mm. For the crack widths ranging from 0.13 mm to 0.17 mm, the silane-based gel yet appeared to be the most effective in reducing the water absorption, chloride ingress and thus prevent rebar from corroding. However, no results are done by Dai, et al. (2008) for the crack widths from 0.14 mm to 0.17 mm.

2.6 Effect of Various Types of Water Repellent Agent on the Lightweight Foamed Concrete

According to Ma and Chen (2016), the water repellents used in their study are siloxane-based polymer (SP), calcium stearate (CS) and potassium trimethylsilanolate (PT). Ma and Chen (2016) had tested for compressive strength, thermal conductivity, sorptivity and hygroscopicity for respective 7 days and 28 days. Results showed that the optimum dosage of water repellent is 1.0 wt% regardless of CS, SP or PT used. SP showed the highest 28 days compressive strength of 1.77 MPa that incorporated in the lightweight foamed concrete (LFC) as compared to the same amount of CS and PT added into the respective specimen. The thermal conductivity with 1 % of SP, CS and PT were respective 0.150 W/m K, 0.159 W/m K, 0.154 W/m K. This might be due to the calcium and potassium are alkaline metals that good in conductivity. Therefore, the incorporation of SP in LFC has an excellent insulation property.

Furthermore, the sorptivity of LFC is assessed after 48 hours of soaking through the water absorption and strength retention coefficient (R_S). SP also exhibited the lowest 48-hour water absorption with the value of 2.5 % (by volume) as compared to 3.6 % of LFC without waterproofing admixture. Besides, the incorporation of SP has the most impressive effect on R_S that equals to 0.989 with 1 % SP. The last type of test is the hygroscopic moisture test, $W(\phi)$. As for CS and PT contents rising from 0.2 % to 1.2 %, the foamed concrete showed a gradually decreasing trend in $W(\phi)$, however for the SP case was only slight differences. Based on the four tests from Ma and Chen (2016), the optimum amount of water repellent is 1.0% for SP, CS and PT. SP gives the best effect on all the tests and shows a more reliable water repellent in the construction industry.

In the recent research carried out by Liu, et al. (2019), incorporating 4 types of powdery water repellents (PWR) into the ultra-light foamed concrete (ULFC) was studied. After obtaining the best water repellent effect of the selected PWR, further study was conducted by using another two types of liquid water repellents (LWR). The PWR such as calcium stearate (CS), zinc stearate (ZS), redispersible latex powder (RDL) and polysiloxane (PS); while LWR includes hydrogenated silicone oil (HSO) and methyl polysiloxane resin (MPR). The tests included were compressive strength, water absorption and thermal conductivity. In the water absorption test, a silane coupling agent (KH550) was introduced into the concrete to boost LWR to make the waterproofing film more rigid. Results showed that ULFC incorporated with CS had the lowest water absorption with 23.6 wt% when conducted for 72 hours soaking time. Moreover, CS is more suitable for the manufacturing of waterproofing ULFC with the optimum dosage of 4 wt%. This 4 wt% dosage remained the compressive strength of ULFC. Because the strength loss coefficient tested had proven the ULFC mixed with 4 wt% of CS had the lowest strength loss coefficient of 0.01 as compared to ULFC doped with ZS, PS and RDL. To further test the waterproofing effect, two LWR was coated on the surface of respective ULFC treated with calcium stearate. Besides, the water absorption of ULFC treated by the surface coating method is more exceptional than the soaking method. The water absorption of ULFC treated with LWR can be proven by 72 hours of water absorption test as shown in Table 2.2. Therefore, it can be concluded that the water repellent effect of HSO is better than MPR.

Table 2.2: The Water Absorption of ULFC Treated with LWR at 72 Hours Soaking Time (Liu et al., 2019).

Concrete Sample	Water absorption at 72 hours, W_v (wt%)
CS_{CHK}	7.3
CS_{SHK}	4.4
CS_{CMK}	27.4
CS_{SMK}	10.8

Note: CS_{CHK} – ULFC-CS treated by Coating with HSO and KH550; CS_{SMK} – ULFC-CS treated by Soaking with MPR and KH550. Subscript C, S, H, M and K stand for coating, soaking, HSO, MPR and KH550 respectively.

In addition, the research done by Lee, et al. (2018) was carried out on the investigations of foamed concrete incorporated with calcium stearate (CS) as a water repellent admixture. The investigations included testing of compressive strength, water absorption, initial surface absorption test and sorptivity. Firstly, Lee, et al. (2018) did the trial mixes for various water-to-cement (w/c) ratio to determine the optimum w/c ratio without adding the CS. After that, the optimum w/c ratio continued applied in the later mix. Before adding CS into foamed concrete (FC), the FC would undergone several measurements such as flow table test, consistency, stability and compressive strength. Results proved that the optimum w/c ratio was 0.48 with an average compressive strength of 3.57 MPa. Furthermore, the w/c ratio of 0.48 mix was used as the reference mix for the subsequent samples containing CS. The doping of CS into the FC had reduced the compressive strength. At 28 days, the compressive strength of control mix, FC incorporated with 0.2 % CS (FC0.2) and FC incorporated with 0.4 % CS (FC0.4) were 5.41 MPa, 3.82 MPa and 3.57 MPa respectively. This might be due to less water absorbed into the FC0.2 and FC0.4, thus the hydration process to form C-S-H gel was retarded. For water absorption, initial surface absorption and sorptivity tests, CS proved the enhanced properties for the FC as the dosage increased from 0.2 % to 0.4 % of the cement weight. Nevertheless, 0.4 % dosage of CS was deemed to be overdosing due to FC0.4 had the lowest 28 days compressive strength among other mixes. Hence, calcium stearate with 0.2 % of the cement weight was best recommended by these researches.

According to Maryoto, et al. (2020), several tests such as compressive strength, water absorption, chloride ion infiltration and accelerated corrosion had been studied. Results showed the incorporation of calcium stearate (CS) with Portland cement and fly ash had reduced the compressive strength as compared to the control mix (without the CS). This might be due to the wax-like constituent was formed when CS reacted with cement and water. This composite had a weak bond as compared to the strong bond made by C-S-H gel. Hence, the wax-like constituent in the self-compacting concrete (SCC) decreased the compressive strength (Maryoto, Gan and Aylie, 2017). However, in the Maryoto, et al. (2020) study, calcium stearate at 1 kg/m^3 in SCC with 10 % fly ash can enhance the mechanical and physical properties. When 1 kg/m^3 of calcium stearate was used, the reduced compressive strength of SCC was not too significant as compared to the control mix.

2.7 Effect of Various Types of Water Repellent Agent on the Cement Mortar

Li, Yang and Yang (2019) analysed the effect of calcium stearate (CS) on the compressive strength and water sorptivity of the alkali-activated slag cement (AASC). For a given water-to-binder (w/b) ratio of 0.35, the compressive strength of AASC as a control mix was 81.5 MPa, while the AASC incorporated with 4 % and 8 % of CS by slag weight was 71 MPa and 55 MPa respectively. This proved that overdosing of CS would decrease the compressive strength of AASC. Furthermore, for a given w/b of 0.35, the water sorptivity for AASC without CS was 2.0×10^{-3} mm/s$^{1/2}$. Meanwhile, the ordinary Portland cement (OPC) mix had lower sorptivity, which was 0.9×10^{-3} mm/s$^{1/2}$. Thus, the water sorptivity of the OPC sample is lower than the AASC sample that can be proven by the research of Yang, et al. (2016). Nonetheless, for the AASC incorporated with CS of respective 4 % and 8 % dosage, the respective sorptivity was reduced to 4.0×10^{-4} mm/s$^{0.5}$ and 3.9×10^{-4} mm/s$^{0.5}$. In conclusion, Li, Yang and Yang (2019) recommended the optimum dosage of CS was 4 %.

Gong, et al. (2016) stated that the incorporation of vitrified microsphere (VM) in the mortar mix would decrease the compressive strength, dry density and thermal conductivity when the VM content increased. Two methods were applied in this research such as the surface coating on VM with the organosilicon hydrophobic agent (OHA) and integral blended OHA with cement. When VM content was 25 %, the compressive strength and dry density of mortar were 2.8 MPa and 663 kg/m^3 respectively. This downtrend was applied to the VM content of up to 55 %, where the compressive strength and dry density were 0.25 MPa and 312 kg/m^3 respectively. Besides, the results also showed that the contact angle of the untreated mortar, surface coating VM with OHA and blending OHA with cement were 0°, 81° and 123° respectively. Therefore, it is noted that the water absorption for blending OHA in the mortar was the lowest among all. Based on the testing results of water absorption, water seepage depth and water level decline, the blending OHA with cement was more effective than surface coating in terms of waterproofing performance of the mortar. Gong, et al. (2016) claimed that VM content of 40 % was optimum in terms of thermal insulation and impermeability.

Song, et al. (2019) had found a new technique about the surface coating for producing non-fluorinated and inexpensive superhydrophobic concrete. The water repellent agent used in this technique is a water-based stone protector (containing siloxane and silane). Figure 2.4 shows the schematics of the fabrication processes for superhydrophobic concrete. Results showed that a 3 mm thick coating is useful in anti-corrosion and anti-icing of reinforced concrete. Hence, this environmental-friendly and economical coating can be applied widely in the construction sector.

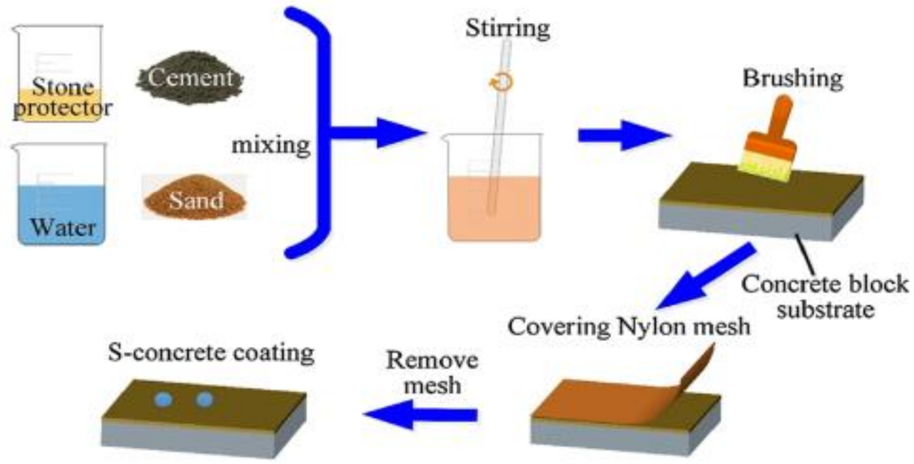


Figure 2.4: The Fabrication Processes of the Superhydrophobic Concrete Coating (Song, et al., 2019).

