FABRICATION AND ENGINEERING PROPERTIES STUDIES ON LIGHTWEIGHT GREEN CONCRETE

DEREKTHY CHOONG KAH JIAN

UNIVERSITI TUNKU ABDUL RAHMAN

FABRICATION AND ENGINEERING PROPERTIES STUDIES ON LIGHTWEIGHT GREEN CONCRETE

DEREKTHY CHOONG KAH JIAN

A project submitted in partial fulfilment of the Requirement for the award of Bachelor of Engineering (Honours) Environmental Engineering

Faculty of Environmental and Green Technology
Universiti Tunku Abdul Rahman

August 2019

DECLARATION

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

Signature : _________________________________

Name : _________________________________

ID No. : _________________________________

Date : _________________________________

APPROVAL FOR SUBMISSION

I certify that this project entitled **"FABRICATION AND ENGINEERING PROPERTIES STUDIES ON LIGHTWEIGHT GREEN CONCRETE"** was prepared by DEREKTHY CHOONG KAH JIAN has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons) Environmental Engineering at Univerisiti Tunku Abdul Rahman.

Approved by,

Signature : _______________________________

Supervisor : Dr. Leong Kah Hon

Date : _______________________________

Specially dedicated to

my beloved father and mother

ACKNOWLEDGEMENTS

I would like to express my gratitude to my FYP supervisor, Dr. Leong Kah Hon for his invaluable advice, guidance and his enormous patience throughout my whole project study.

In addition, I would like to express my gratitude to the lab officers, Mr. Tamilvanan a/l Muniandi, Ms. Ng Suk Ting, Mr. Cheah and Mr. Ekhwan that given great assistance throughout my labwork. Special thanks to my senior, Ms. Tan Shi Ching for providing guidance on my project. Also, to my FYP mate, Doris Chin Zhi Xin, Joseph Lim Kuan Yong, Daniel Lim Chiu Giap, Lee Siew Weng, Wang Lian Yang, Ng Yee Leng and Liau Kok Siong who always supported me physically and mentally throughout the progress in completing this project.

Last but not least, I would like specially dedicated to my beloved family members especially my parents for their never ending support and encouragement in my whole project.

FABRICATION AND ENGINEERING PROPERTIES STUDIES ON LIGHTWEIGHT GREEN CONCRETE

ABSTRACT

High global emission of carbon dioxide (CO_2) has considered as one of the significant environmental problems which caused the global warming problem and affected the ecosystem. According to the research study of Andrew (2018), it is approximately 1500 million tons CO_2 emission from the cement production which is approximately 5 percent of the global CO_2 emission. Next, the waste glass bottle, also known as one of the environmental problems which have occupied most space of the landfill as waste glass, is non-biodegradable material. According to the research study of Kara and Korjakins (2012), the glass has pozzolanic effect in the state of excellent powder which can help to enhance the mechanical and durability properties of the concrete as it contains a high amount of silica. Besides, titanium dioxide (TiO_2) is a standard white pigment which usually used in painting, printing inks, plastic, cosmetics, food, and others. Titanium Dioxide can be applied in multiple fields due to its non-toxic, non-reactive, and glowing properties. According to Yurtoglu (2018), titanium dioxide has a pozzolanic effect which can help to enhance the mechanical and durability properties of the concrete and titanium dioxide also can reduce the pore structures of the concrete by filling up the minor void. In this research study, the fabrication of lightweight green concrete in this research study is incorporating with green colored waste glass powder with a particle size of 125 - 180 μm and TiO_2 to reduce the usage of cement in the concrete production which can help to minimize the environmental problems and ground granulated blast furnace slag (GGBS) will act as the lightweight aggregate. In this research study, the properties of fresh concrete are determined by the flow table test, the mechanical properties of the concrete are determined by compressive strength test, flexural strength test and scanning electron microscopy test (SEM), the durability properties of the concrete are determined by water absorption test, porosity test, air permeability test, and chloride penetration test. The analysis of the results obtained from various lab test is used to compare the lightweight green concrete with the control concrete to investigate the effects of the substitution materials and improvement on properties of concrete. The optimum green lightweight concrete has been determined, and the optimum concrete is incorporating with 20% substitution portion of green-colored glass powder and 1% substitution portion of TiO_2 for partial cement replacement. The optimum green lightweight concrete has achieved a compressive strength of 104 N/mm^2 and excellent performance in the durability of concrete. Lastly, lightweight green concrete is successfully fabricated as a potential sustainable construction material in the near future.

TABLE OF CONTENTS

LISTS OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ ABBREVIATIONS

%	Percentage
<	Less than
>	More than
≤	Less than equal
≥	More than equal
cm^3/s	Cubic centimeter per second
g	Gram
kg	Kilogram
kg/m^3	Kilogram per cubic meter
km	Kilometer
km/s	Kilometer per second
kN	Kilo newton
kN/s	Kilo newton per second
kV	Kilo volt
m	Meter
m^2	Meter square
m^3	Meter cube
m^2/kg	Meter square per kilogram
mm	Millimeter
mm^2	Millimeter square
µm	Micrometre
N	Newton
N/mm^2	Newton per millimeter square
s	Second

μm	Micrometer
RM	Ringgit Malaysia
Al_2O_3	Alumina
BaO	Barium oxide
CaO	Calcium oxide
CO_2	Carbon dioxide
Cr_2O_3	Chromium (III) oxide
Fe2O3	Iron oxide
K_2O	Potassium monoxide
MgO	Magnesia
MnO	Manganese (II) oxide
Na_2O	Sodium oxide
NaCl	Sodium chloride
SiO_2	Silicon dioxide
SO_3	Sulfur trioxide
TiO_2	Titanium dioxide
$AgNO_3$	Silver nitrate
$CaCO_3$	Caclium carbonate
LOI	Loss on ignition
SLAC	Sustainable lightweight aggregate concrete
CH	Calcium hydroxide
C-S-H	Calcium silicate hydrate
EDX	Energy dispersive X-ray
GGBS	Ground granulated blast furnace slag
LWC	Lightweight concrete
MBG	Mixed broken glass
SEM	Scanning microscopy electron
UPV	Ultrasonic pulse velocity

CHAPTER 1

INTRODUCTION

1.1 Research Background

Concrete is an essential material in the construction industry, and it is the combination of binding material and inert material such as cement, water, fine and coarse aggregates such as sand, gravel, crushed stones, and others. Cement can be defined as an inorganic finely ground powder substance made by limestone and clay. The cement reacts with water to form the paste that sets and hardens by hydration process. The cement reacts with water formed binding effect to bind the fine and coarse aggregates together to form concrete.

Several reasons cause concrete to be the first option for most of the building construction project. First, the cost of concrete is economical, it required low maintenance and rigidity. The availability of material for concrete is widespread, and it is suitable for structural and architectural function. The usage of concrete has involved in small structure building, superstructure building, bridge, culvert, and others. This is due to concrete has high workability and able to construct any shape of the structure. Due to the rapid population growth and development of the countries, the demand of construction by using concrete was increasing with the generation rate of almost 3 tons of concrete per person every year (Elia, 2018). The massive production of concrete has led negative impacts to the environment and human health, during the production of concrete the calcination process will break down the limestone into calcium oxide (CaO) and carbon dioxide which cause carbon emission. According to the study of Flower and Sanjayan (2007), cement is the highest contributor to carbon emissions in the actual production process, which up to 81%. Based on the study of Andrew (2018), the production of concrete generated about 1500 million tons of carbon dioxide emission yearly, which mainly contributed by the usage of cement. The concrete business is a potential anthropogenic wellspring of air contamination, and it is a significant contributor to nitrogen oxides (NO_x), dust, sulphur oxides (SO_x) and carbon monoxide (CO).

As a result, in the study of fabricating sustainable concrete, partial replacement of cement with waste materials has become one of the vital topics. The waste glass will be an excellent option to replace part of the cement in the concrete production as it will show pozzolanic properties in the state of very fine powder (Shilpa and Kumar, 2014). Besides cement reduction, the partial replacement of cement with wastes glass could help in reducing the amount of waste glass in the landfill, which is non-biodegradable products (Jani and Hogland, 2014).

Besides of waste glass, titanium dioxide nanoparticle also one of the materials that can replace part of the cement in the production of concrete. Titanium dioxide is a white inorganic compound, which has been utilized for around 100 years in countless items. It relies upon it for its non-toxic, non-reactive and glowing properties, which securely uplift the whiteness and brilliance of numerous materials. Furthermore, TiO_2 nanoparticles able to enhance crack resistance of the concrete by filling the pore structure and move the circulated pores to innocuous and less-hurt pores. Besides, it could enhance the compressive strength of the concrete due to it accelerates the hydration process, which accelerates the calcium silicate hydrate (C-S-H) gel formation (Ali and Shadi, 2011). Titanium dioxide could help to enhance the air quality by reducing or absorb the air pollutant such as volatile organic compounds (VOC) and nitrogen oxides in the presence of ultraviolet (UV) light (Davis and Divya, 2015).

Other than the discharge of carbon dioxide from the generation of concrete, ordinary concrete additionally experiences the ill effects of overwhelming weight that makes it unfeasible for specific applications, and it has increased the cost of construction due to the additional worker and machine needed to carry out the construction project. Due to these problems, lightweight concrete has been invented and become popular in the construction project nowadays. Lightweight concrete is a mixture of cement, water, and lightweight aggregates as filler materials, lightweight concrete show relatively low density compare to the ordinary concrete. Ground granulated blast furnace slag is a feasible choice of lightweight aggregates for the lightweight concrete production, it is gotten by extinguishing liquid iron slag (a result of iron and steel-production) from a blast furnace in water or steam, to create a smooth, granular item that is then dried and ground into a fine powder (Suresh and Nagaraju, 2015).. The chemical composition of ground-granulated blast-furnace slag are calcium oxide, silica, alumina (Al_2O_3), and magnesia, and it will able to enhance the compressive strength of the lightweight concrete due to it contains a high percentage of calcium oxide. Furthermore, ground granulated blast-furnace slag is considered as a waste of iron production, by using it as lightweight aggregates can help to reduce the environmental issue.

In this study, titanium dioxide is used to replace part of the cement with different percentage of substitution. The green-coloured wastes glass powder with a size of 125-180 μm will replace 20% of the cement in the lightweight concrete. Besides that, the ground granulated blast-furnace slag will be lightweight aggregates. Hence, this study will way greener and economic course of fabricating lightweight concrete for different development applications in the future.

1.2 Problem Statement

Global warming and climate change have become one of the vital environmental problems, and it would have adverse effects on human health and the ecosystem. The production of cement is one of the origins which cause global warming which is 40% from combustion and 60 % from calcination, and it has contributed approximately 5 percent of the global carbon dioxide emission which is about 1500 million tons of carbon dioxide according to Andrew (2018). As the world population is increasing gradually, it leads to an increasing amount of construction project and the usage of cement, according to Afshinnia and Rangaraju (2016), there is approximately 0.9

pounds of carbon dioxide release to the environment for every pound of cement produced.

The ground granulated blast furnace slag is the by-product of the production of iron, and it has generated approximately 360 tonnes per year according to the study of Rashad and Sadek (2017). A large amount of ground granulated blast furnace slag is considered as one of the environmental issues due to limited landfill and disposal site, and its disposal process is costly and non-productive.

Besides the problem of carbon dioxide emission and GGBS, massive amount of waste glass disposal also consider as one of the environmental issues because there are limited disposal sites and landfill. Glass is considered as non-biodegradable material due to it does not decompose over a short period of time, glass can take one million years to decay. At the point when quite a bit of this glass sits in landfills, advances into our oceans or is littered all through characteristic living spaces, the outcomes of untrustworthy reusing can be annihilating. Glass reusing in Malaysia is still in its earliest stages. Under 30% of new jugs are produced using reused glass contrasted with 80% in Thailand and 60-70% in Europe, a larger part of glass still ends up at landfills (Tiew, Ahmad Basri, Watanabe, Abushammala and Bin Ibrahim, 2014). Next, the cost of the recycling process of glass is expensive, and the procedure is difficult. First, most of the waste glass mixed with others waste materials in the landfills, although there are drop-off recycling center and curbside recycle dustbin the efficiency is low, therefore the glass need to undergo the segregation process before the recycling process. The waste glass has to go through sorting process due to differences in colour and composition, and the recycler will reject some of the glass due to contaminated (Blengini, Busto, Fantoni and Fino, 2012).

Besides, cracking has become a common phenomenon for conventional concrete slab, column, and beam, this is due to plastic shrinkage, expansion, and contraction, heaving and settling, overload, improper drying and others (Gesoglu, Ozturan and Guneyisi, 2004). On the off chance that these cracks are changeless and are not solve promptly, they could likewise permit the entrance of aggressive agents, for example, chloride, sulphate, and carbonates, which may instigate the erosion of steel support and the carbonation of cement to abbreviate the service life of concrete structures. Besides, it also will cause damage from freeze and thaw, and during the flood, the building located near to the seawater will cause huge chloride to enter the structure. According to Jacobsen, Marchand and Boisvert (1996), the pore structure of the concrete also a critical criterion as it will affect the compressive strength and characteristics of the concrete.

The emission of volatile organic compound is one of the critical environmental issue, the volatile organic compound are common air pollutants which can be discharged from the cement and building materials in the indoor situation. These able to arouse adverse effects on human health such as eye irritation, damage to liver, headaches, and other health problem. Next, in the outdoor environments, the volatile organic compound are discharged from the power plant and vehicles, the volatile organic compound react with the nitrogen oxide under the sunlight to form particulate matter (PM) (Cha, Saqlain and Seo, 2019). The nitrogen oxide is generated during the process of combustion, where the reaction between nitrogen and oxygen gases occur. In the urban area with high motor vehicle traffic usually will have high emission of nitrogen oxides to the environment like an air pollutant, it caused negative effects to the vegetation and human health such as poor respiratory condition.

Furthermore, the construction project using conventional concrete has a relatively higher cost compared to the lightweight concrete due to the heavyweight of conventional concrete. This issue will cause unfeasible for specific construction job applications and require additional worker and machine needed to carry out the construction project. Besides, the heavy load of conventional concrete also increase a dead load of the structure, the require construction elements and reinforcement steel bar, which will increase the cost of construction.

In this manner, this investigation is center to these main issues in the development business for a superior and cleaner condition sooner rather than later.

1.3 Aim and Objectives

The aim of this study is to determine the characteristics of the sustainable lightweight aggregate concrete (SLAC) with cement replacement of 20% of green colour waste glass powder with size 125-180 μm and further reduce the cement with different portion of titanium dioxide (TiO_2). Hence, the optimum substitution portion of titanium dioxide (TiO_2) for the cement replacement will be determine in this study.

The objectives of the research study are shown as following:

i) To fabricate sustainable lightweight aggregate concrete (SLAC) with incorporation of titanium dioxides (TiO_2), green colour waste glass and ordinary Portland cement (OPC).

ii) To determine the optimal ratio of titanium dioxides (TiO_2) in the sustainable lightweight aggregate concrete (SLAC) design.

iii) To study the engineering and durability properties of the sustainable lightweight aggregate concrete (SLAC)

1.4 Scope of Study

The scope of the study for this research is concentrating on determining the characteristics of the sustainable lightweight aggregate concrete with the fixed 20% substitution of green coloured waste glass particles with size 125-180 μm and a various portion of titanium dioxide. The laboratory experiment will be carried out to investigate the workability, engineering and durability properties of the sustainable lightweight aggregate concrete with the partial replacement of cement with 20% of green coloured waste glass and various portion of titanium dioxide, the substitution portions of titanium dioxides for the partial cement replacement will be 0.5%, 1%, 2% and 3%.