2.8 Summary

Lightweight aggregate concrete (LAC) is produced by a mixture of Portland cement, sand, water and lightweight aggregate. Besides, lightweight foamed concrete (LFC) is produced by a mixture of Portland cement, sand, water and preformed foam. Foamed concrete is formed by mechanically entraining foams into the plastic mortar during the mixing process. Both LAC and LFC are widely used nowadays because of their lightweight. This is attributed to lightweight will reduce the total dead loads of structure, and subsequently will save the total construction cost. Due to the highly porous structure of the LAC and LFC, water repellent admixtures are indeed required for both LAC and LFC to reduce the excessive amount of water absorption.

Furthermore, studies conducted on the performance of the water repellent admixtures toward LAC and LFC have been reviewed and discussed. Water repellents that will be used in this study are calcium stearate, zinc stearate, sodium oleate, silane and siloxane. Based on most researchers, the strength of concrete containing water repellent is said to be smaller than those without water repellent because of the hydrophobic behaviours that might retard the hydration of the cement process. Several tests would be conducted, such as compressive strength, water sorptivity, chloride penetration and thermal conductivity; these tests are used to evaluate and choose the best water repellent among all. Lastly, two methods of applying water repellent admixtures would be adopted, such as surface impregnation and integral mixing of concrete. Table 2.3 shows the summary of different types of concrete or mortar with varying water repellent agents.

Table 2.3: Summary of Different Types of Concrete or Mortar with Different Types of Water Repellent Agents.

Author	**Types of Concrete or Mortar Used**	**Types of Water Repellent Agent**	**Method: Integral Mixing or Surface Coating of Concrete**
Yu, Glas and Brouwers (2020)	LAC - Natural Expanded Silicate (NES)	Silane	Integral Mixing with the surface of NES treated with silane
Záleská, et al. (2019)	LAC - Crushed Waste Expanded Polypropylene (EPP)	Calcium Stearate and Sodium Oleate	Integral Mixing and Surface Coating
Zhu, et al. (2013)	LAC – Recycled Aggregates Derived from Demolition Wastes	Siloxane	Integral mixing and Surface Coating
Qu and Yu (2018)	LAC - Natural Expanded Silicate	Stearic Acid	Integral Mixing
Ma and Chen (2016)	LFC	Calcium Stearate (CS), Siloxane-Based Polymer (SP) and Potassium Trimethylsilanolate (PT)	Integral Mixing
Liu, et al. (2019)	LFC	Calcium Stearate (CS), Zinc Stearate (ZS), Polysiloxane (PS) and Redispersible Latex Powder (RDL); Methyl Polysiloxane Resin (MPR) and Hydrogenated Silicone Oil (HSO)	Integral Mixing

Table 2.3 (Continued)

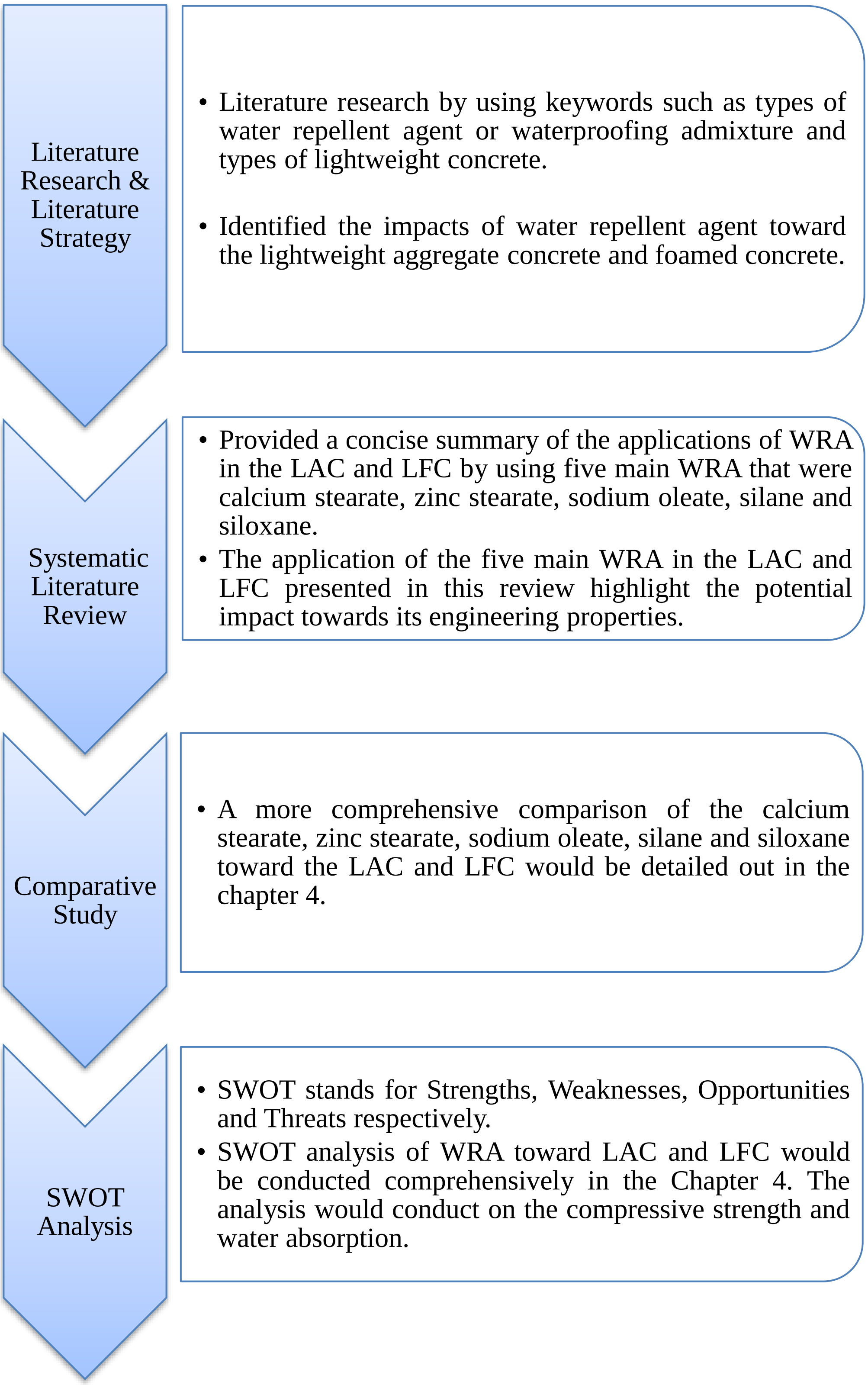
Lee, et al. (2018)	LFC	Calcium Stearate (CS)	Integral Mixing
Maryoto, et al. (2020)	LFC	Calcium Stearate (CS)	Integral Mixing
Li, Yang and Yang (2019)	Alkali-Activated Slag Cement (AASC)	Calcium Stearate (CS)	Integral Mixing
Gong, et al. (2016)	Cement Mortar with Vitrified Microsphere (VM)	Organosilicon Hydrophobic Agent (OHA)	Integral Mixing and Surface Coating
Dai, et al. (2008)	Cracked Reinforced Concrete	Silane	Surface Coating
Song, et al. (2019)	Ordinary Concrete Block	A Mixture of Stone Protector, Cement, Sand and Water	Surface Coating

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In Chapter 3, an analysis of the research methodology was undertaken. Furthermore, this chapter would describe the steps taken to conduct the systematic literature review; and also provides the bibliometric indicators which depict the body of literature being reviewed. This chapter would start with literature research then followed by research strategy. Besides, the data collection method would also be described. This study aims to evaluate the impact of various types of water repellent agent on lightweight concrete in terms of engineering properties. The water repellent agents (WRA) that would be focused on in this study were calcium stearate (CS), zinc stearate (ZS), sodium oleate (SO), silane and siloxane. Figure 3.1 shows the flowchart of the project work scope.



- Literature research by using keywords such as types of water repellent agent or waterproofing admixture and types of lightweight concrete.
- Identified the impacts of water repellent agent toward the lightweight aggregate concrete and foamed concrete.

- Provided a concise summary of the applications of WRA in the LAC and LFC by using five main WRA that were calcium stearate, zinc stearate, sodium oleate, silane and siloxane.
- The application of the five main WRA in the LAC and LFC presented in this review highlight the potential impact towards its engineering properties.

- A more comprehensive comparison of the calcium stearate, zinc stearate, sodium oleate, silane and siloxane toward the LAC and LFC would be detailed out in the chapter 4.

- SWOT stands for Strengths, Weaknesses, Opportunities and Threats respectively.
- SWOT analysis of WRA toward LAC and LFC would be conducted comprehensively in the Chapter 4. The analysis would conduct on the compressive strength and water absorption.

Figure 3.1: Flowchart of Project Work Scope.

3.2 Literature Research

For this study, the qualitative method had been adopted wherein an extensive review of research articles had been carried out. Furthermore, keywords such as types of water repellent agent or waterproofing admixture and types of lightweight concrete were used for journals and articles searching. The journals and articles reviewed in this study had been accumulated from reputed journals - Cement and Concrete Composites, Construction and Building Materials, Advances in Materials Science and Engineering, Restoration of Buildings and Monuments and Jurnal Teknologi. These reputed journals had provided an initial set of journals to start with the review. Besides, these journals and articles would promote other literature which was cited within the journals.

In the next step, the water repellent agent or also known as waterproofing admixture from each of the reviewed articles were taken up for further analysis in this study. However, some of the studies had identified the impacts of different types of water repellent agent on lightweight concrete. Yet, the top five water repellent agent from the reviewed journals were adopted for analysis. Besides that, the common impact on the concrete engineering properties due to the addition of water repellent agent was identified. The consequences were used to carry out the analysis in Chapter 4.

3.3 Research Strategy

The research plan was a step-by-step initiative that given guidance to thought and making efforts. It allows for the systematic and scheduled execution of the research to deliver consistent results and accurate reporting (Dinnen, 2014). Thus, it was essential to implement the research strategy to obtain data related to the topic chosen and more realistic data. The research strategy was crucial in conducting this research.

Besides, the primary data was used for research studies. The primary data such as articles, journals and websites had contributed a lot to carry out this study. The primary data were obtained easily through many sources like Google Scholar, Research Gate, Science Direct and Dissertation. Because the information obtained from these sources had proven and cited by the respective author. Also, the textbooks such as “Properties of Concrete” by Neville (2002), “Concrete Technology” by Neville and Brooks (2010) and “Lightweight Aggregate Concrete” by Chandra and Berntsson (2002) were used to search for the definition of lightweight concrete and the nature of lightweight concrete. There were a variety and reliable information that might be obtained through primary data. Many information and data were obtained from online sources. For instance, the primary data was useful when determining the problem statement, aim, objectives and literature review in this study. However, the online journals and articles might need to filter before referring to them as some of the information was outdated. Prior to select the primary data, the reliability and suitability of data must be concerned to obtain the most valuable data.

3.4 Systematic Literature Review

This section would provide a concise summary of the applications of WRA in the LAC and LFC by using five main WRA in the construction field. The five main WRA were calcium stearate, zinc stearate, sodium oleate, silane and siloxane. The application of the five main WRA in the LAC and LFC presented in this review highlight the potential impact on its engineering properties.

Besides, the products of LAC and LFC continuously interacting with the surrounding environment, which was why this review considered various aspects alongside the construction sector. In the future, if LAC and LFC become more common in the construction field, the WRA has the potential to be made cheaper, faster and more efficient. Other than that, the international scientific influence is an essential variable when evaluating the performance of research. By using the bibliometric indicators, the quantitative assessment assists with qualitative research. Also, the papers referred should be up-to-date, accurate, sophisticated that combined with expert knowledge.

Furthermore, the bibliometric analysis had given details on the research focus of the country as well as makes comparisons with other research communities at an international level. This study adopted the number of papers indicators that focus on the publication type and keywords, year of publication and country of authors. With these three indicators, all the related data were directly compiled from the referred papers. After that, the referred article was exported to Mendeley, a platform for the analysis of bibliographic data. As for the keyword analysis, the term lightweight concrete had the highest number of counts, followed by lightweight aggregate concrete or foamed concrete, water repellent and waterproofing admixture. As a result, the following section highlighted the SWOT of WRA incorporated in the LAC and LFC.

3.5 SWOT Analysis

SWOT stands for Strengths, Weaknesses, Opportunities and Threats, respectively. In general, the main objective of conducting the SWOT analysis was to study the positive and negative impacts of the internal and external environments on a company or individual life situations. The internal environment can be related to the strengths and weaknesses of the company or organisation. The external environment can be related to the opportunities and threats of the organisation (Madsen, 2016).

Strengths generally refer to the organisation that experts at which field or there is something that can be distinguished from other competitors. In general, if something brings the organisation an obvious advantage, then it only can be said as a strength. In this study, the organisation is referred to as the water-resistant lightweight concrete. The primary strength of the water-resistant lightweight concrete is less water absorption. For instance, if the water-resistant lightweight concrete is exposed to a seawater environment, then the water-resistant lightweight concrete is more durable than the normal lightweight concrete. Therefore, it requires less maintenance than other normal lightweight concrete. Because the absorbed water containing chloride ions will erode the steel reinforcement in the lightweight concrete.

Weaknesses typically refer to what the water-resistant lightweight concrete is short of. It requires being honest when conducting the weaknesses analysis. Therefore, any unpleasant truths of the water-resistant lightweight concrete can be known. Both strengths and weaknesses are the inherent aspects of the water-resistant lightweight concrete. The weakness, such as the lower compressive strength of the water-resistant lightweight concrete, needs to be focused on. The lower compressive strength of the water-resistant lightweight concrete requires to be compensated by adding the chemical admixtures to enhance the compressive strength to meet the market requirements. Most importantly, to compare the water-resistant lightweight concrete among other competitors about how to improve the compressive strength.

Opportunities are the chances or openings for something positive to occur, but the opportunities require to see how good is the water-resistant lightweight concrete. The opportunities are the external positive factor that might bring the prosperity of the water-resistant lightweight concrete. The opportunity, for instance, the need for affordable housing prices. Because the water-resistant lightweight concrete is lighter than other normal-weight concrete. Therefore, the building with water-resistant lightweight concrete panels will reduce the size of the rebar and foundation used, thereby reducing the overall construction cost. As a result, the developer can reduce housing prices to attract more people to buy.

Threats are something that can affect the overall performance of the water-resistant lightweight concrete from the external environment. The threats, for instance, the price of concrete increased due to the cost of raw materials increased and shifts in market requirements. It is essential to initiate the action to tackle the threat such as the price of cement and waterproofing admixtures increase. When the price of both materials is increased, it will cause the cost of manufacturing the water-resistant lightweight concrete to increase. However, to compete with other competitors, the selling price of water-resistant lightweight concrete should increase by surveying the up-to-date price. Because of the selling price of water-resistant lightweight concrete is too high, it will cause the buyers to buy from other competitors. Besides, always consider the quality standards and product specifications are good enough to compete with other competitors.

After examining all the four aspects of SWOT, the water-resistant lightweight concrete will encounter a long list of potential actions to undertake. The water-resistant lightweight concrete needs to build on the strengths, improve the weaknesses, impede any threats and make use of the opportunities to make the demand for water-resistant lightweight concrete is high in the future around the construction sector.

3.6 Summary

A total of 165 papers were obtained from the searches in three databases, for instance, Google Scholar, Research Gate and Science Direct. After removing the duplicates, implementing reviewing the abstracts and inclusion and exclusion criteria, 68 papers were chosen for review and study. Paper concerning the Autoclaved Aerated Concrete was not included in this review because less journal was pertaining to the AAC treated with water repellent agents. Lastly, a more comprehensive comparison of the calcium stearate, zinc stearate, sodium oleate, silane and siloxane toward the LAC and LFC was detailed in chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Types of Water Repellent Agent

There are 5 types of water repellent agent (WRA) used for studying in this report. For instance, calcium stearate, zinc stearate, sodium oleate, silane and siloxane. These 5 types of WRA were adopted in the lightweight concrete such as lightweight aggregate concrete (LAC) and lightweight foamed concrete (LFC). After that, to compare the engineering properties between the concrete with WRA and the concrete without WRA. The concrete engineering properties consist of compressive strength, water absorption and thermal conductivity. Hence, in this study, the impact of 5 types of WRA on the LAC and LFC in terms of the engineering properties are studied in detail.

4.2 Concrete Engineering Properties

Speaking about the inherent engineering properties of the lightweight concrete treated with water repellent agent undoubtedly would link to compressive strength, water absorption, thermal conductivity and acoustic insulation. However, in this study, only the compressive strength and water absorption are studied in detail together with the water repellent agent used. This is due to minimal literature discussing the impact of water repellent agents on lightweight concrete, but lots of normal weight concrete were studied by previous researchers.

4.3 Compressive Strength

The most significant impact of WRA on lightweight concrete would be the compressive strength. This is because WRA will restrict the movement of water to participate in the cement hydration process. Therefore, the impact of WRA on lightweight aggregate concrete and lightweight foamed concrete will be discussed in the following sections.

4.3.1 Compressive Strength of Lightweight Aggregate Concrete Treated with Various Water Repellent Agent

Based on the research done by García-Vera, et al. (2018), they adopted the integral mixing method to carry out the test. It showed that zinc stearate (ZS) was one of the best resistants toward the acid attack. This is because the mass loss of the zinc stearate mortar in the sulphuric acid exposure was the lowest one as compared to other mortars treated with different WRA. Furthermore, when the ZS mortar was undergone normal curing without any acid attack. In this case, the 28 days strength of the ZS mortar was 56.0 MPa, while the control mortar was 59.9 MPa. However, at 90 days of compressive strength, the ZS mortar showed a higher gaining in strength than the control mortar, which was respective 60.8 MPa and 60.2 MPa.

Furthermore, when ZS and control mortars were exposed to sulphuric acid, ZS mortar had a relatively small compressive strength variation from 28 to 90 days of strength. However, the control mortar had a significant compressive strength variation. The variation for ZS and control mortars was -8.4 % and -22 %, respectively, as shown in Figure 4.1. The negative signs indicated the compressive strength at 90 days was smaller than 28 days. The mortar's compressive strength would reduce for the situation as mentioned above was due to the migration of sulphate ions into the mortar, accompanied by the decomposition of calcium silicate hydrate (C-S-H) gel and gradual dissolution of Portlandite ($Ca(OH)_2$) (García-Vera, et al., 2018).

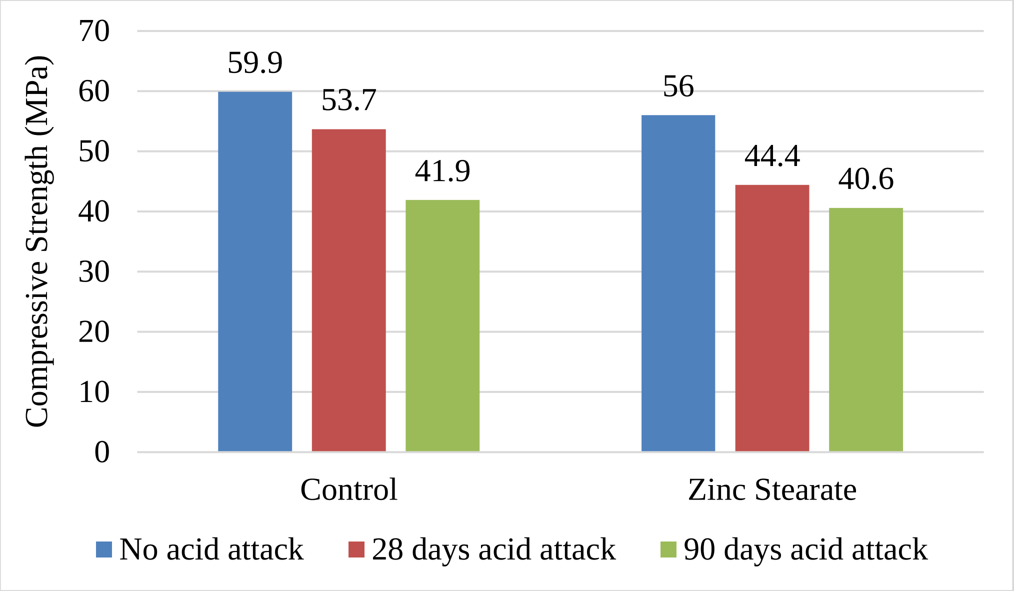


Figure 4.1: The Compressive Strength of Control and Zinc Stearate Mortars (García-Vera, et al., 2018).