In this research, the ratio of cement to ground granulated blast furnace slag is 1: 2.6, and the water-cement ratio is 1.0. The concrete mould of 50mm × 50mm × 50mm cube, 40mm × 40mm × 160mm beam and cylinder with 40mm height and

45mm diameter will be used in this research. All concrete specimens will undergo the curing process of 7 days, 14 days, and 28 days. Next, the compressive strength test, flexural test, scanning electron microscopy, water absorption test, porosity test, chloride penetration test and air permeability test will be carried out in this research to determine the characteristics and performance of the sustainable lightweight aggregate concrete with the effect of various portion of TiO_2.

1.5 Thesis Organization

This research consists of five chapters, which are the introduction, literature review, research methodology, results and discussion, and conclusion respectively.

Chapter 1: Introduction

This chapter discusses the background of concrete, ground granulated blast furnace slag, waste glass, and titanium dioxide. Besides, this chapter also discusses the problem statement, aim and objectives, and scope of the study for this research.

Chapter 2: Literature Review

This chapter traces the comprehensive research study report on literary works. It explains the foundation of concrete creation and its application chiefly in the construction industry. Other than that, it additionally audits on the disadvantages of these construction materials and its risk to the earth. It likewise explains the solution to conquering such downsides.

Chapter 3: Research Methodology

This chapter discusses the preparation of the required materials and the procedure of the fabrication process of the sustainable lightweight aggregate concrete (SLAC). Besides, the procedure and detail of the various testing method for the engineering and durability properties of sustainable lightweight aggregate concrete will explain in this chapter.

Chapter 4: Results and Discussion

This chapter presents the result of the various testing method of the engineering and durability properties of the sustainable lightweight aggregate concrete. The optimum substitution portion of TiO_2 for partial replacement of cement will discuss in this chapter.

Chapter 5: Conclusion and Recommendations

This chapter summarizes the critical result of the research from various experiment testing and provides recommendations for future studies.

CHAPTER 2

LITTERATURE REVIEW

2.1 History of Concrete

Concrete is an important material for the construction sector, which is the composite material of cement, water, fine aggregate, and coarse aggregate. There is a long history for the evolution of concrete, the earliest record of concrete is in 6500BC at the area of Jordan and Syria. The inadvertent discovery of lime to act as a building material due to the perpetual flame pits which used for heating and cooking purpose, this prompted a crude calcining of encompassing rock. The Nabataea dealer constructed the concrete floor, building structures, and underground reservoirs (Richard, 1995).

At 3000BC, archaeologists have likewise discovered cement material in the area of Gansu Province which located at the northwest of China, it is greenish black in shading and utilized for floors and contained a bond blended with sand, broken earthenware, bones, and water according to the study of Richard (1995). Besides, the people of China utilized mud blended with straw to tie the dried blocks. They additionally utilized gypsum mortars and mortars of lime to construct the Great Wall of China.

At that point, a wall painting from Thebes in Egypt is the soonest known illustration of concrete work from around 1950 BC, which showed the reason for mortar and concrete and different stages in the production.

At 300BC, the first Roman concrete is produced, Roman has improved the production of concrete technically by referring to the history of the evolution of concrete. Romans gave a name to this binding material with the word of concrete which came from Latin ‘concretus' which means compound and grown together. At 75BC, Romans has invented concrete which is produced with pozzolanic and hydraulic cement, it was a ground blend of lime and volcanic ash which remains containing silica and aluminum, and it is founded close to Pozzuoli, Italy and named as pozzolanic cement.

The Roman engineer was intended to create lighter weight and thinner wall section, and they utilized bronze strips and rod as the reinforcement for their concrete. However, the attempt failed, the reinforcement of bronze strips and the rod has slightly improved the tensile strength of the concrete, but it causes harmful effects on the concrete, which is cracking and spalling. This is due to the bronze has a higher rate of thermal expansion compared to the concrete, and this is the origin why Romans building only carry a load in compression in the Romans concrete generation according to Stanley (1999).

In the year 1830, reinforced concrete was first determined in the Encyclopedia of property, cabin and town plan which recommended that a network of iron tie shafts could be embedded in concrete to outline a housetop. A standout amongst the first utilization of reinforced concrete was in a few houses worked in 1866 by Joseph Tall at Bexleyheath in Kent (Stanley, 1999). A cross section of band iron was inserted in the first level rooftops, and he utilized his patent strategy for formwork for throwing the concrete walls.

2.2 History of Portland Cement

The Renaissance and Age of Enlightenment brought better approaches for the deduction, which prompted the industrial revolution. In eighteenth-century Britain, the interests of industry and realm agreed, with the need to construct shore beacons on presented rocks to counteract shipping misfortunes. The steady loss of vendor boats and warships drove cement innovation forwards.

In 1759, John Smeaton discovered a mortar which hardened under the reaction of water while constructing the third Eddystone lighthouse in Southwestern England, the composition of the mortar are lime, clay and crushed slag from the production of iron. In 1824, Joseph Aspdin had invented Portland cement and took out a patent, the method he utilized to produce Portland cement was heated the limestone and finely-ground clay until the limestone was calcined. Joseph Aspdin named this building material as Portland cement due to the production of concrete with this cement alike Portland stone, which is a common building stone in England (John, 1929).

According to Stanley (1999), the high quality and availability of raw materials, chalk, and clay of the Portland cement have made it well perform in the area of north Kent along the banks of the Medway and Thames rivers. In 1828, Joseph Aspdin performed his first cement work at Kirkgate in Wakefield.

Joseph Aspdin is known as the inventor of Portland cement, the cement designed by him was not generated at a high temperature to be the forerunner of modern Portland cement. In 1845, Isaac Johnson created the first modern Portland cement which is almost the same as the cement nowadays, Isaac Johnson heated the composite material of clay and chalked with a higher temperature which approximate 1400˚C to 1500 ˚C, the clinkering occur and the highly reactive and strong cementitious mineral formed. In the evolution of modern Portland cement, there are three crucial developments in the generating process which are the development of rotary kilns, grind the clinker and raw materials with ball mills, and control the setting with the addition of gypsum (Pepin, 2017).

2.3 Application of Concrete

Concrete is the most common building material it the world due to it has several characteristics that are very suitable for the construction activities. Conventional concrete is a composite material of Portland cement, water, fine aggregate and coarse aggregate which the Portland cement react with water to create a binding effect to bond the fine and coarse aggregate together. Concrete is a cost-effective and durable building material, it required low maintenance for an extended period, and it is high in compressive strength but low in tensile strength material, usually reinforce it will rebar to enhance the tensile strength. Concrete suitable for many types of a construction project such as small structure building, superstructure building, bridge, culvert, and others.

There are different usage for different strength of concrete, for concrete which the compressive strength is less than 14MPa is consider as shallow strength concrete, it is utilized for the purpose for creating lightweight concrete. The standard lightweight concrete is to replace the filler material with lightweight aggregate; the negative effect of this is the compressive strength of the concrete reduced. Next, concrete with compressive strength ranging from 20MPa to 32MPa is the often an option for the standard construction project such as house slab, driveways, footpaths, footing, and beams and column for a single storey or double storey buildings.

Besides, concrete with compressive strength higher than 40MPa is considered as high strength concrete, and it is often utilized in a mega construction project, which required high compressive strength to support the superstructure building. It is more expensive compared to ordinary concrete but with better durability. This type of concrete generally used for the lower floor columns of a high-rise building to minimize the required size of the column, it also used in the construction of a bridge which reduces the number of the required spans by using high strength concrete.

According to Kosmatka (2011), the application of concrete is suitable for construct the pathway, and another usage which is related to the transportation such as roads, airport, tunnels, road curb, rail tracks and others due to the concrete has excellent performance in withstand of high load and it is durable material which required low maintenance. Next, the excellent performance of concrete allowed it to become the material which used to build a building which is required to control or contain water. Most of the dams in the world are constructed with concrete and is also used to construct reservoirs. Concrete plays a vital role in the underground drainage system and sewerage system, concrete can construct any shape of culvert due to its workabilities such as pipe culvert and box culvert which is the common culvert for the underground drainage system.

2.4 Environmental Impact Caused By Conventional Concrete

The massive production of concrete has caused several negative impacts on the environment and human health. The cement industries released a huge amount of carbon dioxide, which is approximately 5% of the global carbon emission to the environment, which will cause the problem of global warming. In the production of cement, 40% of the carbon dioxide is produced by the combustion process, and 60% from the calcination process (Abu-Allaban and Abu-Qudais, 2011). The rapid development in the world has caused the usage of concrete increasing gradually, and it also directly increase the demand for cement. According to the study of Flower and Sanjayan (2007), cement is the highest contributor to carbon emissions in the actual production process, which up to 81%. Based on the study of Andrew (2018), the production of concrete generated about 1500 million tons of carbon dioxide emission yearly, which mainly contributed by the usage of cement.

Besides, according to the study Abu-Allaban and Abu-Qudais (2011), The cement industry is one of the air pollution contributors, it contributes a huge amount of nitrogen oxides, dust, sulphur oxides and carbon monoxide. The nitrogen oxides can cause acid rain, which will affect the vegetation sector and animal habitat. Besides, it also caused several problems towards human health, which are the respiratory problem, reduction of immunity toward lung infections, and others. The concrete business is a potential anthropogenic wellspring of air contamination, and it is a significant contributor to nitrogen oxides, dust, sulphur oxides and carbon monoxide .

Furthermore, the conventional concrete was too heavy, and it caused a higher cost for the construction project compared to the lightweight concrete. The heavyweight of the conventional concrete caused it unfeasible for specific construction job application. Besides, the heavyweight also increase transportation fees and increase the number of workers required. It also increases the dead load of the building due to the size of the column and beam, and it will increase the number of construction element and reinforcement steel bar required.

2.5 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag is a waste product from the blast furnace which utilized for the production of iron. The mixture of iron ore, coke and limestone are used for the operation at the temperature of 1500°C. The iron ore is decreased to iron and rest of the materials from a slag coast over the iron. The slag is occasionally tapped off as a liquid fluid, and if it is to be utilized for the production of ground granulated blast furnace slag, it must be quickly quenched in the huge volumes of water. The quenching enhanced the cementitious properties and generated granules like coarse sand. The granulated slag dried and ground to a fine powder (Suresh and Nagaraju, 2015).

The advancement of concrete design able to minimize the usage of natural resources, energy consumption, and reduce environmental pollutants. The huge amount of ground granulated blast furnace slag is produced from iron production, and it caused negative impacts on the environment and human due to the expensive and non-productive disposal. Ground granulated blast furnace slag is a white powder with 2.9 specific gravity, 1200 kg/m^3 of bulk density and 350 m^2/kg of fineness, and it is feasible for the substitution of aggregate in the production of concrete. The chemical composition of GGBS is 40% calcium oxide (CaO), 35% of silicon dioxide (SiO_2), 13% of alumina and 8% of magnesia, and it is similar to the chemical composition of Portland cement (Mali, Bagul, Biyani, Pandhare, Bafna and Joshi, 2017).

According to the study of Suresh and Nagaraju (2015), Ground granulated blast furnace slag is more durable compared to the ordinary Portland cement (OPC) and cementitious materials, it increases the life span of the building about 50 years to 100 years and during the process of hydration, it helps to reduce the production of heat thereby reduce the risk of thermal carking. The replacement of aggregate with GGBS reduced the cost of the concrete as GGBS is a waste material, it also enhances the compressive strength, durability, and chemical resistance of the concrete by reducing the pore structure of the concrete and produced more C-S-H gel in the concrete which can increase the strength of the bonding in the concrete.

The ground granulated blast furnace slag enhance the workability of the concrete mixture, it makes the placing and compacting process more manageable during the construction project especially when using the mechanical vibrator and cement pump (Modamed, 2018). Besides, it also caused the concrete to become less permeable and chemically more stable than conventional concrete. According to Karri et al., 2015, the improvement of the concrete resistance to any types of deleterious attacks such as disintegration due to sulphate attack, corrosion of reinforcement due to chloride attack and the alkali silica reaction which cause the cracking problem. From the literature survey, it is evident that the ground granulated blast furnace slag can enhance the properties of concrete. The study pertaining to it is reviewed and summarized in Table 2.1.

Table 2.1: Literature Studies on the Effects of Ground Granulated Blast Furnace Slag (GGBS) in Concrete

Title	Type of Material	Function	Substitution portion (%)	Compressive strength (MPa)	Reference
Experimental investigation of Mechanical properties of Geo polymer concrete with GGBS and Hybrid Fibers.	GGBS	Partial replacement of fly ash	0, 20, 40, 60 and 80	42.8	(Kumar, Muthu, Sagar and Yadav, 2018)
High performance concrete with GGBS and ROBO sand	GGBS and ROBO sand	Partial replacement of cement	0, 40, 50 and 60	39.0	(Malagavelli and Rao, 2010)
An experimental study on optimum usage of GGBS for the compressive strength of concrete	GGBS	Partial replacement of cement	0, 40, 50 and 65		(Oner and Akyuz, 2007)
Abrasion resistance and mechanical properties of Roller Compacted Concrete with GGBS	GGBS	Partial replacement of cement	0, 10, 20, 30, 40, 50 and 60	45.15	(Rao, Sravana and Rao, 2016)

2.6 Waste Glass as Partial Replacement of Cement

The huge amount of wastes glass disposal is considered as one of the environmental issues due to the limited disposal sites and landfills. The amount of waste glass is increasing gradually and occupied huge parts of the disposal site and landfill, the waste glass is non-biodegradable material, and this characteristic has caused waste glass will occupy space of landfill for a very long period (Heriyanto, Pahlevani, and Sahajwalla, 2018). At the point when quite a bit of this glass sits in landfills, advances into our oceans or is littered all through characteristic living spaces, the outcomes of untrustworthy reusing can be annihilating. According to the study of Abdul Kadir et al. (2016), recycle waste glass will be one of the solutions to minimize this environmental impact to reduce the usage of the landfill by the waste glass and conserve the raw material. Waste glass as an alternative material for part of the cement will be the solution, which can reduce the usage of cement and recycle waste glass.

The partial replacement of cement with waste glass able to reduce the usage of cement and the cost of concrete, thereby straightforwardly diminish the carbon dioxide emanation which is identified with the generation of concrete and decrease the production of concrete as the waste glass is utilized to replace part of the cement. According to Shilpa and Kumar (2014), waste glass is a suitable option to partially replace the cement in the generation of concrete as wastes glass has pozzolanic properties in the state of very fine powder.

The waste glass has the chemical composition of approximately 75% of silicon dioxide, sodium oxide (Na_2O), calcium oxide, iron oxide (Fe_2O_3) and other minor additives. Table 2.2 shows the chemical composition of cement, clear wastes glass, and green-coloured waste glass. According to the requirements of American Society for Testing and Materials ASTM C618-17a (2013), the minimum standard for pozzolans is 70%, the chemical properties of glass have higher than the standard and qualify to act as a pozzolanic cementitious material.

Furthermore, as a pozzolanic cementitious material, the glass powder gives increasingly uniform dissemination and a better volume of hydration product. The replacement of cement with glass powder able to adjust the cement paste structure.

The resulting pastes contain a higher amount of the solid calcium silicate hydrates and less of the powerless and effectively solvent calcium hydroxides (Ca(OH)2) than the conventional cement pastes (Vandhiyan, Ramkumar and Ramya, 2013). The calcium silicate hydrate formed in the pozzolanic reaction acts as a binding material to holds the bonding together, and it is the major source of the strength of concrete. The pozzolanic reaction is the reaction of silica and calcium hydroxide in the presence of water to form calcium silicate hydrate, which shown in Figure 2.1. Besides, the calcium hydroxide able to react with carbon dioxide to form a solvent slat which will drain through the concrete and can cause blossoming.