ZycoSil Max is a type of waterproofing admixtures composed of 100 % silane. ZycoSil Max is soluble in water, reactive and breathable technology. It can penetrate 2 to 4 mm into the substrate and protect the structure from water seepage. With the breathable waterproofing technology, the water cannot seep through; however, the water vapour can escape from the concrete through its capillary pores (Zydex Industries, n.d.). Swamynadh and Muthumani (2018) had experimented by using the oil palm shells as lightweight coarse aggregates. The oil palm shell (OPS) aggregates were treated with silane (ZycoSil Max) before making the OPS concrete.

Furthermore, there were four types of concrete being tested for their compressive strength. First, lightweight concrete (LWC) as a control mix; second, LWC with the replacement of 15 % silica fume (LWC SF 15 %); third, LWC with the replacement of 15 % ground granulated blast-furnace slag (LWC GGBFS 15 %); fourth, the normal weight concrete (NWC) for the comparison purpose. Figure 4.2 shows the LWC SF 15 % possesses the highest compressive strength compared to other lightweight concrete. Although the NWC has greater compressive strength than LWC SF 15 %, LWC SF 15 % exhibits similar strength as NWC because the micropores in the lightweight aggregates are filled with silica fume. The compressive strength of

NWC was the highest, with the value of 34 MPa among other LWC is due to the bonding between cement paste and aggregates is much higher than that of LWC.

Moreover, the 28 days compressive strength of these lightweight concrete mixes are within the range (17 – 63 MPa) of structural application in the construction industry (ASTM, 2000). The LWC GGBFS 15 % had the lowest 28 days compressive strength, which was 27 MPa. This is mainly due to less tricalcium silicate (Alite), C_3S is available in the hydration process of cement at the initial stage, which delays the heat of hydration. Therefore, the gaining in early strength of LWC GGBFS 15 % is retarded. The results also prove that cement replacement with silica fume has a higher compressive strength than the pure LWC, even if the OPS aggregates are treated with silane, as shown in Figure 4.2. In theory, the compressive strength of concrete will reduce when the WRA is adopted in the concrete mix. This is because the WRA will hinder the concrete from absorbing the optimum amount of water for cement hydration, which turns out concrete with lower strength. However, in this case, contrary to expectations, it is possible to speculate that silica fume will provide high early strength and low penetrability of concrete. Other than that, the extremely fine particles of silica fume to be located in very close proximity to the aggregate particles, that is, at the aggregate-cement paste interface. Consequently, the concrete with silica fume has higher compressive strength (ASTM, 2005).

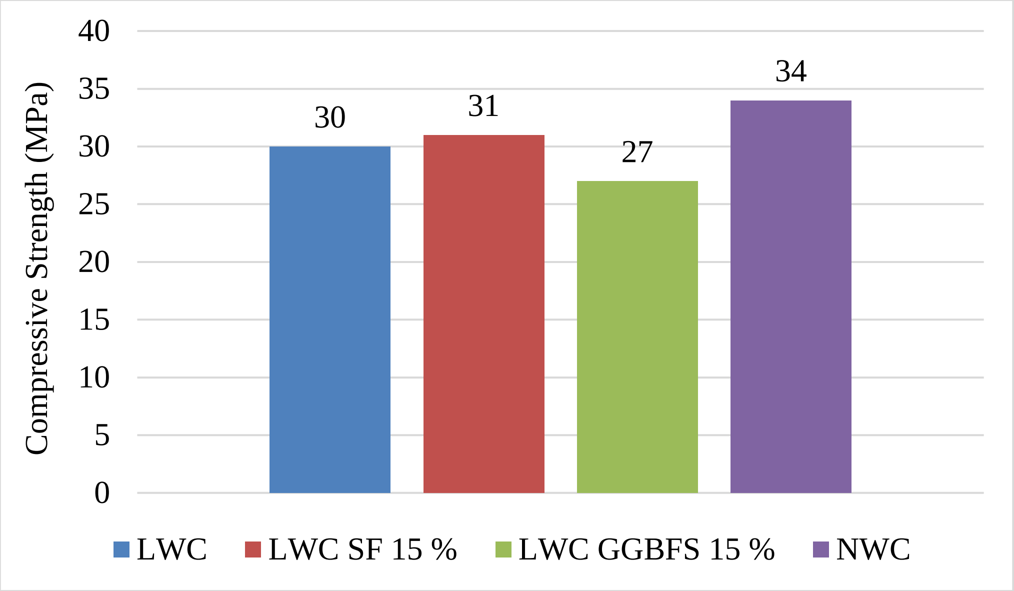


Figure 4.2: Compressive Strength of Various Concrete at 28 days (Swamynadh and Muthumani, 2018).

Apart from the silane agent, sodium oleate (SO) was also utilised to investigate LAC’s compressive strength after adding the SO. Ma, et al. (2013) experimented on how the SO affects the LAC’s compressive strength. As shown in Figure 4.3, it can be deduced that the optimum amount of SO to be added into the concrete mix is 0.20 % based on the percent of cement weight. As compared to the control mix that contained no SO, the addition of SO will decrease the LAC’s compressive strength when the SO content is below 0.2 %. This can be adequately explained by the SO contains much of the oleic acid, which means SO possesses a high content of unsaturated fatty acids. Thus, it shows no gelling effect, eventually cause the compressive strength to decrease. Also, the double bonds in the oleic acid structure easily oxidise with the dissolved oxygen of the tap water during the curing period and eventually lead to microscopic cracks in the cement. All these factors, therefore, cause the declination in the compressive strength of LAC. The results validate that unsaturated oleic acid is not suitable to be adopted as a grinding agent in cement production (Ma, et al., 2013).

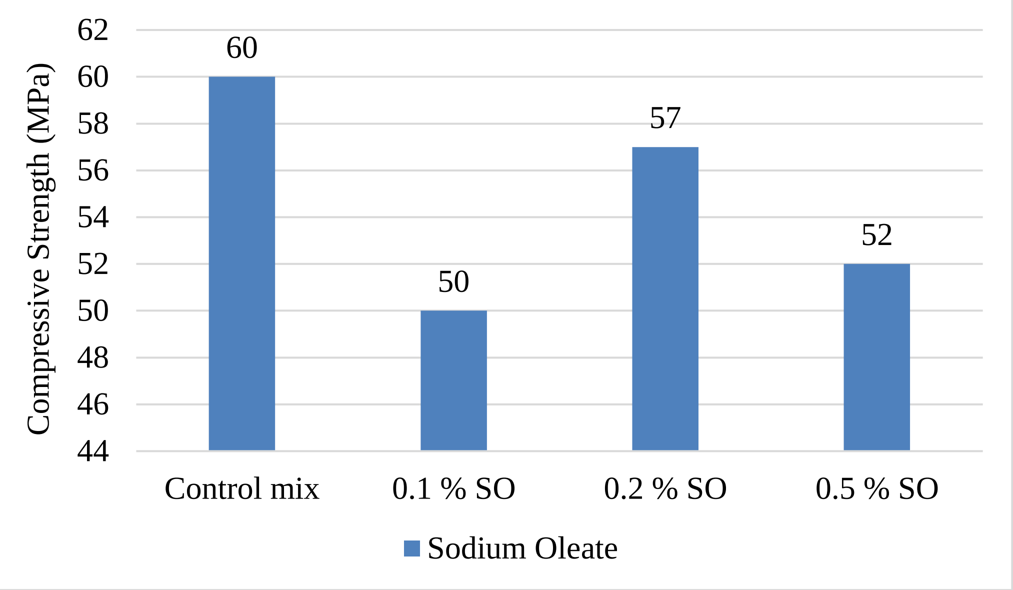


Figure 4.3: Compressive Strength of Sodium Oleate Concrete at 28 days (Ma, et al., 2013).

Calcium stearate (CS) is widely available in the market. Also, it is found to be the most used WRA as compared to other types of WRA. CS is incorporated in various kinds of concrete, such as normal weight and lightweight concrete. In this section, the primary thing that would like to highlight is the CS to be added into the LAC. Some researchers had conducted several tests (Maryoto, et al., 2020; Yao, et al., 2021; Chari, Naseroleslami and Shekarchi, 2019), they showed that when CS was incorporated into concrete, no matter normal weight or lightweight, the concrete's compressive strength would decrease to some extent. Furthermore, the results showed that the research was done by Li, Yang and Yang (2019) had proven the incorporation of CS into LAC would cause the compressive strength of LAC to decrease. This case can be further demonstrated by Li, et al. (2012), which showed that the compressive strength of the concrete reduced from 34.6 MPa to 31.0 MPa as the CS dosage was increased from 0.5 % to 1.0 % related to the cement weight.

In addition, Table 4.1 shows the compressive strength of the slag cement incorporated with CS. The results showed that when the CS dosage was increased, the compressive strength for the slag cement was decreased significantly from 50 MPa to 36 MPa when the CS dosage was 8 %, as shown in Table 4.1. Thus, the slag cement encountered a loss of 28 % in the compressive strength with respect to the mix without CS. This mainly caused by the strong hydrophobic effect of CS, which delay the hydration process of cement.

Apart from the abovementioned WRAs, siloxane is also a WRA used in the LAC. Table 4.1 also shows the compressive strength of the recycled aggregate concrete (RAC) incorporated with siloxane emulsion. The data proved that the addition of siloxane into the RAC could reduce the compressive strength. The siloxane concrete encountered a 21.1 % reduction in compressive strength when the siloxane dosage was about 1 %. This can be adequately explained by after the hydrolysis of siloxane, the reactive silanol group could anchor to the aggregates or cementitious materials, which would make the concrete surface to be hydrophobic. Therefore, the degree of hydration process of cement could be retarded by the presence of siloxane emulsion, which eventually leads to the loss of compressive strength (Zhu, et al., 2013).

Table 4.1: Compressive Strength of Various LAC with Various WRA.

Author(s)	Concrete Sample	Water Repellent Agent	Method	Compressive Strength (MPa) at 28 days
Li, Yang and Yang (2019)	SC – 0 %	CS	IM	50
	SC – 4 %			45
	SC – 8 %			36
Zhu, et al. (2013)	RAC – 0 %	Siloxane	IM	38
	RAC – 1 %			30

Note: SC – 4 % refers to Slag Cement incorporated with 4 % of water repellent agent based on the cement weight; CS – Calcium Stearate;
RAC – Recycled Aggregate Concrete.
IM – Integral Mixing.

Besides, Table 4.2 shows a summary of the impact of water repellents on the compressive strength of LAC. Table 4.2 provides clear evidence for the effectiveness of WRA on the slight reduction of compressive strength of LAC. All the data are gathered from the abovementioned information.

Table 4.2: Summary of the Impact of WRA on Compressive Strength of LAC.

Author(s)	Water Repellent Agent	Method	Reduction rate (%) compared to the compressive strength of the control mix
Li, Yang and Yang (2019)	CS	IM	10
Zhu, et al. (2013)	Siloxane	IM	21.1
García-Vera, et al. (2018)	ZS	IM	6.51
Swamynadh and Muthumani (2018)	Silane	IM	10
Ma, et al. (2013)	SO	IM	5.0

Note: IM – Integral Mixing

4.3.2 Compressive Strength of Lightweight Foamed Concrete Treated with Various Water Repellent Agent

As shown in Figure 4.4, the compressive strength of the LFC was decreasing when the amount of CS added was increasing. In this case conducted by Lee, et al. (2018), the highest compressive strength of 5.41 MPa at 28 days belonged to the LFC – 0 (control mix). This might due to the ceaseless hydration process from water curing, which creates denser C-S-H gel. From the results, it can be deduced that the LFC without the WRA will possess a higher compressive strength as compared to that concrete mix with WRA. Furthermore, when the CS dosage increases from 0.2 % to 0.4 % of the cement weight. The extra 0.2 % of CS will cause the compressive strength to decrease further, as shown in Figure 4.4, which dropped to 3.57 MPa from 3.82 MPa. Thus, the LFC – 0.4 encountered a 34.01 % drop of LFC – 0 compressive strength. A plausible explanation for that reduction in compressive strength is the addition of CS in the LFC, reducing the water absorption capabilities. Therefore, the hydration process of cement was retarded and eventually caused the 28 days compressive strength was the lowest among those LFC at the same curing age. It is worth noting that the CS dosage of 0.4 % incorporated in the LFC had brought long-term adverse effects on its compressive strength. Thus, the recommended CS dosage to be incorporated is 0.2 % of cement weight. Although the compressive strength of the CS concrete will reduce, CS is beneficial for the LFC to absorb less water for ensuring the concrete is durable and last for many years without maintenance (Lee, et al., 2018).

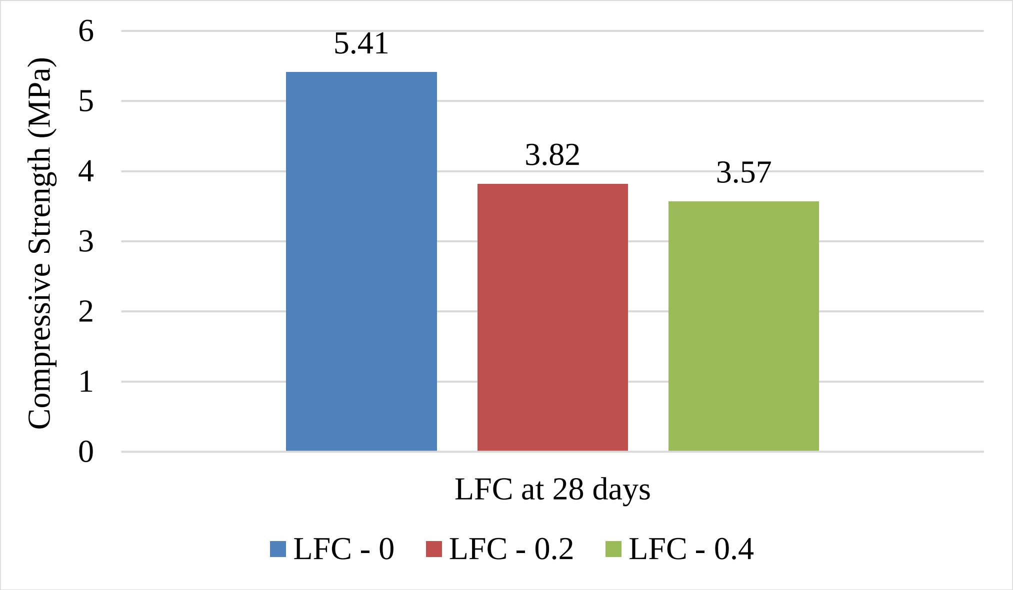


Figure 4.4: Compressive Strength of LFC with Calcium Stearate at 28 days (Lee, et al., 2018).

Furthermore, zinc stearate (ZS) and siloxane were tested by Liu, et al. (2019) to investigate their effects on the compressive strength. The results showed that the optimum amount of ZS to be incorporated into the LFC was 1.5 % of the cement weight. As shown in Table 4.3, the incorporation of ZS into the LFC was appeared to have the greatest compressive strength of LFC. ZS and siloxane concrete reached the maximum compressive strength when the dosage was 1.5 % of the cement weight. The respective ZS concrete and siloxane concrete were 0.8 MPa and 0.77 MPa, which still above the minimum requirement of low-density concrete under the lightweight concrete category, that is 0.7 MPa in accordance with ACI (2001). As for the CS concrete, the optimum amount of CS dosage was 2 %, which leads the CS concrete to reach its maximum compressive strength of 0.75 MPa.

Moreover, sodium oleate (SO) and calcium stearate (CS) are the familiar commercial water repellent agents adopted by Yao, et al. (2021). A recent study proved that CS was superior to SO in terms of compressive strength and hydrophobicity. When 0.1 % and 0.2 % of CS were added into the concrete mixture, the data proved that 28 days compressive strength of the LFC remains almost steady. This situation also applied to the SO mixture. When the CS and SO dosage increased from 0.4 % onwards, the 28 days compressive strength of the LFC decrease inconsistently. This might because the amount of hydration products for LFC increases after 28 days of curing. Another factor associated with that CS is CS can add more air content into the LFC. In consequence, the changes in compressive strength were inconsistent, as shown in Table 4.3. Furthermore, when SO added into LFC, the compressive strength started to reduce as well. It is essential not to overlook that when the CS and SO dosage were both 0.4 %, the compressive strength of SO concrete, 55 MPa was smaller than that of CS concrete, 59.5 MPa. This might because SO can react with calcium hydroxide, a by-product of cement hydration, to form calcium oleate. After that, the calcium oleate precipitation can only fill some micropores of the LFC. Therefore, comparing to the CS concrete, the SO concrete would encounter high open porosity of LFC, eventually leads to increased water absorption and low compressive strength of LFC. In a word, CS is beneficial to the compressive strength and water absorption of the LFC. Therefore, CS is a more suitable internal mixing water repellent agent as compared to SO.

Siloxane and CS had been adopted by Ma and Chen (2016). As seen in Table 4.3, the CS and siloxane were both mixed with the LFC integrally. The data showed that when the dosage of CS and siloxane were 1 % of the cement weight, the compressive strength of the respective concrete reached the maximum compressive strength. Also, the data showed that when the CS and siloxane dosage go beyond 1 %, the compressive strength of LFC will drop. The possible reason might be that CS and siloxane content was excess; hence the hydrophobic effect becomes more pronounced, which may cause less water to participate in the cement hydration reaction. From the results, it can be noticed that the siloxane concrete obtained a higher compressive strength than the CS concrete when the dosage was the same. Thus, the recommended dosage of siloxane and CS is 1 % in terms of compressive strength. However, no control mix without the CS and siloxane had been tested. Therefore, in accordance with most researchers' study, the water repellent agents make the compressive strength of LFC lower than that of the composite without WRA.

The performance index (PI) of a lightweight foamed concrete specimen is used to determine the compressive strength per 1 000 kg/m^3 density. However, each specimen with a different hardened density will not be accurate to compare the mechanical properties. Hence, PI is introduced, allowing comparison of concrete specimen for compressive strength with the difference in hardened density. The performance index is calculated using Equation 4.1, and thus the index is recorded in Table 4.3 (Ng, 2020).

$$PI = \frac{F}{Hardened\ Density/1000} \tag{4.1}$$

where

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

F = Compressive Strength of the specimen, MPa

Table 4.3: Compressive Strength of LFC with Various Water Repellent Agent at respective 7 days and 28 days.

Author(s)	Water Repellent Agent	Method	Density (kg/m^3)	7-day (MPa)	28-day (MPa)	Performance Index (MPa per 1000 kg/m^3)
Liu, et al. (2019)	CS – 2%	IM	481	0.50	0.75	1.56
	ZS – 1.5 %		491	0.54	0.80	1.63
	Siloxane – 1.5 %		485	0.52	0.77	1.59

Table 4.3 (Continued)

Yao, et al. (2021)	CS – 0.1 %	IM	1150	-	67.3	58.5
	CS – 0.2 %		1153		65.0	56.4
	CS – 0.4 %		1161		59.5	51.2
	CS – 0.8 %		1164		56.0	48.1
	CS – 1.2 %		1172		54.8	46.8
	SO – 0.1 %		1144	-	68.0	59.4
	SO – 0.2 %		1151		65.2	56.6
	SO – 0.4 %		1147		55.0	48.0
	SO – 0.8 %		1149		48.0	41.8
	SO – 1.2 %		1147		40.0	34.9
Ma and Chen (2016)	CS – 0.2 %	IM	548	1.05	1.28	2.34
	CS – 0.4 %		553	1.07	1.4	2.53
	CS – 0.8 %		551	1.1	1.5	2.72
	CS – 1.0 %		555	1.22	1.68	3.03
	CS – 1.2 %		562	1.12	1.65	2.94
	Siloxane – 0.2 %		557	1.2	1.45	2.60

Table 4.3 (Continued)

	Siloxane – 0.4 %		547	1.35	1.55	2.83
	Siloxane – 0.8 %		553	1.4	1.62	2.93
	Siloxane – 1.0 %		549	1.52	1.75	3.19
	Siloxane – 1.2 %		542	1.51	1.72	3.17

Note: CS – 2 % refers to LFC incorporated with 2 % CS of the cement weight.
IM – Integral Mixing.