According to the research study of Tan (2018), the green-coloured glass powder has more exceptional performance than the clear glass powder in the substitution of cement in the production of concrete. This is due to the presence of iron oxide in the coloured glass, the small amount of Fe_2O_3 able to improve the mechanical properties of the hardened concrete (Elaqra and Rustom, 2018). The partial replacement of cement by glass powder can improve the mechanical properties of the concrete such as reduction of pore structure in the concrete, enhancement of compressive strength and more durable and chemically stable with the reduction of CH. From the literature survey, it is evident that the partial replacement of cement with glass is effective in enhancing the properties of concrete. The studies pertaining to it is reviewed and summarized in Table 2.3.

Table 2.2: Chemical composition of Portland cement, clear glass and coloured glass (Allahverdi, Maleki and Mahinroosta, 2018; Ibrahim and Meawad, 2018)

Element	**Portland cement (%)** **Allahverdi, Maleki and Mahinroosta, 2018**	**Clear glass (%)** **Ibrahim and Meawad, 2018**	**Coloured glass (%)** **Ibrahim and Meawad, 2018**
SiO_2	22.50	75.20	71.28
Na_2O	0.24	11.10	14.61
CaO	63.26	12.55	10.83

Table 2.2: Continue

Element	Portland cement (%) Allahverdi, Maleki and Mahinroosta, 2018	Clear glass (%) Ibrahim and Meawad, 2018	Coloured glass (%) Ibrahim and Meawad, 2018
MgO	3.50	0.01	1.30
Fe_2O_3	3.44	0.04	0.50

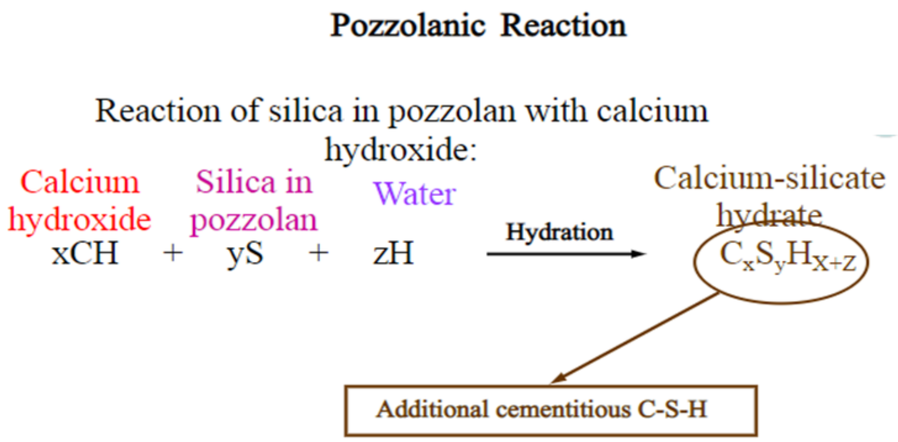

Figure 2.1: Pozzolanic Reaction (Ramyar, 2016)

Table 2.3: Literature studies on effects of waste glass in the properties of concrete

Title	Type of Material	Function	Substitution portion (%)	Compressive strength (MPa)	Reference
Utilization of waste glass powder in the production of cement and concrete	Clear Glass	Partial replacement of cement	5, 10, 15, 20 and 25	49.92	(Aliabdo, Abd Elmoaty and Aboshama, 2016)
Waste glass powder as partial replacement of cement for sustainable concrete practice	Clear Glass	Partial replacement of cement	5, 10, 15, 20 and 25	33	(Islam, Rahman and Kazi, 2017)
Study The Effect of Recycled Glass on The Mechanical Properties of Green Concrete	Green Glass	Partial replacement of cement	11,13 and 15	31.75	(AL-Zubaid, Shabeeb and Ali, 2017)
Effect of using glass powder as cement replacement on rheological and mechanical properties of cement paste	Clear Glass	Partial replacement of cement	10, 20, 25 and 30	51	(Elaqra and Rustom, 2018)

Table 2.3: Continue

Title	**Type of Material**	**Function**	**Substitution portion (%)**	**Compressive strength (MPa)**	**Reference**
Use of glass powder residue for the elaboration of eco-efficient cementitious materials	Mixed Glass	Partial replacement of cement	10, 20 and 50	38	(AL-Zubaid, Shabeeb and Ali, 2017)
Assessment of waste packaging glass bottles as supplementary cementitious materials	Glass	Partial replacement of cement	20	48	(Ibrahim and Meawad, 2018)

2.7 Titanium Dioxide (TiO_2) as Partial Replacement of Cement

Titanium Dioxide is a white organic compound which commonly utilized as a pigment in painting, printing inks, plastic, cosmetics, food, and others. Titanium Dioxide can apply in multiple fields due to it is non-toxic, non-reactive, and glowing properties. According to Yurtoglu (2018), titanium dioxide is commonly produced with two processes, which are sulphate process and chloride process, as shown in **Figure 2.2**. In the process of sulphate, ilmenite ($FeTiO_3$) which is a common material of iron and titanium oxide is utilized for the process, the concentrated sulphuric acid (H_2SO_4) is used to treat the ilmenite , and the titanium oxygen sulphate ($TiOSO_4$) is randomly converted into titanium dioxide. Furthermore, the chloride process is established to separate the titanium dioxide form the ores. The ilmenite is used to generate titanium dioxide from the chloride process, and it is treated with carbon and chlorine gas at the temperature of 1000°C.

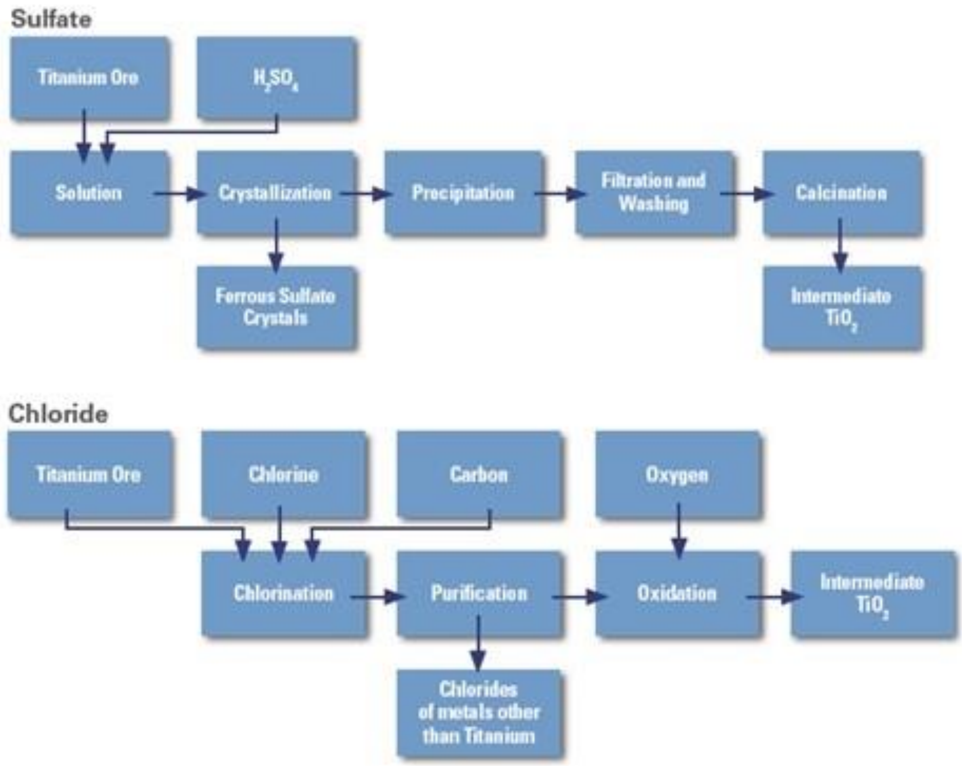

Figure 2.2: Manufacturing process of titanium dioxide (TiO_2)

Titanium dioxide applied in the production of concrete can reduce the air pollutants such as nitrogen oxides, carbon monoxide, volatile organic compounds, chlorophenols and aldehydes from the vehicle and industrial emanations. In Europe and Japan, The concrete products with self-cleaning effect have utilized for the facades of buildings and road paver. Furthermore, some studies have shown that titanium dioxide has the ability to accelerate the hydration process of the concrete at an early age, it can help to enhance the mechanical properties of the concrete such as compressive strength, flexural strength, crack resistance and abrasion resistance (Adul Hafiz and Prakash, 2017).

According to the study of Adul Hafiz and Prakash (2017) as shown in Table 2.4, the substitution portion of cement with titanium dioxide is inversely proportional to the initial setting time and final setting time of the concrete. The increase of substitution portion of cement with titanium dioxide has caused the decreasing in the initial setting time and final setting time for the concrete due to the titanium dioxide particle as fill up the pore structure of the concrete mixture. As a result, the titanium dioxide decreased the workability of the concrete as the substitution portion increase, and this is due to the titanium dioxide particle affected the fresh concrete mixture become sticky and stiff thereby decreasing the flow.

Table 2.4: Initial and final setting time (Adul Hafiz and Prakash, 2017)

% replacement of cement by TiO_2	Initial setting time (min)	Final setting time (min)
0%	90	410
0.5%	80	380
1.0%	70	350
1.5%	65	300
2.0%	60	280

The substitution of cement by titanium dioxide can enhance the mechanical properties of the concrete, such as compressive strength, flexural strength, and crack resistance. According to Ma, Li, Mei, Li and Chen (2015), the compressive and flexural strengths as the substitution portion of cement with titanium dioxide increase in the ranging from 0% to the optimum substitution portion. The crystallization process of the hydration product has enhanced the crystal orientation of CH between the hardened cement pastes and aggregates, and it also decreases the grain size of CH. Besides, the appropriate amount of titanium dioxide substitution has increased the form of C-S-H gels in the concrete which can enhance the mechanical properties of the concrete by minimizing the number of pore structures in the concrete. However, when the amount of substitution portion has beyond the optimum portion, the compressive strength and flexural strength of the concrete are reduced due to it caused more microcracks between the hardened cement pastes and aggregates, and drying shrinkage distortions of the concrete are expanded.

According to Lu, He, Ping, Wang, and Hu (2016), the partial replacement of cement by titanium dioxide able to enhance the shear strength and lateral strength of the concrete. The titanium dioxide particle has filled the pore structure in the concrete and imparting a dense microstructure to concrete. The cracks caused by shear force and lateral force is usually due to the pore structure in the concrete, the shear and lateral force pressure towards the concrete and the crack occur and follow the direction of the pore holes as shown in Figure 2.3. Besides, at the optimum substitution portion, the pozzolanic effect of titanium dioxide enhance the bonding in the concrete, which improved the lateral strength, shear strength, and crack resistance of the concrete.

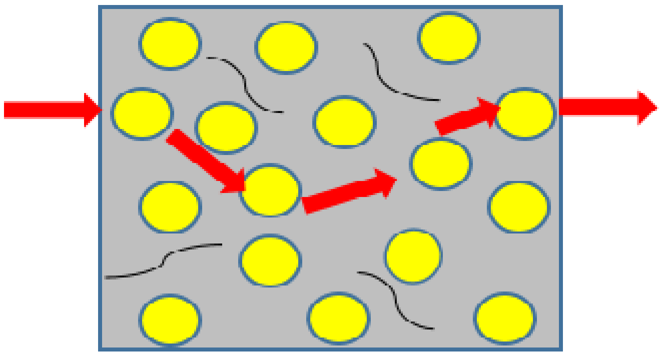

Figure 2.3: Cracking Behaviour of Concrete

The previous research studies are fabricating concrete with various substitution portion of cement with TiO_2 in the generation of concrete. The partial replacement of cement with various portion of TiO_2 and compressive strength achieved by previous research studies are shown in Table 2.5.

Form the previous research studies on partial replace cement with titanium dioxide, and it showed the titanium dioxide has positive effects on the fabrication of sustainable lightweight aggregate. It has improved the mechanical properties of the concrete such as compressive strength, flexural strength, shear strength and crack resistance, this is due to the appropriate amount of titanium dioxide in the composition of concrete has accelerate the hydration process, fill up and minimize the pore structure in the concrete, and titanium dioxide has influenced the amount of produced C-S-H gel during the production of concrete which can strengthen the bonding of binding material and filler material in the concrete.

Table 2.5: Previous Research Studies Related to Substitution of Titanium Dioxide (TiO_2) in Concrete

Title	Type of Material	Function	Substitution portion (%)	Compressive strength (MPa)	Reference
Effect of TiO_2 Nanoparticles on Physical and Mechanical Properties of Cement at Low Temperatures	TiO_2	Partial replacement of cement	1, 2, 3, 4 and 5	66.0	(Wang, Zhang and Gao, 2018)
Effect on Addition of Nano "Titanium Dioxide" (TiO2) on Compressive Strength of Cementitious Concrete.	TiO_2	Partial replacement of cement	0.50, 0.75, 1.00, 1.25 and 1.50	60.0	(Sorathiya, Shah and Kacha, 2017)
Evaluating the Effects of Titanium Dioxide (TiO2) and Carbon-Nanofibers (CNF) as Cement Partial Replacement on Concrete Properties.	TiO_2 and CNF	Partial replacement of cement	3 and 5	44.5	(Joshaghani, 2018)
Strengths and durability performances of blended cement concrete with TiO_2 nanoparticles and rice husk ash.	TiO_2 and rice husk ash	Partial replacement cement	0, 1, 2, 3, 4 and 5	48.0	(Praveenkumar, Vijayalakshmi and Meddah, 2019)

Table 2.5: Continue

Title	Type of Material	Function	Substitution portion (%)	Compressive strength (MPa)	Reference
Corrigendum to "The effect of TiO2nanoparticles on water permeability and thermal and mechanical properties of high strength self-compacting concrete	TiO_2	Partial replacement cement	0, 1, 2, 3, 4 and 5	50.1	(Nazari and Riahi, 2011)
Influences of Nano-TiO2 on the Properties of Cement-based Materials: Hydration and Drying Shrinkage	TiO_2	Addition of TiO_2	0, 1, 3 and 5	55.0	(Zheng, Cheng, Hou and Ye, 2015)
Experimental Investigation on The Effect of Nano-TiO_2 Particles on The Properties of Concrete.	TiO_2	Partial replacement of cement	0.0, 0.5, 1.0, 1.5 and 2.0	37.18	(Abdul, Hafiz and Prakash, 2017)

Table 2.5: Continue

Title	Type of Material	Function	Substitution portion (%)	Compressive strength (MPa)	Reference
The Use of 1% Nano-Fe3O4 and 1% Nano-TiO2 as Partial Replacement of Cement to Enhance the Chemical Performance of Reinforced Concrete Structures	TiO_2 and Fe_3O_4	Partial replacement of cement	1	33.0	(Braganca, Portella, Gobi, Silva and Alberti, 2017)
Influences of Nano-TiO2 on the Properties of Cement-based Materials: Hydration and Drying Shrinkage	TiO_2	Addition of TiO_2	0, 1, 3 and 5	55.0	(Zheng, Cheng, Hou and Ye, 2015)
Experimental Investigation on The Effect of Nano-TiO_2 Particles on The Properties of Concrete.	TiO_2	Partial replacement of cement	0.0, 0.5, 1.0, 1.5 and 2.0	37.18	(Abdul, Hafiz and Prakash, 2017)

Table 2.5: Continue

Title	Type of Material	Function	Substitution portion (%)	Compressive strength (MPa)	Reference
Compressive Strength of Concrete Reinforced by TiO2 Nanoparticles	TiO_2	Partial replacement cement	0, 2, 4, 6 and 8	39.3	(Yu, Kang and Long, 2018)
Experimental Analysis of Workability and Characteristic Strength of M40 and M60 Grade of Concrete by Partial Replacement of Cement with Nano TiO2	TiO_2	Partial replacement cement	0, 0.5, 1.0, 1.5 and 2.0	73.55	(Bhargavi, Revathi and Kumar, 2019)
Experimental Study of Photocatalytic Concrete using Titanium Dioxide	TiO_2	Addition of TiO_2	0.0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0	25.0	(Sakthivel, Kitcha, Dhanabal, Aravindan and Aravindh, 2018)

2.8 Lightweight Concrete (LWC)

Lightweight concrete is a concrete mixture with lightweight coarse aggregate or fine aggregate instead of the conventional aggregate such as rock (Bremner, 2008). According to Chaipanich and Chindaprasirt (2015), the lightweight concrete is categorized based on the density and the air-dried density not higher than 1920 kg/m^3 which is lesser compared to the conventional concrete 2400 kg/m^3 according to the ACl Committee 213 Guide for Structural Lightweight Aggregate Concrete (ACl 213, 2001).