Besides, Table 4.4 shows a summary of the impact of water repellents on the compressive strength of LFC. Table 4.4 provides clear evidence for the effectiveness of WRA on the small reduction of compressive strength of LFC. All the data are gathered from the abovementioned information.

Table 4.4: Summary of the Impact of WRA on Compressive Strength of LFC.

Author(s)	Water Repellent Agent	Method	Reduction rate (%) compared to the compressive strength of the control mix
Lee, et al. (2018)	CS	IM	29.4
Liu, et al. (2019)	CS	IM	28.3
	ZS	IM	29.6
	Siloxane	IM	31.2
Yao, et al. (2021)	CS	IM	21.1
	SO	IM	23.4
Ma and Chen (2016)	CS	IM	25
	Siloxane	IM	29.1

Note: IM – Integral Mixing

4.3.3 Summary of the Impact of Water Repellent Agent on Compressive Strength of LAC and LFC

To summarise five different types of WRA, it is easy to compare all the WRA in the table form, which is shown in Table 4.5. The compressive strength of LAC treated with WRA is summarised in Table 4.2. Meanwhile, for the compressive strength of LFC, the measurement for the most effective water repellent agent is adopting the small reduction rate (%) compared to compressive strength at the 28-day of control mix, which can be obtained from Table 4.4. Some notes that need to be taken in Table 4.5 are 1 – 5 represents the ranking; 1 refers to the less impact of WRA on the compressive strength of concrete; 5 refers to the significant negative impact of WRA on the compressive strength of concrete.

Table 4.5: Summary of the Impact of WRA on Compressive Strength for LAC and LFC.

Water Repellent Agent	LAC	LFC
Calcium Stearate	3	1
Zinc Stearate	2	3
Sodium Oleate	1	2
Silane	4	5
Siloxane	5	4

4.4 Water Absorption

Water absorption is another main problem that lightweight concrete will encounter. This is because lightweight aggregates usually come with many pores in which pores can contribute to concrete permeability. The pore structure of foamed concrete consists of capillary pores, gel pores as well as air voids. The air voids are purposely formed by the foaming agent in which air can be entrained into the concrete and make it lightweight. In consequence, the entrapped pores of foamed concrete will absorb excessive water. Hence, the water repellent agent is much needed in dealing with this undesired situation.

4.4.1 Water Absorption of Lightweight Aggregate Concrete Treated with Various Water Repellent Agent

Research conducted by Li, Yang and Yang (2019), which used calcium stearate (CS) as a water repellent in the LFC to seek the impact on the water absorption rate of LFC. The recommended CS dosage by Li, Yang and Yang (2019) is 4 % of cement weight, beyond which no significant changes in water absorption rate can be detected. As can be seen in Figure 4.5, it shows that the water absorption rate of alkaline-activated slag (AAS) cement is greater than the ordinary Portland cement (OPC), which conforms with the research conducted by Yang, et al. (2016). Hence, WRA is much needed in the LAC manufactured by AAS cement. The results shown in Figure 4.5 prove that the water absorption of AAS cement reduced about by 82 %. This indicates that CS can reduce the water absorption of AAS cement until the sorptivity value is half of the OPC sample.

Moreover, the data also proves 4 % of CS content would be sufficient for reducing the tendency of AAS cement to absorb unwanted water. When the CS content is beyond 4 %, CS seems to be no more significant impact on the sorptivity of AAS cement. In summary, CS is a good WRA in solving the high water absorption rate of cement.

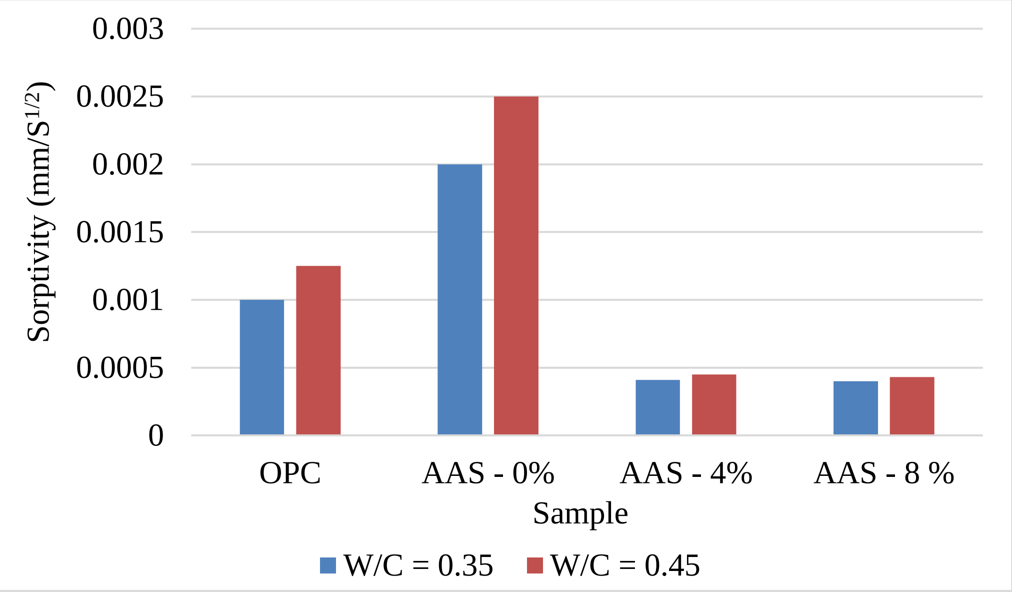


Figure 4.5: Water Sorptivity of LAC Manufactured by AAS Cement and OPC (Li, Yang and Yang, 2019).

Zhu, et al. (2013) used siloxane in the LAC to examine its impact on the water absorption rate of LAC. Integral mixing and surface coating are the two different methods conducted in the research. The results indicate that the siloxane had a significant impact on the water absorption of the LAC. As shown in Table 4.6, the water absorption coefficient of the recycled aggregate concrete for respective RACI – 0.5, RACI – 1, RACS – 100 and RACS – 200 were dwindled by 61 %, 72 %, 95 % and 96 % as compared to the pure recycled aggregate concrete without siloxane. Meanwhile, the water absorption coefficient of NACI – 0.5, NACS – 100 and NACS – 200 were dwindled by 63 %, 80 % and 81 %, respectively, as compared to pure natural aggregate concrete without siloxane. The results indicate that the surface coating treatment was more dominant than the concrete prepared by direct mixing with siloxane (integral water repellent treatment).

Moreover, the experimental results also exhibit that the surface siloxane treatment was more effective for recycled aggregate concrete than natural aggregate concrete. This can be better accounted for by the porosity of recycled aggregate concrete was greater. Thus, the siloxane can penetrate deeper into the concrete, as shown in Table 4.7. In line with the research of Hankvist and Karlsson (2001), the protection of concrete against any chloride penetration and intruding salty water usually increase with the penetration depth of the siloxane.

Table 4.6: Water Absorption Coefficient and Decrease Rate of Concrete Treated with Siloxane (Zhu, et al., 2013).

Mix notation	Capillary water absorption coefficient ($kg/(m^2.h^{0.5})$)	Decrease rate (%) as compared to RAC0 or NAC0
RAC0	1446.0	-
RACI – 0.5	560.9	61
RACI – 1	402.2	72
RACS – 100	77.6	95
RACS – 200	62.8	96

Table 4.6 (Continued)

NAC0	732.8	-
NACI – 0.5	268.0	63
NACS – 100	148.1	80
NACS – 200	137.3	81

Note: RAC0 – Recycled Aggregates Concrete without siloxane.

NAC0 – Natural Aggregates Concrete without siloxane.

I – 0.5 refers to Integral mixing with 0.5 % of siloxane based on cement weight.

S – 100 refers to the Surface coating of 100 g/m^2 siloxane.

Table 4.7: Siloxane Impregnation Depth of Surface-treated Concrete (Zhu, et al., 2013).

Mix notation	Impregnation depth (mm)
RACS – 100	7.8
RACS – 200	9.1
NACS – 100	6.8
NACS – 200	8.5

Water absorption is also one of the significant impacts if WRA is adopted in lightweight concrete. From the research of García-Vera, et al. (2018), the LAC incorporated with zinc stearate exhibited the lowest capillary water absorption coefficient among other LAC treated with different WRA. The ZS mortar had the lowest absorption coefficient, both in aggressive and non-aggressive environments, as shown in Figure 4.6. However, when the ZS mortar had 90 days of sulphuric acid exposure, it was found that the absorption coefficient was larger than the non-acid exposure. A possible reason for this increment of the coefficient is that the gypsum coating created on the mortar surface was weaker and more external than the control and treated mortar.

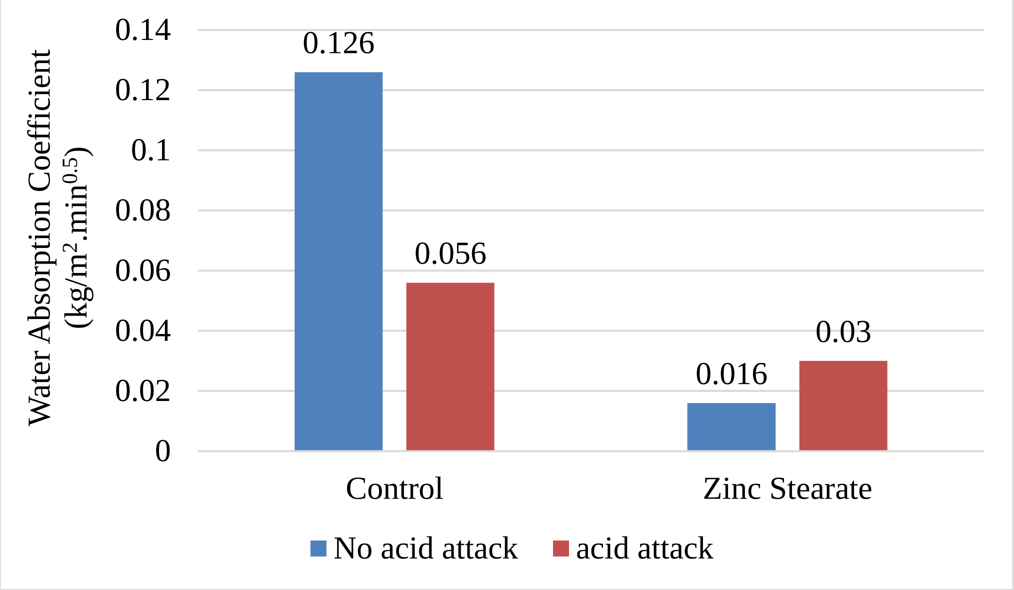


Figure 4.6: Capillary Water Absorption Coefficient at 90 days (García-Vera, et al., 2018).

Water absorption of oil palm shell (OPS) is around 23 – 30 % (Swamynadh and Muthumani, 2018), which is 60 – 70 % higher than that of normal-weight concrete (Ardakani and Yazdani, 2014). The data obtained from Swamynadh and Muthumani (2018) validates that silane as a WRA can reduce the water absorption of OPS aggregates. When the silane content is increased, the OPS tends to absorb lesser water. The results appear to confirm that the OPS show decrease in water absorption rate from 24 % to 2 % when the silane content is 20 ml. With the silane aid in OPS, it provides good workability and slump value for the OPS concrete. Therefore, silane is useful in reducing water absorption, especially those aggregates with many capillary pores.

Besides, sodium oleate (SO) is also one of the WRAs incorporated in the concrete to reduce the water absorption capability. In light of the experiment done by Záleská, et al. (2019), the water absorption coefficient for the LAC incorporated with expanded polypropylene (EPP) and SO was 0.084 $kg/m^2.min^{0.5}$, while for the LAC-EPP incorporated with other types of WRA, which known as boiled linseed oil was 0.042 $kg/m^2.min^{0.5}$. The resulting values show that the LAC-EPP incorporated with SO possesses a higher value of water absorption coefficient, which SO appears to be less effective in providing the water repellent effect for the LAC. Moreover, when it comes to the pure LAC without EPP and SO, it exhibited the coefficient with 0.012 kg/m^2.min$^{0.5}$. The water absorption coefficient was much smaller than those of LAC-EPP treated with WRA. This might be due to the porosity of the expanded polypropylene (EPP) aggregates are much more than the silica sand. Therefore, the porosity of the LAC incorporated with EPP would increase significantly. Also, SO might not effective in reducing the water absorption capability for LAC. In summary, sodium oleate might not be good at reducing the water absorption for LAC.

Besides, Table 4.8 shows a summary of the impact of water repellents on the water absorption of LAC. Table 4.8 provides clear evidence for the effectiveness of WRA on the reduction of water absorption of LAC. All the data are gathered from the abovementioned information.

Table 4.8: Summary of the Impact of WRA on Water Absorption of LAC.

Author(s)	Water Repellent Agent	Method	Reduction rate (%) compared to water absorption of control mix
Li, Yang and Yang (2019)	Calcium Stearate	IM	82
Zhu, et al. (2013)	Siloxane	IM	72
	Siloxane	SC	96
García-Vera, et al. (2018)	Zinc Stearate	IM	87.3
Swamynadh and Muthumani (2018)	Silane	IM	78.6
Záleská, et al. (2019)	Sodium Oleate	IM	The result shows SO is not even better than the uncommon use of WRA.

Note: IM – Integral Mixing; SC – Surface Coating

4.4.2 Water Absorption of Lightweight Foamed Concrete Treated with Various Water Repellent Agent

Another concern which brought to the attention is the water absorption of LFC. LFC is susceptible to an aggressive environment. This might be due to the fact that the pore structure of LFC is easy to capture excessive or unwanted water containing chloride ions. Hence, Ma and Chen (2016) had run the research to seek the solution for the LFC to handle unwanted water.

There were two different water repellents utilised by Ma and Chen (2016), known as calcium stearate (CS) and siloxane. CS is a typical well-known commercial water repellent in the construction industry. The 6 hours and 48 hours of water absorption were studied. As seen in Table 4.9, the row of Ma and Chen (2016) shows the influence of CS content on the water absorption of LFC. From the table itself, it is noted that as the CS content increased, the tendency of LFC to absorb water decreased. This phenomenon same goes for the LFC with siloxane content. When the CS dosage was 1 % and 1.2 %, the 48-hour water absorption of the samples were both less than 10 %, which implies that the water absorption of LFC had reached its desired rate. Besides, as shown in Table 4.9, it can be noticed that a small dosage of siloxane can reduce water absorption dramatically. For example, 0.2 % of siloxane was enough to reduce the water absorption rate to 13.2 %. Also, it is worth to note that the siloxane makes the water absorption of LFC at 6 and 48 hours remain almost unchanged regardless of siloxane content. When comparing both CS and siloxane, siloxane is dominant over CS in terms of the water absorption. Nevertheless, CS is still preferable in the construction industry than the siloxane, because siloxane reduce extremely much of the water absorption capability of LFC in which siloxane might retard the cement hydration process greatly. Comparing the CS and siloxane content of 1 %, the results show that water absorption of CS concrete was 7.4 %, which was more than double of the water absorption of siloxane concrete, that was 3.1 %. Therefore, in order for the concrete still has the capability to absorb the needed water, thus CS is chosen in which the long-term gain in strength of LFC would reach its peak value.

Sodium oleate and calcium stearate were adopted by Yao, et al. (2021). When CS was incorporated in the LFC, the water absorption of LFC at 6-hour reduced from 9.1 % to 6.0 % as the CS content increased from 0.2 % to 1.2 % in which a decrease of about 34.1 %. Furthermore, the water absorption of SO concrete at 6-hour reduced from 7.9 % to 4.5 %, which was a decrease of 43 %. The different effects of CS and SO can be associated with their solubility. CS is insoluble and agglomerates in cement during the hydration process, while SO is soluble in water and can be evenly spread in cement paste. Therefore, the water absorption of SO concrete is lower than that of CS concrete after 6 hours of immersion, as can be seen in Table 4.9. The data proves that the SO possesses a better effect on reducing the water absorption than the CS at the early stage, which is 6 hours of water absorption.

Nevertheless, when coming to the 48 hours of water absorption test, CS concrete appeared to have almost the same hydrophobic effect than the SO concrete. CS and SO concrete had respective 10.1 % and 10.0 % of water absorption. Besides, the magnitude of the water contact angle can reflect the hydrophobicity of concrete specimens. The larger the contact angle indicates that the concrete has better hydrophobicity. From Figure 4.7, it shows the contact angles of water with different WRA. From Figure 4.7, it can be seen that when the dosage of CS and SO increased from 0 % to 1.2 %, the water droplet on the concrete surface is more extensive and larger. This is due to the fact that the incorporated LFC with WRA tends to become more hydrophobic instead of hydrophilic. Also, the results show that the contact angle of LFC without WRA addition was about 25° as shown in Figure 4.7. This might be due to the capillary pores of the LFC were filled with water in a quick moment, which caused the flow velocity of water in the capillary pores become slower, thus creating a comparatively stable contact angle. The results also show that the maximum contact angle for CS and SO concrete was only up to 82°, which is less than the recommended 90°. It means that the CS and SO concrete still cannot be categorised as hydrophobic concrete. Similarly, CS and SO showcase their capability to reduce the water absorption of LFC. In summary, both CS and SO can be adopted as WRA in LFC because they can enhance the hydrophobicity and reduce the water absorption of LFC.

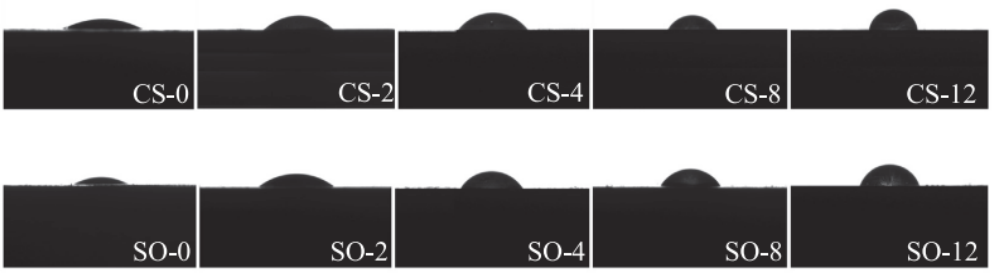


Figure 4.7: Water Contact Angles of LFC with Various WRA (Yao, et al., 2021).

Calcium stearate, zinc stearate and siloxane are the WRA used by Liu, et al. (2019) to investigate their effects on the water absorption rate of LFC. With the addition of CS, ZS and siloxane, the water absorption of LFC is significantly reduced. The same expectation can be drawn from this research; that is, when the CS, ZS, and siloxane content increases, the lower is the water absorption rate of LFC. As shown in Table 4.9, compared with the control mix without the WRA, the results show that CS, ZS and siloxane were good enough to reduce the water absorption rate of LFC. This might be due to the fact of CS, ZS and siloxane can weaken the capillary forces of capillary pores by modifying the pore structure of LFC, which make the LFC is hard for absorbing water to reach the saturated state. Furthermore, the optimum dosage of CS, ZS and siloxane suggested by Liu, et al. (2019) was 4 %. This can be adequately explained by the graph as shown in Figure 4.8. When the CS content is increased from 0.5 % to 4 %, the strength loss coefficient of LFC is also reduced. This indicates that 4 % of CS content result in higher compressive strength of LFC than that of LFC with 0.5 % of CS content. However, this trend is total as opposed to ZS and siloxane concrete. As seen in Figure 4.8, as the ZS and siloxane content increased, the strength loss coefficient is also increased. This provides clear evidence for ZS and siloxane content would cause the compressive strength of LFC to drop further as the ZS and siloxane content is increased. In a word, CS dosage is the most beneficial to the water-resistant effect of LFC, which reduced the water absorption rate up to 73.3 % at 48 hours of soaking and also helped to maintain its compressive strength as compared to the control mix.