Lightweight concrete has been used as building material in the early 1900s in the United States, it used to construct many types of construction work such as multi-storey building, long-span bridges, offshore platforms and others superstructure building based on Mindess, Young and Darwin (2003) There are several advantages in using low-density lightweight concrete in the construction such as low density, low thermal conduction, low shrinkage, and high heat resistance. Besides, it helps to reduce the cost of the construction project as it reduced the dead load of the building, it might lead to minimizing the size of the column and beam and also reduced the required material and reinforcement rebar. Besides, lightweight concrete also caused lower haulage cost and faster building rate, according to Wongkeo, Thongsanitgarn, and Chaipanich (2012).

Lightweight aggregate concrete can be divided into two types based on the type of aggregate which is full lightweight concrete which involved both fine and coarse lightweight aggregate in the concrete mixture, and the lightweight sand concrete which involved ordinary sand as its lightweight fine aggregates. The lightweight aggregate can be divided into three component, such as industrial waste lightweight aggregate, natural aggregate, and lightweight artificial aggregate. The industrial waste lightweight aggregate is the waste product of the industrial products such as fly ash ceramisite, expanded slag ball, ground granulated blast furnace slag (GGBS) and light sand. The natural aggregate considers as which is processed by the natural porous stone, for example, volcanic cinder, pumice, light sand, and others. The lightweight artificial aggregate is which is manufactured with local material such as ceramisite, clay, and expanded perlite.

Furthermore, according to Chaipanich and Chindaprasirt (2015), there are several types of lightweight concrete with various compressive strength for different purpose as shown in Table 2.6. The low-density concretes has compressive strength of 0.7 to 2.0 Mpa with the density ranging from 300 to 800 kg/m^3, it normally used to produce the concrete product which is not required to withstand heavy load such as lightweight brick. The moderate-strength concrete has compressive strength of 7 to 14 MPa with the density ranging from 800 to 1350 kg/m^3, it is normally used to construct light duty construction activities such as human walkway. And culvert. Next, the structural concretes has compressive strength of 17 to 63 MPa with the density ranging from 1350 to 1920 kg/m^3, it is used to construct superstructure building such as bridge, high-rise building and others.

Table 2.6: Types of lightweight concrete

Types	Compressive Strength, MPa	Density kg/m^3
Low-density concrete	0.7-2.0	300-800
Moderate strength concrete	7.0-14.0	800-1350
Structural concrete	17.0-63.0	1350-1920

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In this chapter, the sustainable lightweight aggregate concrete with 20% substitution of cement with green-coloured glass powder with size 125 - 180 μm and various substitution portion of titanium dioxide will be undergoing the various laboratory tests to achieve the goal of the research. Furthermore, the fabrication process, laboratory tests, which consist of engineering properties testing, and durability properties testing, will be discussed in this chapter. All the laboratory tests involved in this research study are according to the British Standard European Norm (BS EN) and the international standard of American Society for Testing and Materials (ASTM). The process of fabrication in this research study is shown in Figure 3.1.

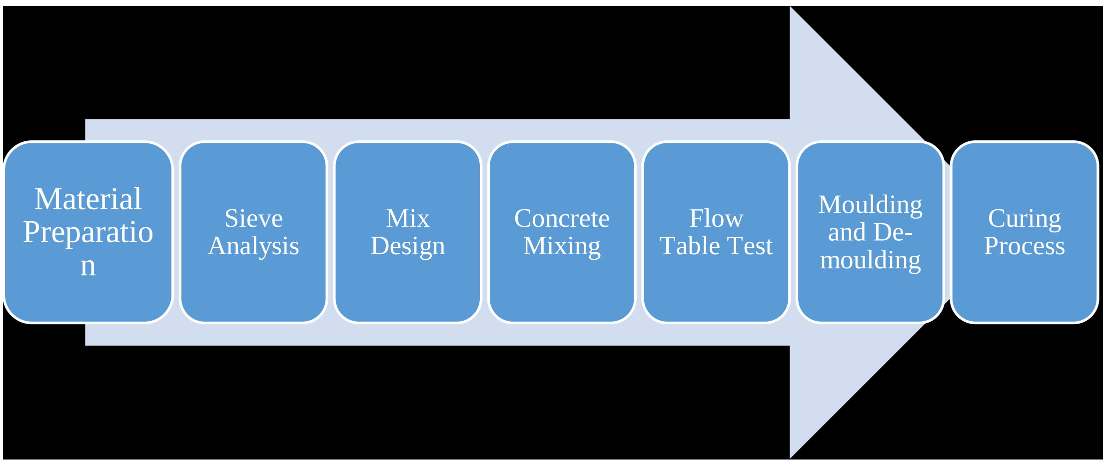

Figure 3.1: Process of fabrication of this research

3.2 Material Preparation

3.2.1 Ordinary Portland Cement (OPC)

In this research study, the Ordinary Portland Cement from Hume Cement Company is used as the binding material of the sustainable lightweight aggregate concrete. The quality of the Ordinary Portland Cement is obey to the British Standard European Norm (BS EN 197-1:2011) requirements, it is consider as the main material in the process of concrete production which react with water to bind the fine and coarse aggregates. The Ordinary Portland Cement used in this research study is shown in Figure 3.2.

Figure 3.2: Ordinary Portland Cement from Hume Cement Company

3.2.2 Green Coloured Waste Glass

The green-coloured waste glass is selected as the material to partial replace the cement in this research due to it will have pozzolanic properties in the state of very fine powder according to Shilpa and Kumar (2014). The coloured waste glass has the better improvement on the mechanical properties of the concrete compared to the clear waste glass due to the presence of iron oxide. According to the study of Elaqra and Rustom (2018), the small amount of iron oxide can enhanced the mechanical properties of hardened concrete. In this research, the green colour Carlsberg glass bottle as shown in Figure 3.3 is collected from few bistro and restaurants and it used as the green-coloured waste glass in this research. Furthermore, the green-coloured waste glass powder with particles size of 125 - 180 μm is used to substitute 20% of the cement in this research.

Figure 3.3: Green-coloured Carlsberg Glass Bottle

3.2.3 Titanium Dioxide (TiO_2)

Titanium dioxide is white organic compound as shown in Figure 3.4 which produce with the sulphate process and chloride process. Titanium dioxide is the common pigment for printing inks, painting, plastic, cosmetics and food due to its non-toxic, non-reactive and blazing characteristic. Furthermore, titanium dioxide has several advantage to the concrete such as enhance mechanical properties, self-cleaning effect, enhance crack resistance, enhance flexural strength and others. In this research, the sustainable lightweight aggregate concrete with substitution part of the cement with titanium dioxide which are 0.5%, 1.0%, 2.0% and 3.0%. Several laboratory test conducted to determine the optimum portion of the titanium dioxide in the sustainable lightweight aggregate concrete.

Figure 3.4: Titanium Dioxide (TiO_2)

3.2.4 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag is one of the suitable option for the lightweight aggregate which use to react with water and cement to form sustainable lightweight aggregate concrete, it is a waste product of the production of iron. The chemical composition of the ground granulated blast furnace slag are 8% of magnesia, 13% of alumina, 35% of silica and 40% of calcium oxide. Ground granulated blast furnace slag is a white colour powder which has a bulk density of 1200 kg/m^3 and 2.9 for specific gravity. Besides, Figure 3.5 shows the ground granulated blast furnace slag used in this research which is acquire from MDC concrete company and it is obey to the British Standard European Norm (BS EN 15167-1:2006) requirements.

Figure 3.5: Ground Granulated Blast Furnace Slag (GGBS) from MDC Concrete Company.

3.3 Sieve Analysis

In this research, the sieve analysis is conducted to classify the particle size of the green-coloured glass powder, and it is aim to obtain the glass powder with the particle size range of 125 - 180 µm. The green-coloured waste bottles were cleaned and dried for 24 hours by using the oven, then pulverized it with ice water and blended it by using the heavy duty blender to obtain it in powder form as shown in Figure 3.6. The sieve analysis test conducted in the research is obey to the British Standard European Norm (BS EN 410-1:2000) requirements.

The sieve shaker machine comprises of a few sifter sizes, it is setup with a decreasing order start with 300 µm, 180 µm, 125 µm, 106 µm and the bottom part placed with a pan. The process of sieving is approximately 15 minutes and the test is repeated twice to ensure the accuracy of the result. In the sieve analysis process, the waste glass powder will sieve through the bigger sieve pore and placed in the suitable sieve size.

Figure 3.6: Green-coloured Waste Glass Powder

3.4 Mix Design

In this research, the sustainable lightweight aggregate concrete are partially replace the cement with 20% of green-coloured waste glass powder with the size of 125 - 180 μm and various portion replacement of cement with titanium dioxide. The optimum substitution portion of titanium dioxide for the concrete mix design will be determined by various laboratory testing. The various substitution portion of titanium dioxide are 0.5%, 1.0%, 2.0% and 3.0% are shown in the Table 3.1, the water cement ratio is 1.1 and the ratio of cement to ground granulated blast furnace slag is 2.6. Each set of the concrete are required 15 cube specimens, 3 beam specimens and 3 cylinder specimens to conduct different laboratory testing. The dimension of cube specimens are 50mm x 50mm x 50mm, the dimension of beam specimens are 40mm x 40mm x 160mm and the dimension of the cylinder specimens are diameter of 45mm and 40mm of height.

Table 3.1: Quantity of Composites for Each 50mm x 50mm x 50mm Cube Specimen

Mix Design Code	Materials, (g)				
	Cement	GGBS	Waste glass powder	TiO_2	Water
C1	62.5000	162.5	0.0	0.0000	68.75
C2	50.0000	162.5	12.5	0.0000	68.75
T1	62.1875	162.5	0.0	0.3125	68.75
T2	61.8750	162.5	0.0	0.6250	68.75
T3	61.2500	162.5	0.0	1.2500	68.75
T4	60.6250	162.5	0.0	1.8750	68.75
R1	49.6875	162.5	12.5	0.3125	68.75
R2	49.3750	162.5	12.5	0.6250	68.75
R3	48.7500	162.5	12.5	1.2500	68.75
R4	48.1250	162.5	12.5	1.8750	68.75

***C1 - control concrete without any cement replacement

***C2 - 20% substitution portion of green colored glass

***T1 - 0.5% substitution portion of titanium dioxide (TiO_2)

***T2 - 1.0% substitution portion of titanium dioxide (TiO_2)

***T3 - 2.0% substitution portion of titanium dioxide (TiO_2)

***T4 - 3.0% substitution portion of titanium dioxide (TiO_2)

***R1 - 0.5% substitution portion of titanium dioxide (TiO_2) and 20% of glass

***R2 - 1.0% substitution portion of titanium dioxide (TiO_2) and 20% of glass

***R3 - 2.0% substitution portion of titanium dioxide (TiO_2) and 20% of glass

***R4 - 3.0% substitution portion of titanium dioxide (TiO_2) and 20% of glass

3.5 Flow table Test

The flow table test equipment as shown in Figure 3.7 is used to conduct flow table test to determine the workability of the fresh mixed concrete. The flow table test is conducted according to the British Standard European Norm (BS EN 12350-1:2009) requirements. Before conducting the flow table test, the round table surface and mould are cleaned to ensure there are no pollutants to affect the composition of the fresh concrete. Next, the mould is placed at the middle of the round table surface and filled with two layers of fresh mixed concrete. Each of the fresh mixed concrete layer are compacted well-distributed with 25 strokes by using the iron rod. After the first layer of concrete are compacted, filled the second layer of concrete in to the mould and undergo 25 strokes of compaction again then used a trowel to achieve flat surface. Next, the mould is removed vertically with careful, the original base diameter of the fresh mixed concrete are recorded by using the meter ruler. In the duration of 15 second, the round table is raised and drop continuously for 15 times to determine the workability of the fresh mixed concrete. The final average base diameter are recorded and the workability of the fresh mixed concrete is calculated with the Equation 3.1.

$$\text{Flow} = \frac{D_b - D_o}{D_o} \times 100 \quad (3.1)$$

Where,

D_b = Average base diameter, mm

D_o = Original base diameter, mm

Figure 3.7: Flow Table Test Equipment

3.6 Moulding, De-moulding and Curing Process

The concrete specimens required for the laboratory tests are cube specimen with dimension of 50mm x 50mm x 50mm, beam specimen with dimension of 40mm x 40mm x 160mm and the cylinder specimen with the dimension of 40mm height and 45mm diameter which . The concrete specimen mould as shown in Figure 3.8 are cleaned and applied lubricant engine oil on the surface before fill in the fresh mixed concrete to ensure the concrete are protected and easy to demould. The fresh mixed concrete is filled to the concrete specimen mould carefully with two layers, each layer is subjected to vibrate on the vibrating platform for 10 second to minimize the void of the concrete and the surface of the concrete has flatten by using a trowel after the vibration process. Next, the concrete specimen mould filled with fresh mixed concrete are placed at a safe place for setting of 24 hours.

After setting for 24 hours, the concrete specimens are demoulded from the concrete specimen moulds by using screwdriver and hammer. The concrete specimen are labelled with the mix design code and date of production.

The labelled concrete specimens are placed into the water container to undergo the curing process at the temperature of 35 ± 2°C which obey to the British Standard European Norm (BS EN 12390-2:2009) requirements. The concrete specimen cured for 7days, 14days and 28days under wet curing in the water container are took out from the water container and undergo certain laboratory tests such as compressive strength test, flexural strength test and others.

Figure 3.8: Cube Specimen Mould, Cylinder Specimen Mould and Beam Specimen Mould

3.7 Laboratory Test for Identification of the Characteristic of Concrete

In this research, the laboratory test consists of two major component which are the engineering properties and durability properties as shown in Figure 3.9, these tests are conducted to determine the optimum substitution portion of titanium dioxide in the sustainable lightweight aggregates concrete to meet the aim of this research. The engineering properties are tested with compressive strength test, flexural strength test and scanning electron microscopy test. The durability properties are tested with porosity test, water absorption test, air permeability test and chloride penetration test. The quantity of concrete specimen required has tabulated in the Table 3.2.