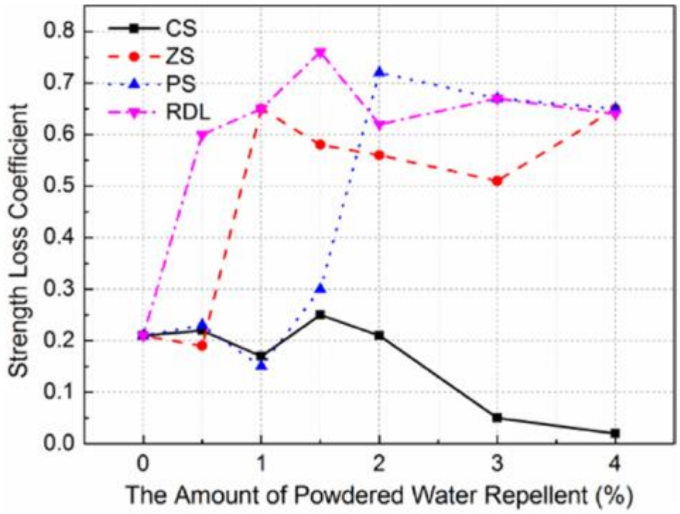


Figure 4.8: Strength Loss of LFC Incorporated with Different WRA after Saturated Water Absorption (Liu, et al., 2019).

Table 4.9: Water Absorption, W_A of LFC with Various WRA at respective 6-hour and 48-hour soaking time.

Author(s)	Water Repellent Agent	W_A at 6-hour (%)	W_A at 48-hour (%)	Reduction Rate (%) compared to W_A at 48-hour of control mix
Liu, et al. (2019)	Control mix	37.5	46.1	100
	CS – 4 %	8.2	12.3	73.3
	ZS – 4 %	9.1	15.6	66.2
	Siloxane – 4 %	15.9	19.3	58.1
Yao, et al. (2021)	Control mix	20.5	26.3	100
	CS – 0.2 %	9.1	11.0	-
	CS – 0.4 %	8.0	11.2	
	CS – 0.8 %	6.5	10.6	
	CS – 1.2 %	6.0	10.1	61.6
	SO – 0.2 %	7.9	10.5	-
	SO – 0.4 %	6.5	10.7	
	SO – 0.8 %	5.5	10.2	
	SO – 1.2 %	4.5	10.0	61.9

Table 4.9 (Continued)

Ma and Chen (2016)	Control mix	57	68	100
	CS – 0.2 %	33	38	-
	CS – 0.4 %	21.2	21	
	CS – 0.8 %	12.7	12.9	
	CS – 1.0 %	7.5	7.6	
	CS – 1.2 %	7.3	7.3	89.3
	Siloxane – 0.2 %	13.2	13.2	-
	Siloxane – 0.4 %	8.5	8.5	
	Siloxane – 0.8 %	5.6	5.6	
	Siloxane – 1.0 %	3.1	3.1	
	Siloxane – 1.2 %	3.1	3.1	95.4

Note: Control mix refers to the concrete without WRA.

All the LFC are treated with integral mixing of WRA.

4.4.3 Summary of the Impact of Water Repellent Agent on Water Absorption of LAC and LFC

To summarise five different types of WRA, it is easy to compare all the WRA in the table form, which is shown in Table 4.10. The water absorption of LAC treated with WRA is summarised in Table 4.8. Meanwhile, for the water absorption of LFC, the measurement of the most effective water repellent agent is adopting the reduction rate (%) compared to water absorption at the 48-hour of control mix, which obtained from Table 4.9. Some notes that need to be taken in Table 4.10 are 1 – 5 represents the ranking; 1 refers to the significant impact of WRA on reducing water absorption of concrete; 5 refers to the less impact of WRA on reducing water absorption.

Table 4.10: Summary of the Impact of WRA on Water Absorption for LAC and LFC.

Water Repellent Agent	LAC	LFC
Calcium Stearate	2	2
Zinc Stearate	1	3
Sodium Oleate	5	4
Silane	3	5
Siloxane	4	1

To summarise the information from Table 4.5 and Table 4.10, the most effective water repellent agent is zinc stearate (ZS) and calcium stearate (CS) for the LAC and LFC, respectively. This indicates that ZS is the optimal WRA for LAC in terms of compressive strength and water absorption. Besides, CS is the optimal WRA for LFC in terms of compressive strength and water absorption.

4.5 SWOT Analysis of Water Repellent Agent towards LAC and LFC

In line with the purpose of the study, SWOT analysis was performed in Table 4.11 to evaluate the strengths, weaknesses, opportunities and threats of the impact of water repellent agent towards the LAC and LFC.

Generally, the SWOT analysis will serve as guide to illustrate the pros and cons of the use of water repellent agent in LAC and LFC. From Table 4.5, the table shows the ranking of the WRA after examining their impact on the compressive strength of LAC and LFC. Meanwhile, Table 4.10 shows the ranking of the WRA after examining their impact on the water absorption of LAC and LFC.

Table 4.11: Summary of SWOT Analysis of Water Repellent Agent towards LAC and LFC.

Strengths	Weaknesses
Less water absorption. Lightweight. Low construction cost.	Lower compressive strength.
Opportunities	**Threats**
Affordable housing prices. Less construction materials are used. Can be used in various industries such as pharmaceutical and food industries.	The price of cement and water repellent agent increased. The quality of water repellent agent.

4.5.1 Strengths

Water is vital for the manufacturing of concrete. However, once the concrete is manufactured out, water is no longer concrete’s friend. Concrete, as a natural porous structure is prone to water infiltration and vulnerable to cracking. Thus, a water repellent agent is indeed crucial for producing a water-resistant LAC and LFC.

As for LAC, zinc stearate is the most effective WRA in reducing the water absorption of LAC, while has less impact on the compressive strength of LAC. Besides, calcium stearate is the most effective WRA for LFC due to CS can reduce the water absorption, while maintaining LFC’s compressive strength.

From the perspective of the construction industry, ZS and CS are suitable to be adopted as WRA. There are some advantages to using these two WRA. Firstly, less water absorption of the concrete. Furthermore, the lightweight panel with these two WRA can enhance the panel’s durability to withstand acidic water. Thus, the lightweight panel with ZS and CS can be installed exteriorly due to the panel can resist life-long exposure to acid rain. In addition, the building with lightweight panels and materials would lead to low construction cost. This is due to the overall building is mainly installed with lightweight panels, thus the overall dead load is reduced. Hence, the total construction cost is reduced.

4.5.2 Weaknesses

Compressive strength is the inherent weakness encountered by LAC and LFC incorporated with ZS and CS, respectively. LAC that treated with ZS has exhibited the lowest strength loss as compared to other WRA adopted in LAC. This situation same goes for the LFC incorporated with CS. Therefore, ZS and CS is less impact on the compressive strength of LAC and LFC, respectively. It is recommended that the ZS and CS can be adopted in the construction industry to produce water-resistant lightweight panels.

The lower compressive strength of LAC and LFC must be incorporated with chemical admixtures to improve the compressive strength. Superplasticizer can be used in the manufacturing of LAC and LFC. The benefits of applying superplasticizer into LAC and LFC are increased workability, increased compressive strength, eliminates segregation of coarse and fine aggregates and allow good dispersion of cement particles in water.

4.5.3 Opportunities

The opportunities are the external factor that will bring some benefits to the LAC – ZS and LFC – CS. First of all, LAC – ZS and LFC – CS panels can help create more affordable housing prices due to their lightweight characteristics. This might due to less construction materials are used to build the high-rise building. The construction materials such as the required steel reinforcement bar is reduced since the building is mainly installed with lightweight panels, which cause the overall building to become lighter than the normal building.

In addition to the construction industry, ZS and CS can also be used in other industries. The industries such as food, pharmaceutical and personal cares, paper and rubber and plastic industry.

4.5.4 Threats

Threats are the external factor that can bring menace to the LAC and LFC by the ZS and CS. First of all, the price of cement and water repellent agent could be a major concern. Because of the price of these two materials are increased, the cost of manufacturing the water-resistant lightweight concrete will be increased. Therefore, the price of finished panels must compare among other suppliers to avoid the panels are overpriced, which cause the sales of the company to decrease.

Furthermore, to remain the quality of lightweight panels, the quality of CS and ZS must be examined properly before purchasing from suppliers. If possible, the manufacturer can try to use the same concrete mix with the same water repellent agent, but from different suppliers, to compare the effectiveness and quality of the water repellent agent. Moreover, the characteristic of concrete with different materials may also cause the water repellent agent to be less effective in reducing the water absorption while maintaining the desired compressive strength. Hence, the concrete mix must be examined well before mixing with WRA.

4.6 Summary

In summary, zinc stearate and calcium stearate are good for lightweight aggregate concrete and lightweight foamed concrete, respectively. Lightweight aggregate concrete incorporated with zinc stearate exhibits a significant low water absorption and less impact on the compressive strength. Furthermore, lightweight foamed concrete incorporated with calcium stearate shows a significant low water absorption, while maintaining the compressive strength. Therefore, zinc stearate and calcium stearate can be widely used in the construction industry to produce lightweight water-resistant concrete.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

After analysing the results gathered from different researchers’ works, the following conclusions can be drawn in accordance with the objectives set for this research.

The first objective was to identify types of water repellent agent used in the current construction industry. The outcome of this research has shown that the applied water repellent agents are calcium stearate, zinc stearate, sodium oleate, silane and siloxane.

The second objective was to investigate the performance of concrete attributed by the use of various types of water repellent agent. This was accomplished as the compressive strength and water absorption for LAC and LFC incorporated with five types of water repellent agent were reduced.

The third objective was to analyse the most effective water repellent agent towards the concrete engineering performance. The results showed that zinc stearate and calcium stearate were the optimal water repellent agents for LAC and LFC, respectively.

5.2 Recommendations for future work

The following recommendations should be considered for future researchers to validate further and enhance the reliability and feasibility of the information found in this thesis.

i. To adopt calcium stearate, zinc stearate, sodium oleate, silane and siloxane in the same concrete mix.
ii. To incorporate various WRA into autoclaved aerated concrete (AAC) to examine the impact of WRA on AAC in terms of engineering properties.
iii. To produce the water-repellent LAC and LFC with sustainable materials such as palm kernel shells (PKS) to investigate the impact of WRA on green water-repellent lightweight concrete.

iv. To carry out more different tests for treated LAC and LFC with WRA. The tests such as compressive strength, water absorption, flexural strength, thermal conductivity and chloride penetration. These tests can be implemented with the treated water-repellent LAC and LFC to enhance further the effectiveness of WRA towards the LAC and LFC.

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