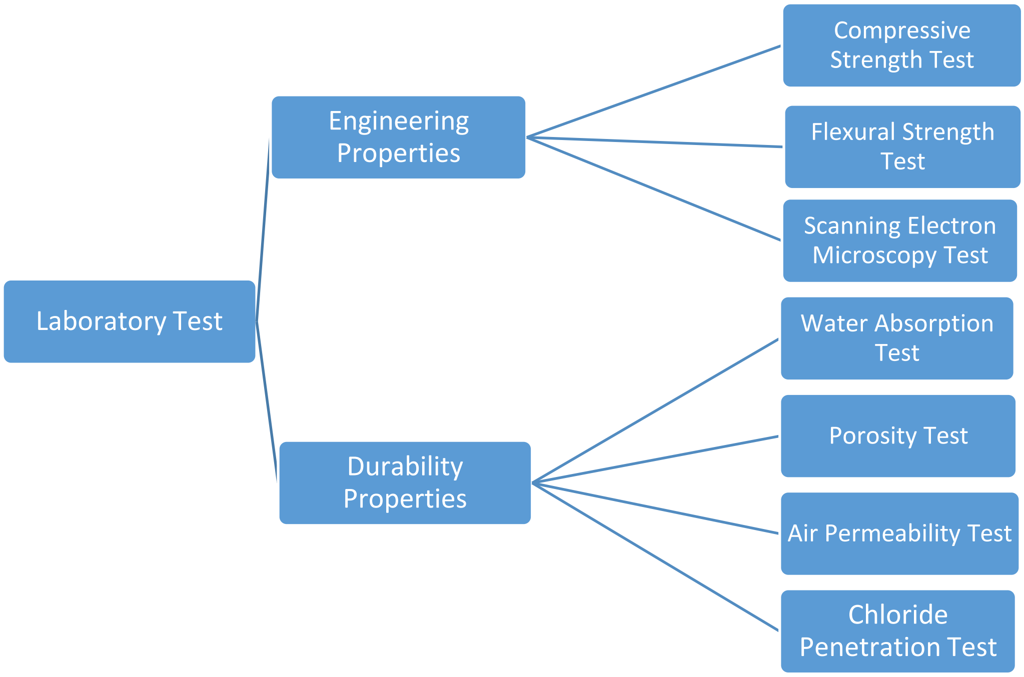

Figure 3.9: The Laboratory Tests of Engineering Properties and Durability Properties

Table 3.2: Quantity of Concrete Specimen for Each Laboratory Test

Tests	Age of Concrete , (Day)	Concrete Cube Specimens, (NO)	Concrete Beam Specimens, (NO)	Concrete Cylinder Specimens, (NO)
Compressive Strength Test	7	1	-	-
	14	1	-	-
	28	1	-	-
Flexural Strength Test	7	-	1	-
	14	-	1	-
	28	-	1	-
Water Absorption Test	7	1	-	-
	14	1	-	-
	28	1	-	-
Porosity Test	7	-	-	1
	14	-	-	1
	28	-	-	1
Air Permeability Test	7	-	-	1
	14	-	-	1
	28	-	-	1
Chloride Penetration Test	7	1	-	-
	14	1	-	-
	28	1	-	-

3.7.1 Compressive Strength Test

In this research study, compressive strength test is conducted by using Kenco compressive strength machine as shown in Figure 3.10 to determine the compressive strength of the sustainable lightweight aggregate concrete. The procedure of compressive strength test is obey to the British Standard European Norm (BS EN 12390-3:2009) requirements, and this test involved three concrete cube specimens which are age of 7 days, 14 days and 28 days respectively. First, the description of the specimen is set on the screen, placed the concrete cube specimen into the Kenco Compressive Strength Machine and run the test according to the instruction. The compressive strength of the cube specimen is recorded after the test and the specimen is removed from the machine and the machine is cleaned.

Figure 3.10: Kenco Compressive Strength Machine

3.7.2 Flexural Strength Test

In this research study, the flexural strength test is conducted by using the T-Machine universal testing machine as shown in Figure 3.11 to identify the flexural strength of the sustainable lightweight aggregate concrete. The procedure of flexural strength test is obey to the British Standard European Norm (BS EN 12504-4:2004) requirements and the test involved 3 concrete beam specimens which are age of 7 days, 14 days and 28 days respectively. The concrete beam specimen is placed into the machine, the three loading points are fixed to ensure the accuracy of the result. The maximum load capacity of the concrete specimen is recorded and the fracture point is observed.

Figure 3.11: T-Machine Universal Testing Machine

3.7.3 Scanning Electron Microscopy (SEM) Test

The scanning electron microscopy test is to identify the morphology of the sustainable lightweight aggregate concrete by using the scanning electron microscopy test machine as shown in Figure 3.12. This testing is obey to the American Society for Testing and Material (ASTM C1723-16:2016) requirements and only required small pieces of cube specimen of age of 28 days. The concrete cube specimen of 28 days age will be crushed into powder form after the compressive strength test, then it used to test for the scanning electron microscopy test.

Figure 3.12: Scanning Electron Microscopy Test Machine

3.7.4 Water Absorption Test

In this research study, the water absorption test is used to examine the water tightness of the sustainable lightweight aggregate concrete. The water absorption test is obey to the British Standard (BS 1881-122:2011) requirements and the test involved 3 concrete cube specimens of age of 7 days, 14 days and 28 days respectively. First the concrete specimen is dried for 24 hours by using the oven, then the concrete has taken out from the oven and the initial weight will be measured. The concrete specimen placed into the water container as showed in Figure 3.13 for 30 minutes and the final wet weight of concrete will be measured.

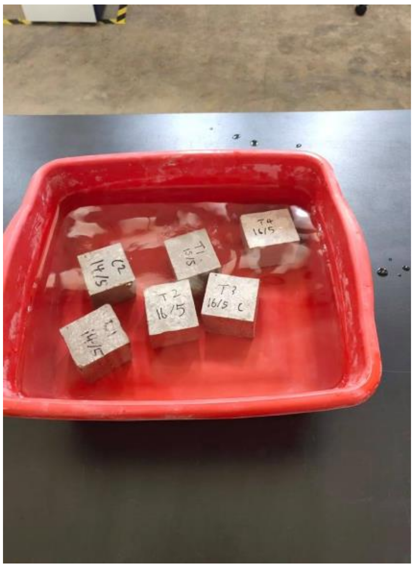

Figure 3.13: Water Absorption Test

3.7.5 Porosity Test

The porosity test is to determine the durability of sustainable lightweight aggregate concrete by using the porosity test apparatus. The procedure of this testing is referring to RILEM Recommendation and the test involved 3 concrete cylinder specimens of age of 7 days, 14 days and 28 days respectively. The cylinder concrete specimen is dried for 24 hours by using the oven and the weight of the dried concrete specimen is measured. The concrete specimen is placed into the desiccator as showed in Figure 3.14 which filled with water that is 1 cm above the height of the cylinder concrete specimen. The desiccator is sealed with high vacuum grease and operate for 15 minutes for the first time and 10 minutes for the second time after 2 hours and the saturated weight are recorded after 24 hours.

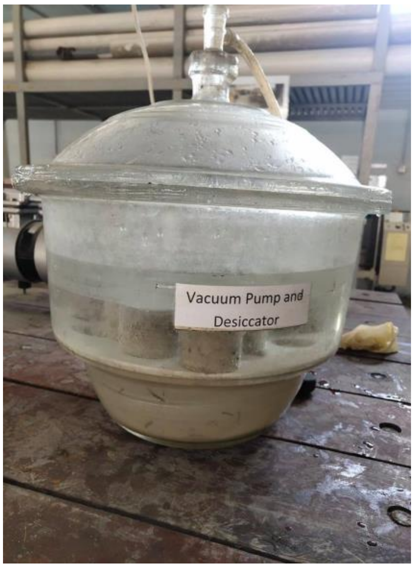

Figure 3.14: Vacuum Pump and Desiccator

3.7.6 Air Permeability Test

In this research study, the air permeability test is to determine the permeability of the concrete by using the air permeability test equipment as showed in Figure 3.15. The test is obey to the British Standard European Norm (BS EN 196-6:2010) requirements and the test involved three concrete cylinder specimens which are age of 7 day, 14 days and 28 days respectively . The concrete specimen is dried for 24 hours by using the oven, then the concrete specimen is cover by a thin layer of silicon rubber and place into the permeability cell. In this test, 2 bars of gas pressure is applied at the same time and the time of gas flow is measured with the bubble meter.

Figure 3.15: Equipment of Air Permeability Test

3.7.7 Chloride Penetration Test

The chloride penetration test is to determine the durability properties of the concrete in term of penetration of chloride. The test is obey to British Standard European Norm (BS EN 12390-11:2015) requirements and the test only involved concrete cube specimens with age of 28 days. The 28 days age concrete specimen is submerged in 4% of NaCl solution and splitted into half by utilizing a miter saw on the planned day. The 0.1 sliver nitrate ($AgNO_3$) is showered on the surface of the newly part of concrete specimen and the depth of the chloride penetration is recorded at the four edge of the splitted section as showed in Figure 3.16.

Figure 3.16: Chloride Penetration Test

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results of workability performance, engineering properties, and durability properties of the sustainable lightweight aggregate concrete will be analyzed and discussed. The analysis of the results will involve the control concrete, and the concrete with difference substitution portion of titanium dioxide and green colored glass with 125 - 180 μm particles sizes for the partial cement replacement.

4.2 Flow Table Test

Flow table test is used to determine the workability of the concrete, a good quality concrete with high workability can enhance the properties of the concrete primarily compressive strength due to an adequate degree of workability able to have minimum pore structure during the casting process, and at the same time, it is free from segregation. In this research study, all type of concrete undergoes flow table test, the diameter of the flows are recorded and presented in Table 4.1 and Figure 4.1, the water-cement ratio for all type of concrete are fixed at 1.1. Besides, all type of concrete in this research study have met the minimum requirement of the BS EN 12350-1:2009 standard, which is 50% of the percentage of flow.

In general, the percentage of flow increased while the while part of the cement is replaced by waste glass. From Table 4.1 and Figure 4.1, C2, which is concrete with 20% substitution portion of waste glass that without titanium dioxide has indicated the highest percentage of flow, which is 78%. On the other hand, T4, which is without substitution of glass, indicated the lowest percentage of flow, which is 54%. This is due to the greater particle size of glass powder resulted in the smaller surface area, and it decreased the ability of water absorption of the fresh concrete, thus increase in workability. Based on the study of Du and Tan (2014), the smooth surface and impermeable of waste glass have lower water absorption compared to cement.

Next, the percentage of flow decreased while the substitution portion of TiO_2 increased. Form Figure 4.1, R1, R2, R3 and R4 are concrete specimen which replaces cement with 20% of waste glass, and a different portion of titanium dioxide TiO_2 and their percentage of flow are 76, 75, 73 and 69 respectively. Besides, T1, T2, T3 and T4 are concrete specimen which replaces cement with a different portion of titanium dioxide only and their percentage of flow are 59, 58, 58 and 55. Both series of concrete are showing a downtrend when the substitution portion of titanium dioxide increased. It is due to the titanium dioxide is a finer particle which has more surface area and more exceptional water absorption ability during the state of fresh concrete. The higher water absorption ability caused the fluidity and workability of the fresh concrete decreased. According to the research study of Senff, Hotza, Lucas, Ferreira, and Labrincha (2012), the finer particle in the fresh concrete will have stronger cohesive van der Waals forces, and it will slightly affect the workability of the fresh concrete.

Lastly, the substitution of titanium dioxide has slightly affected the workability of fresh concrete. However, the workability of the lightweight green concrete incorporating with waste glass and titanium dioxide have still under the category of good quality concrete which is greater the minimum requirement of the BS EN 12350-1:2009 standard.

Table 4.1: Flow Table Test Result

Type of concrete	Flow (mm)	Flow (%)
C1	161	61
C2	178	78
T1	159	59
T2	158	58
T3	155	55
T4	154	54
R1	176	76
R2	175	75
R3	173	73
R4	169	69

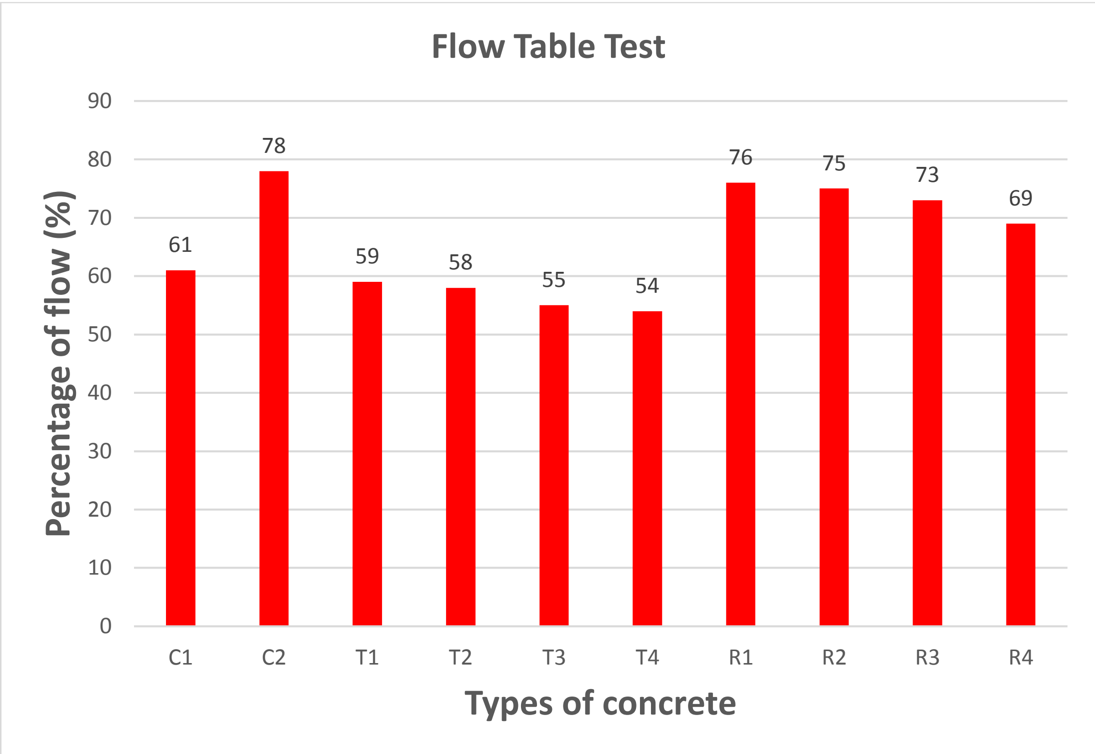

Figure 4.1: Results of Flow Table Test

4.3 Compressive Strength Test

Compressive strength is one of the engineering properties of concrete and the primary concern in the construction field. Table 4.2 and Figure 4.2 are indicating the results of the compressive strength test of all concrete specimen at 7 days, 14 days and 28 days. The compressive strength of the concrete is increasing gradually as the curing age of the concrete is increasing from 7 days to 28 days.

According to Figure 4.2, R2 has the highest compressive strength value which is 104 N/mm^2 at curing age of 28 days and the control specimen C1 has the lowest compressive strength value among all the concrete which is 52 N/mm^2 at curing age of 28 days with the difference of 52 N/mm^2 and R2 specimen achieve the highest pozzolanic activity index of 200% at the curing age of 28 days.

R2 concrete specimen is a lightweight green concrete with 20% substitution portion of green colored waste glass and 1 % of titanium dioxide for partial replacement of cement. The glass powder has higher amorphous silica content than the ordinary Portland cement, and it can undergo the pozzolanic reaction which is fully dissolved in the concrete and reacted with calcium hydroxide to generate calcium silicate hydrate gels (Ramyar, 2016). According to the research study of Fu and Tan (2017), the increase in calcium silicate hydrate gels generation can help to reduce the pore structure of the concrete and improve the compressive strength of the concrete. Besides, colored glass can improve the compressive strength of the concrete rather than non-colored glass due to the colored glass contain iron oxide. According to the study of Elaqra and Rustom (2018), the small amount of iron oxide can help to increase the compressive strength of the concrete.

Besides of 20% substitution of green colored waste glass for partial cement replacement, the R2 concrete specimen has further reduced the amount of cement with 1% of titanium dioxide. Titanium dioxide can generate more calcium silicate hydrate gels through the pozzolanic reaction, and it can help to enhance the mechanical properties of the concrete as it increases the forces of the particle bonding in the concrete. In general, the surface area of the titanium dioxide usually is larger than the micro-material, and it has high efficiency to adsorb more particles around them.

Besides, titanium dioxide can enhance the microstructure of the concrete by filling into it, and it can convert the harmful pore structures into simple pore structures which lead to the enhancement in compressive strength of concrete (Yu, Kang and Long, 2018).

Furthermore, Figure 4.2 showed the compressive strength of the concrete has improvement from 0% to 1% of substitution portion of titanium dioxide for partial replacement of cement, but it shows downtrend when the substitution portion of titanium dioxide is beyond 1%. This phenomenon is due to the decrease of the amount of crystalline which is required for the calcium silicate hydrate gels generation and unsatisfactorily scattered nanoparticles in the concrete matrix (Sorathiya, Shah and Kacha, 2017). Besides, when the dosage of the titanium dioxide is higher than the maximum limit of the substitution portion, it can cause drying shrinkage distortions of the concrete are magnified, it will cause more microcracks in the interface of the concrete resulting in the reduction of the compressive strength of the concrete (Ma, Li, Mei, Li and Chen, 2015).

In conclusion, the R2 concrete specimen has achieved the highest value in the compressive strength test, which is 104 N/mm^2. Thus, it reflected that the optimum substitution portion of titanium dioxide for partial replacement of cement is 1%.

Table 4.2: Compressive Strength Test Results

Concrete Specimen	**Compressive Strength Test (N/mm^2)**		
	7 Days	**14 Days**	**28 Days**
C1	32	44	52
C2	42	48	68
T1	35	56	64
T2	37	64	76
T3	34	60	64
T4	28	48	60
R1	42	68	96
R2	43	74	104
R3	41	72	84
R4	38	64	76

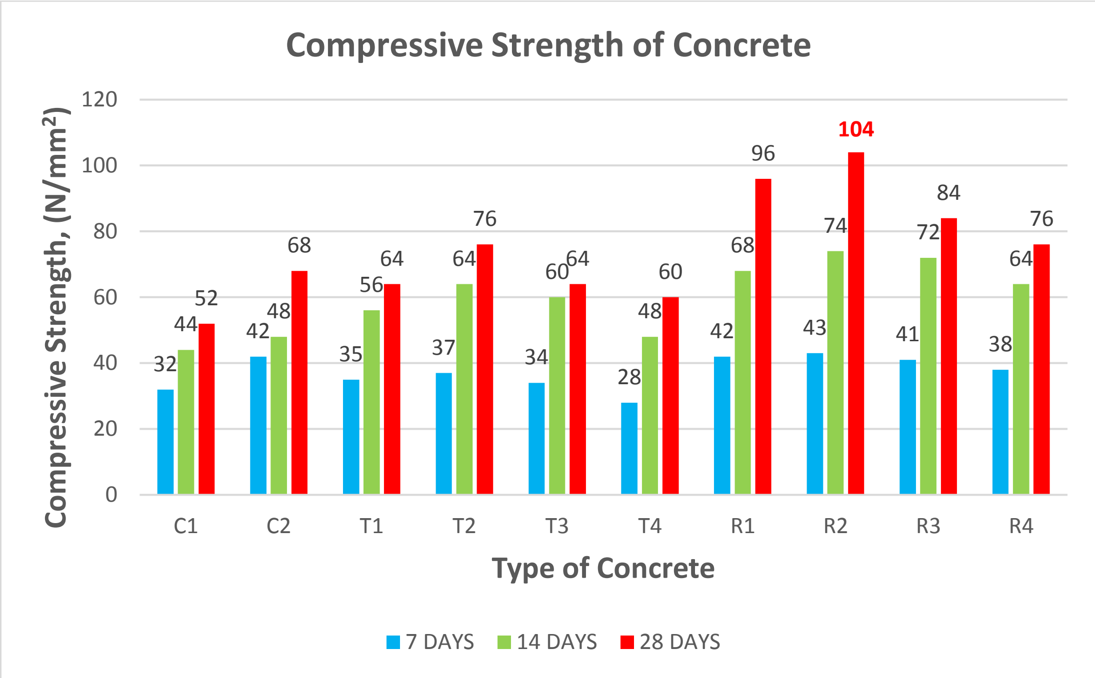

Figure 4.2: Results of Compressive Strength Test

Table 4.3: Pozzolanic Activity Index of green lightweight concrete

Concrete Specimen	**Pozzolanic Activity Index (%)**		
	7 Days	**14 Days**	**28 Days**
C1	100	100	100
C2	131	109	131
T1	109	127	123
T2	116	145	146
T3	106	136	123
T4	88	109	115
R1	131	155	185
R2	134	168	200
R3	128	164	162
R4	119	145	146

4.4 Flexural Strength Test

Table 4.4 and **Figure 4.3** indicated the flexural strength of the various type of concrete specimen conducted in this research study. All the concrete specimen achieved a gradual increment in term of flexural strength as the curing days increased from 7 days to 28 days. This phenomenon due to the pore structure and minor crack in the interface of the concrete will be minimized as the curing days increased.

At the curing age of 7 days, R2 concrete specimen achieve the highest flexural strength among all the concrete which is 7.85 N/mm^2 while the control concrete specimen C1 obtained 5.52 N/mm^2 with the improvement of 42%. On the other hand, the T4 concrete specimen has achieved the lowest flexural strength among all of the concrete, which is 5.33 N/mm^2, and it is lower than the control concrete specimen C1. This phenomenon is due to the T4 concrete specimen, replace part of the cement with 3% of titanium dioxide, which has exceeded the optimum dosage amount of titanium dioxide. According to the study of Ma, Li, Mei, Li, and Chen (2015), excess of titanium dioxide will cause the increase of surface area and water absorption ability, and it reduced the workability and fluidity of the fresh concrete. Therefore, it will be challenging to put into the casting mould compared to another type of concrete, and it can cause more pore structures in the concrete specimen.

At the curing age of 28 days, R2 concrete specimen has achieved the highest flexural strength among all the concrete which is 14.96 N/mm^2, and the lowest flexural strength among all the concrete was achieved by the control concrete specimen C1 which is 8.20 N/mm^2, it indicated the difference of 6.76 N/mm^2 and improvement of 82%. This is due to the glass powder has improved the workability of the concrete due to the greater particle size, it caused the concrete can fill in the mould quickly which lead to minimizing the pore structure during the state of fresh concrete. Besides, the titanium dioxide also generated more C-S-H gels and reduced the minor pore structures in the interface of the concrete specimen, which enhances the mechanical properties of the concrete and prevents the cracking behaviour of concrete. The titanium dioxide particle has filled the pore structure in the concrete and imparting a dense microstructure to concrete (Lu, He, Ping, Wang and Hu, 2016).

Table 4.4: Flexural Strength Test of Green Light Weight Concrete

Concrete Specimen	Flexural Strength (N/mm^2)		
	7 Days	14 Days	28 Days
C1	5.52	7.80	8.20
C2	7.53	7.85	8.94
T1	6.69	8.06	8.56
T2	7.23	8.58	9.79
T3	5.93	8.42	9.67
T4	5.33	7.89	8.36
R1	7.49	9.22	14.48
R2	7.85	11.23	14.96
R3	7.41	9.44	13.18
R4	7.16	8.59	11.61

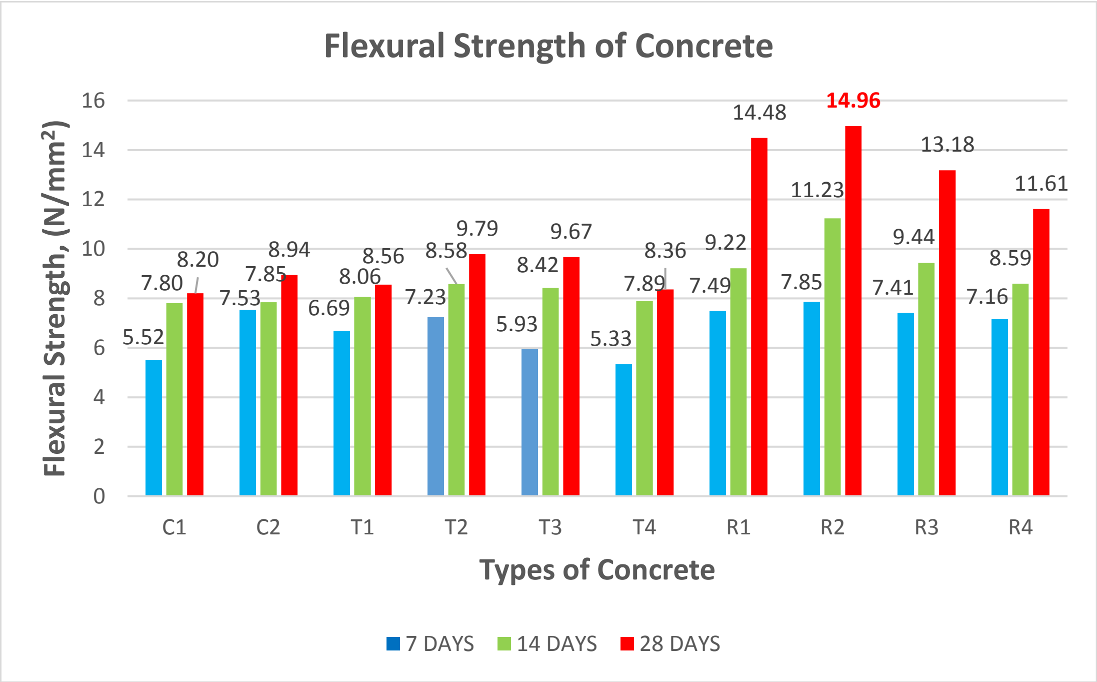

Figure 4.3: Flexural Strength of Green Lightweight Concrete

4.5 Scanning Electron Microscopy Test (SEM)

Figure 4.4 to Figure 4.13 illustrated the SEM images of all type of concrete which conducted in this research study. The amount of CH bond affects the number of pore structures in the concrete. During the hydration process, the CH bond appears in the cement paste, which grows in the fine pore structures. CH bond is considered as one of the soluble substances, and once it dissolved, it will leave the space of pore and is known as the occurrence of pore structures. This phenomenon happened on the control concrete specimen C1 as shown in Figure 4.4, and it has the highest amount of CH bond generated in the concrete due to it has lowest pozzolanic reaction compared with other concrete in this research study. Therefore, it has more void or pore structures.

The R2 concrete specimen, as shown in Figure 4.11, has the least amount of pore structures compared with other concrete involved in this testing. Waste glass as the material for partial cement replacement can produce a dense and uniform microstructure as shown in Figure 4.11. In addition, the titanium dioxide and green coloured waste glass can reduce the amount of CH bond in the concrete, which helps to minimize the void or pore structures in the concrete. Besides, titanium dioxide can fill the microstructure in the concrete, which can make the concrete more compact and less void. Hence, this will improve the strength of the concrete.

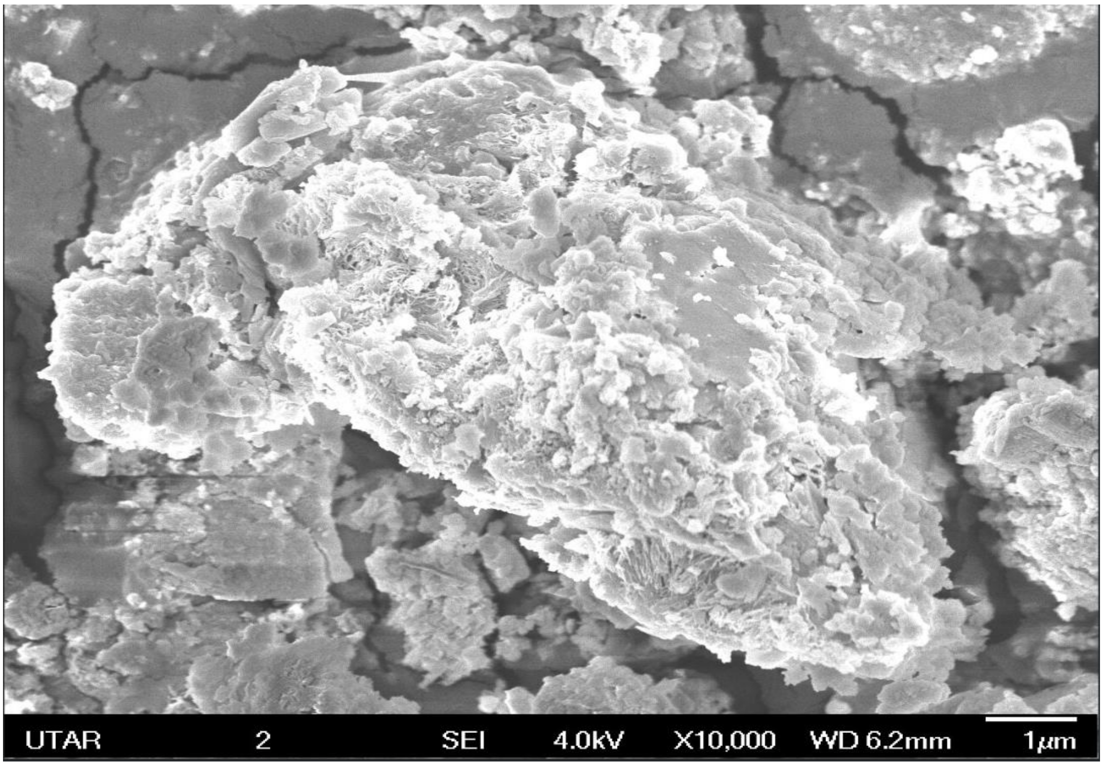

Figure 4.4: SEM Micrograph of C1 at Magnification of 10000

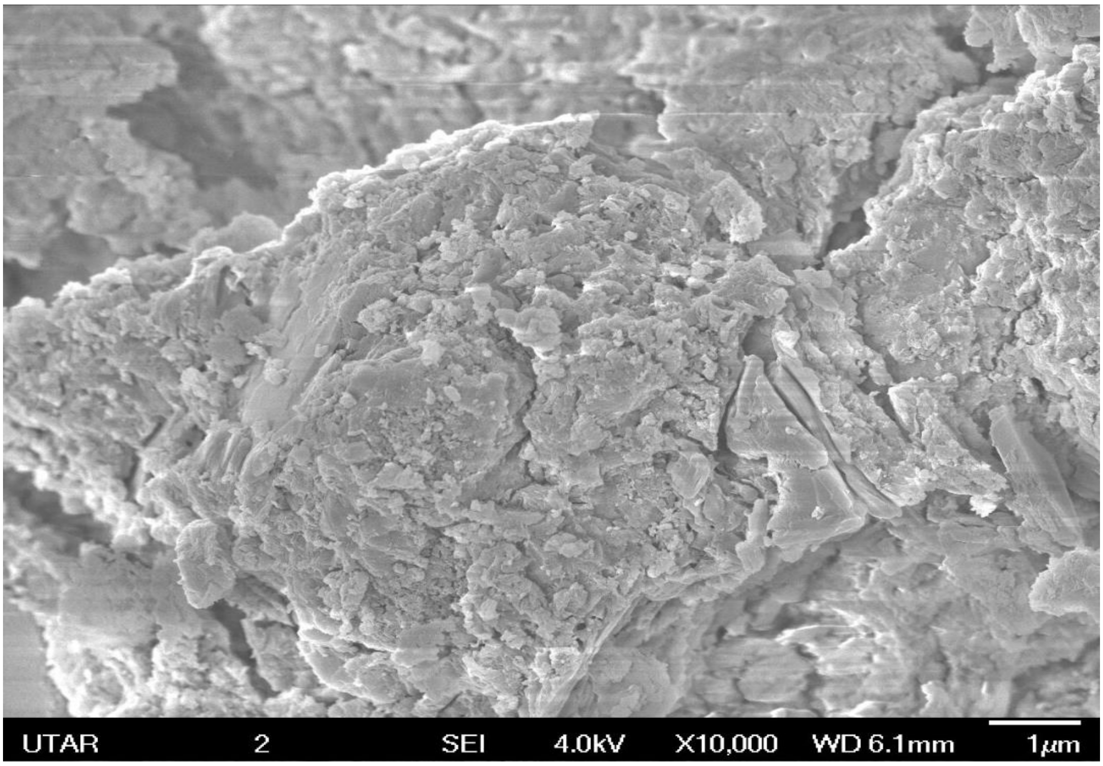

Figure 4.5: SEM Micrograph of C2 at Magnification of 10000

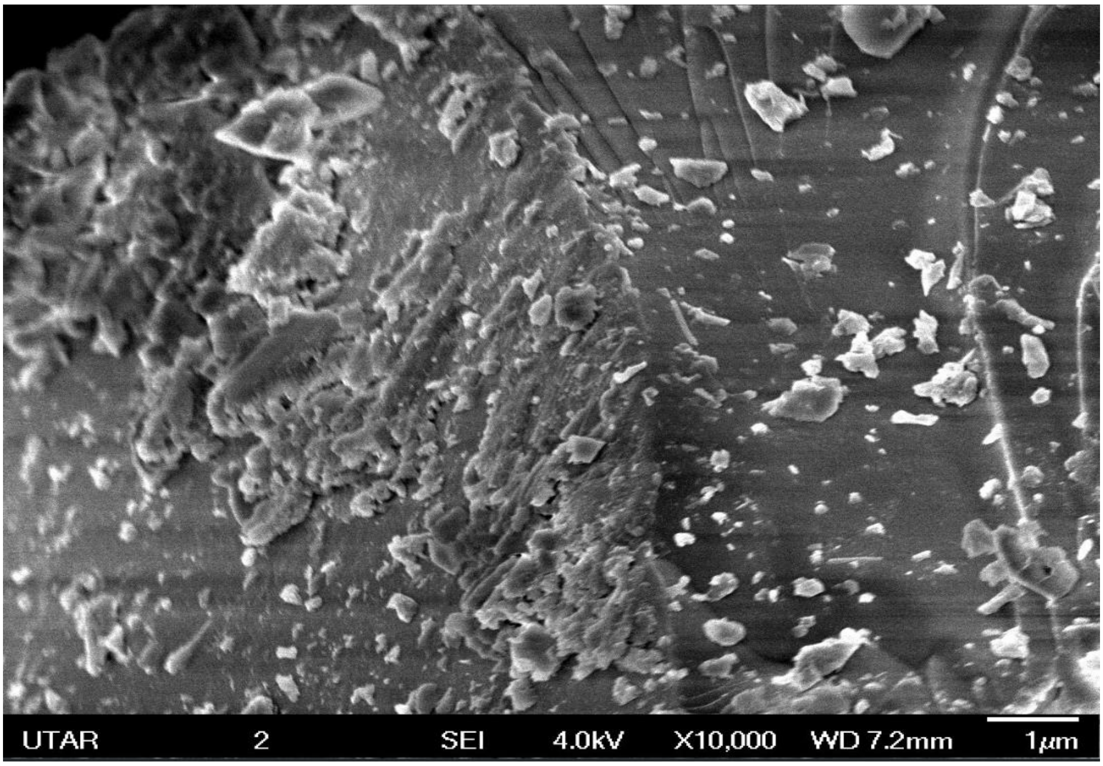

Figure 4.6: SEM Micrograph of T1 at Magnification of 10000

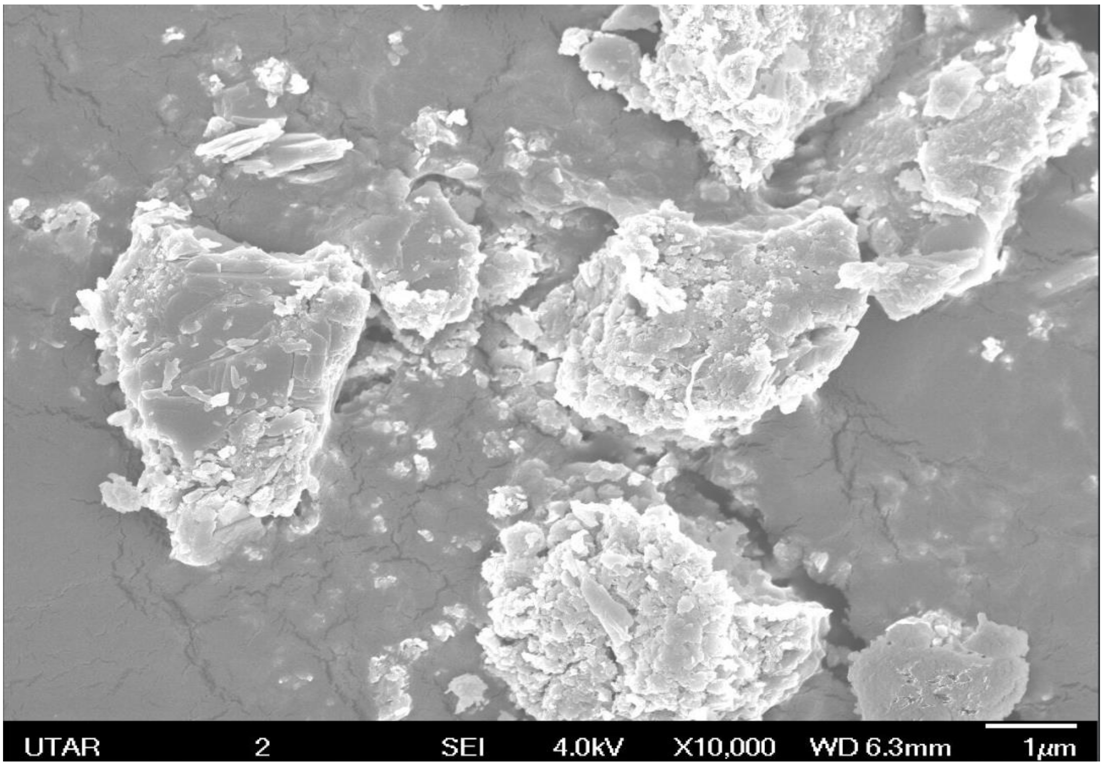

Figure 4.7: SEM Micrograph of T2 at Magnification of 10000

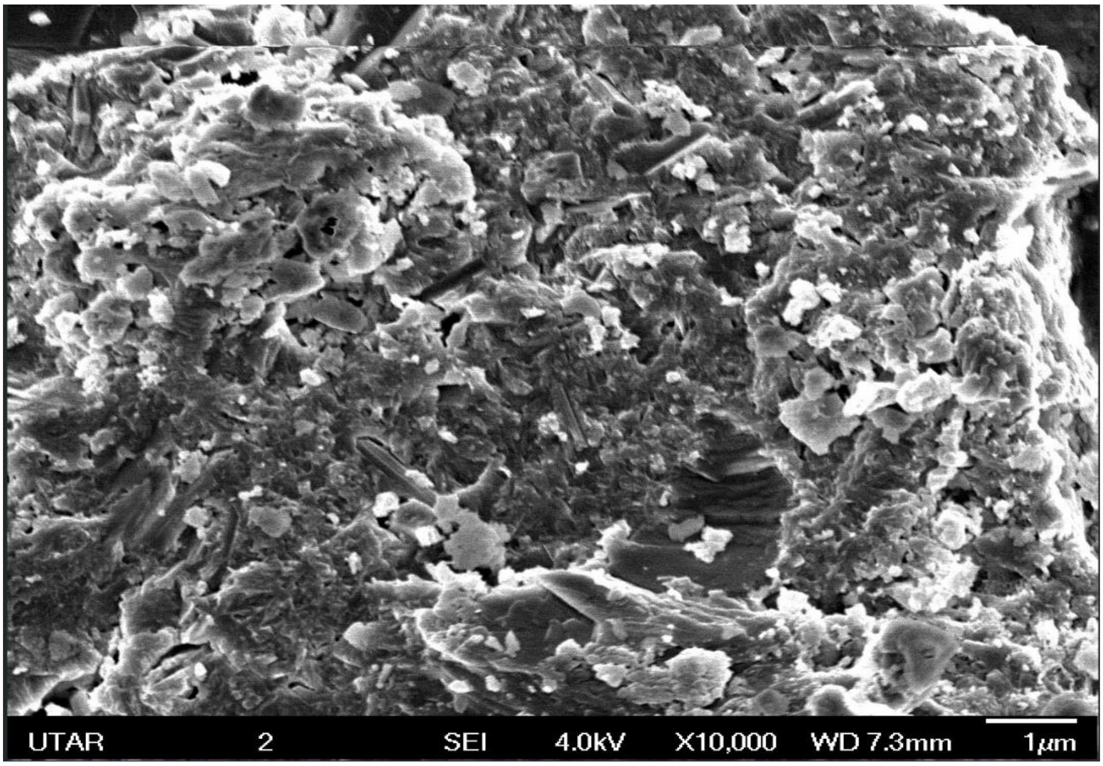

Figure 4.8: SEM Micrograph of T3 at Magnification of 10000

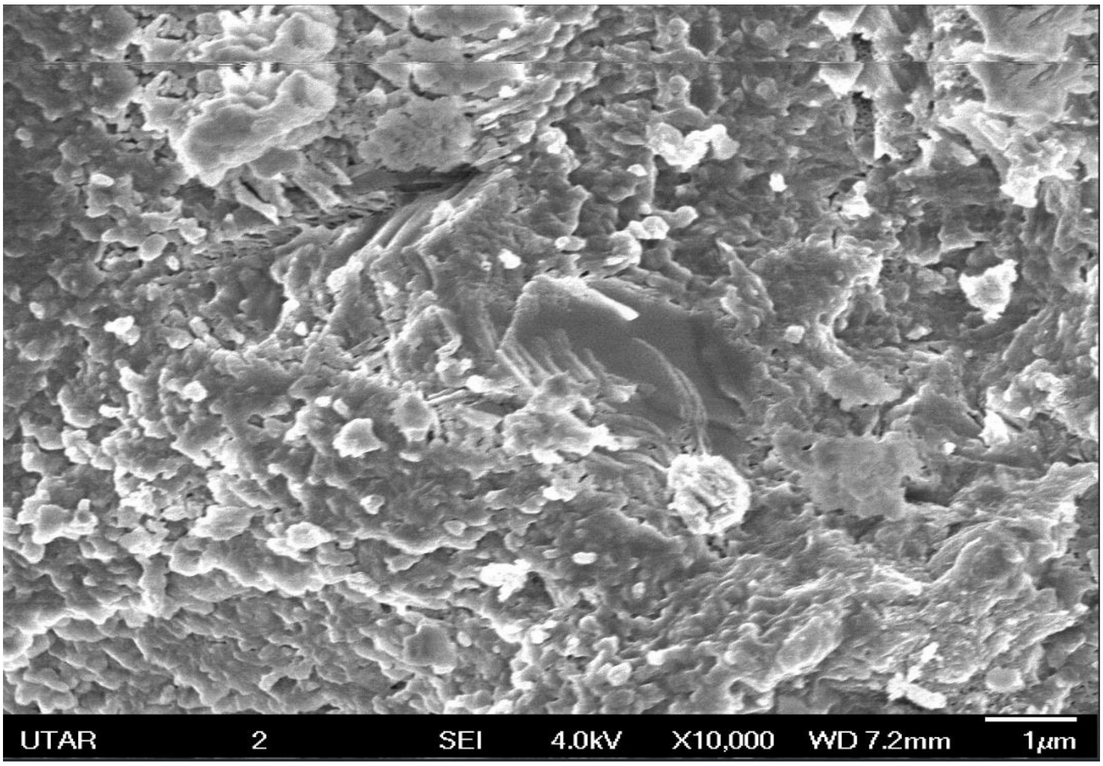

Figure 4.9: SEM Micrograph of T4 at Magnification of 10000

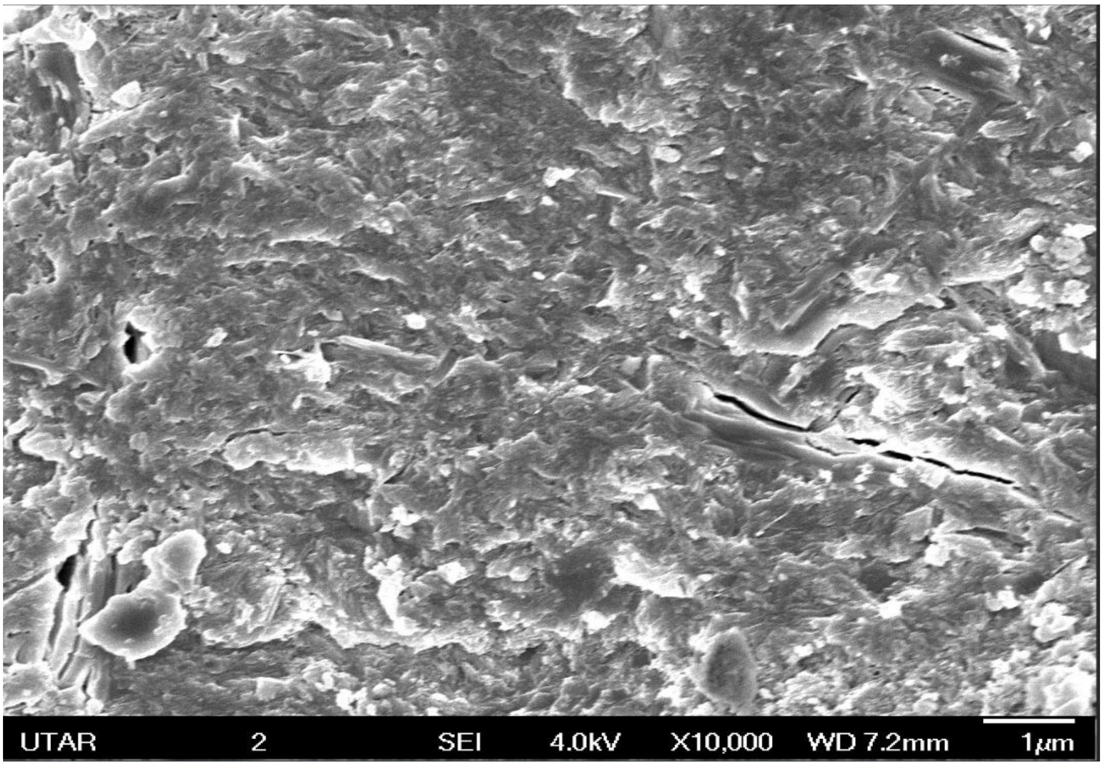

Figure 4.10: SEM Micrograph of R1 at Magnification of 10000

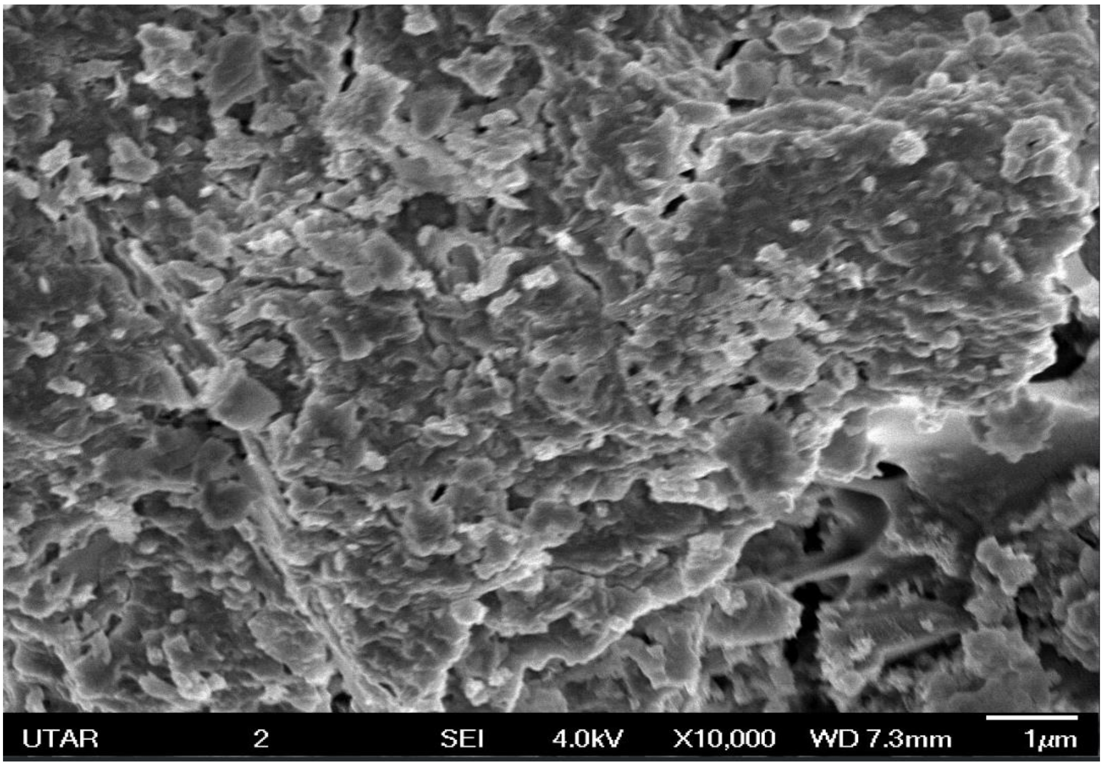

Figure 4.11: SEM Micrograph of R2 at Magnification of 10000

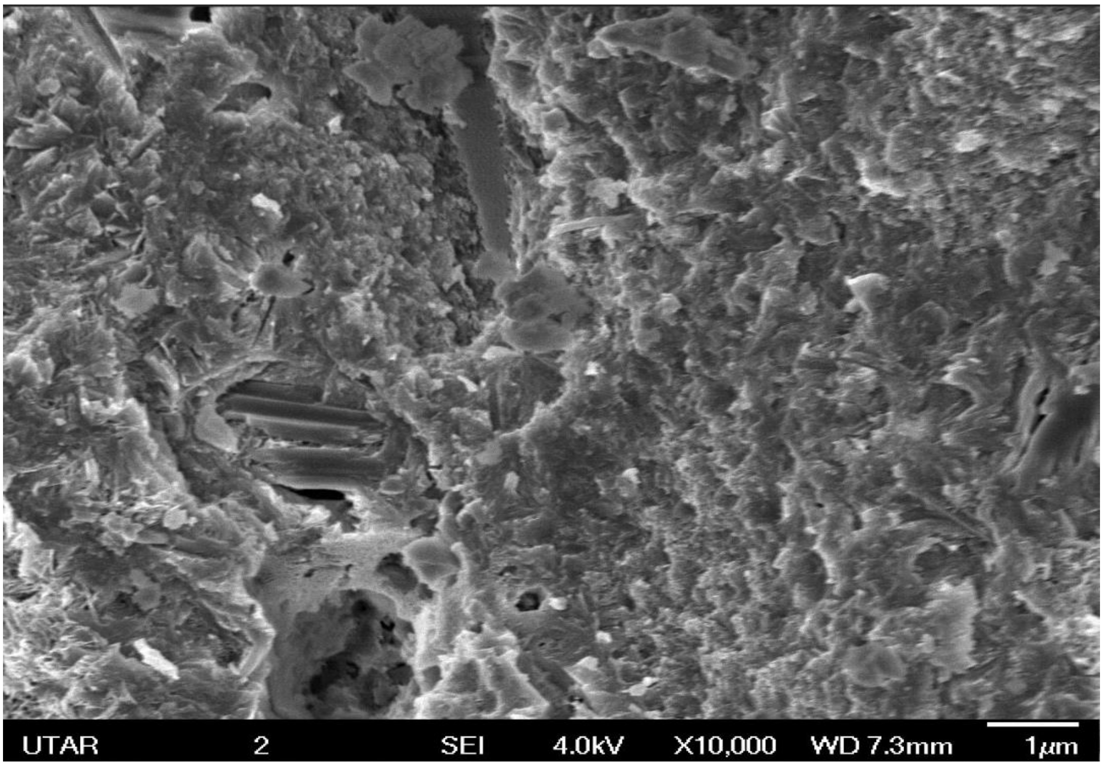

Figure 4.12: SEM Micrograph of R3 at Magnification of 10000

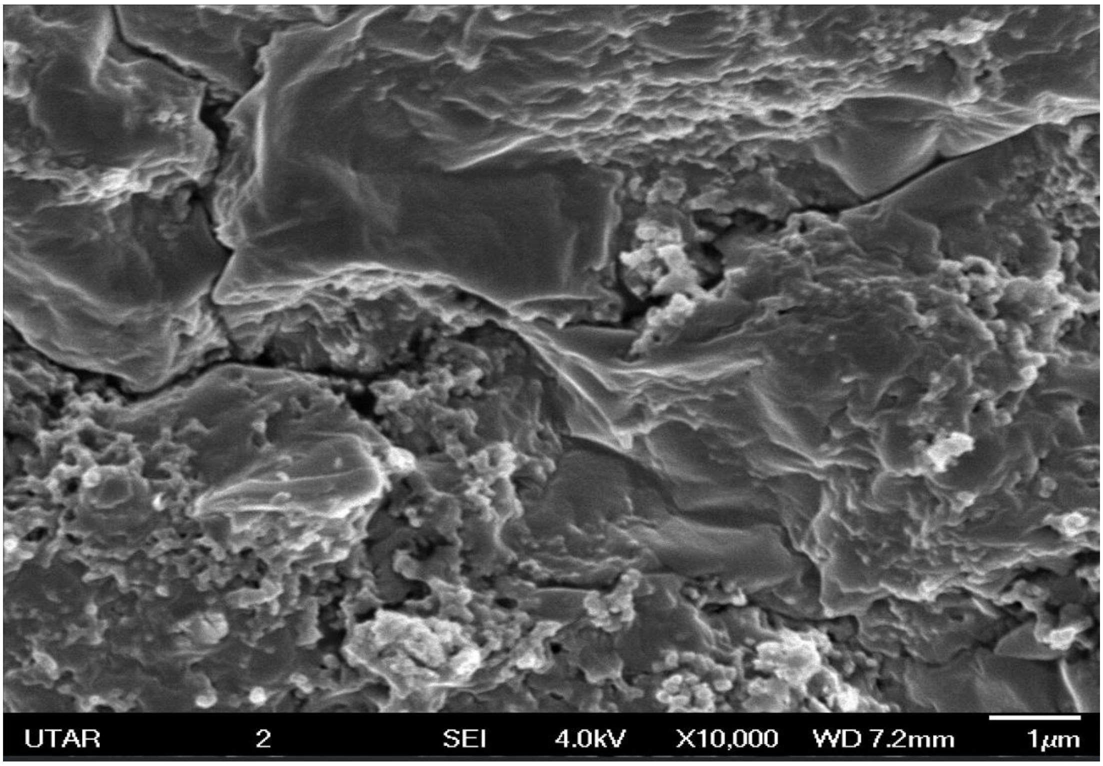

Figure 4.13: SEM Micrograph of R4 at Magnification of 10000

4.6 Water Absorption Test

Table 4.5 and Figure 4.14 indicated that the water absorption of all concrete is decreasing as the curing day increase. This phenomenon is due to the cement hydration process and increment of C-S-H gels, which lead to the reduction of pore structures of the concrete and also strengthened the bonding between the particles.

According to the data indicated at Figure 4.14, R2 concrete specimen has the lowest percentage of water absorption at curing age of 7 days, 14 days and 28 days which are 8.04%, 6.09%, and 3.60% respectively. This is mainly due to the glass powder, and titanium dioxide has generated more C-S-H gels in the concrete which reduced the amount of CH bond efficiency and lead to the minimization of pore structures in the concrete. Besides, the pozzolanic reaction of the glass powder able to abstract the size of the pore structures and porosity of the concrete (Du and Tan, 2017).

Furthermore, titanium dioxide also contributed in reduce the water absorption of the concrete, and it can generate more hydrated products in the early ages of curing, it is due to titanium dioxide can accelerate the hydration process of the concrete (Nazari and Riahi, 2010). It very well may be proposed that with the delayed relieving, expanding the ages and rates of titanium dioxide can lead to a decrease in porous voids. This mainly due to the high activity and the filling effects of the titanium dioxide nanoparticles.

In contrast, the percentage of water absorption of concrete is increasing as the content of titanium dioxide (TiO_2) goes beyond 1%. This phenomenon happen due to the excess content of titanium dioxide (TiO_2) in the concrete reduced the distance between the nanoparticles and the limited space not allow $Ca(OH)_2$ crystal to grow more and the quantity of crystal is decreased. It prompts the ratio of $Ca(OH)_2$ crystal to the reinforcing gel decreased and the shrinkage and creep of the concrete framework expanded, in this way the pore structure of the concrete grid is looser relatively (Nazari and Riahi, 2010).

Table 4.5: Water Absorption Test of Green Lightweight Concrete

Concrete Specimen	Water Absorption (%)		
	7 Days	14 Days	28 Days
C2	11.71	9.01	7.26
C2	11.01	8.26	6.92
T1	9.01	7.69	5.88
T2	8.41	6.60	4.72
T3	9.82	7.62	5.93
T4	10.71	8.49	6.84
R1	8.33	6.87	4.46
R2	8.04	6.09	3.60
R3	8.33	7.69	5.36
R4	8.82	7.63	6.09

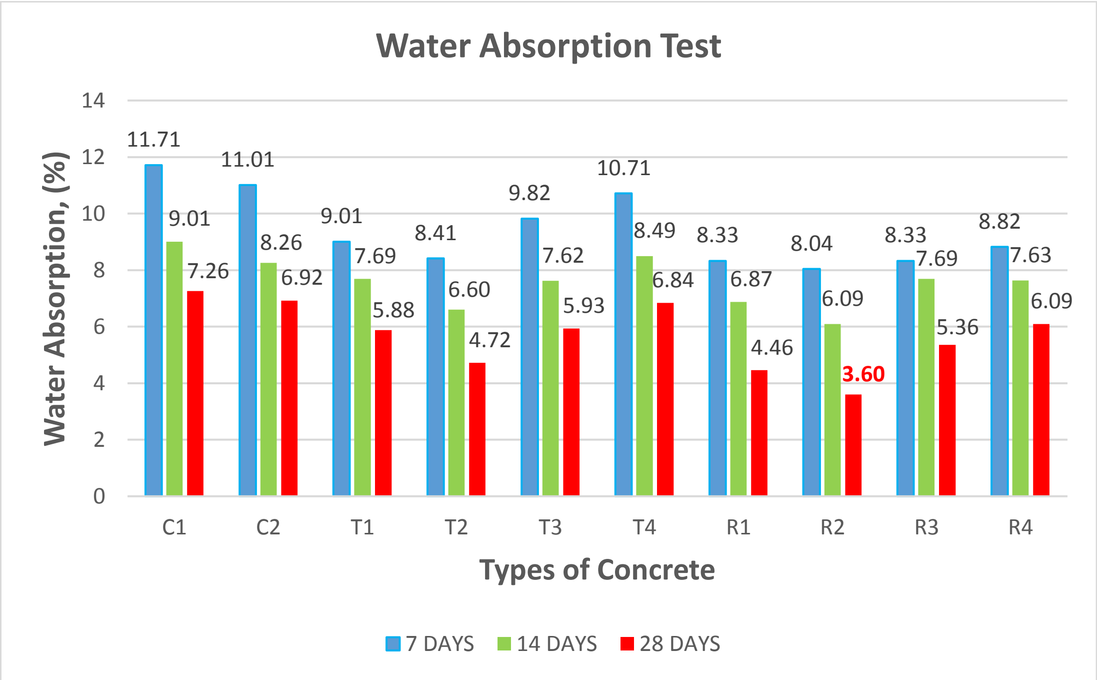

Figure 4.14: Water Absorption Test of Green Lightweight Concrete

4.7 Porosity Test

The porosity test results are tabled in Table 4.6 and shown Figure 4.15 at the curing age of 28 days. This consists of the control concrete series, T series, and R series. R2 concrete specimen achieved the lowest percentage of porosity among all of the concrete, which is 20.77% and the control concrete specimen C1 is 28.5%. Thus, it has an improvement of 7.48%. This phenomenon mainly due to the 20% substitution portion of glass powder and 1% substitution of titanium dioxide for partial cement replacement have increased the pozzolanic reaction in the concrete, which produced more C-S-H gels by consuming the CH bond and it leads to a reduction in pore structures and porosity of the concrete. Besides, the glass powder and titanium dioxide have excellent filling effects toward the pore structures in the concrete, which can minimize the amount of microstructures in the concrete.

On the other hand, T4 concrete specimen has achieved the highest porosity percentage among all the concrete which is 28.26% and the control concrete specimen C1 is 28.25% which is slightly higher than the control concrete specimen C1. This phenomenon due to the titanium dioxide in the T4 concrete specimen has exceeded the maximum limit of the dosage amount. It resulted in the increment on the amount of pore structures and microcracks in the interface of the concrete, the limited $Ca(OH)_2$ crystal are not enough to provide for the excess pozzolanic reaction (Chen, Kou and Poon, 2012).

Furthermore, the R series members have lower porosity percentage compared to the T series. This phenomenon is mainly due to the presence of 20% substitution of glass powder for partial cement replacement in the R series. The glass powder can undergo more pozzolanic reaction than the ordinary Portland cement due to the high content of silica and lead to the reduction of pore structures (AL-Zubaid, Shabeeb and Ali, 2017).

In conclusion, the R2 concrete specimen with 20% substitution portion of glass powder and 1 % substitution portion of titanium dioxide has achieved the best performance in the porosity test among all the concrete in this research study.

.

Table 4.6: Porosity Test of Green Lightweight Concrete

Concrete Specimen	Porosity (%)
C1	28.25
C2	25.21
T1	25.25
T2	22.15
T3	26.32
T4	28.26
R1	22.22
R2	20.77
R3	23.36
R4	24.86

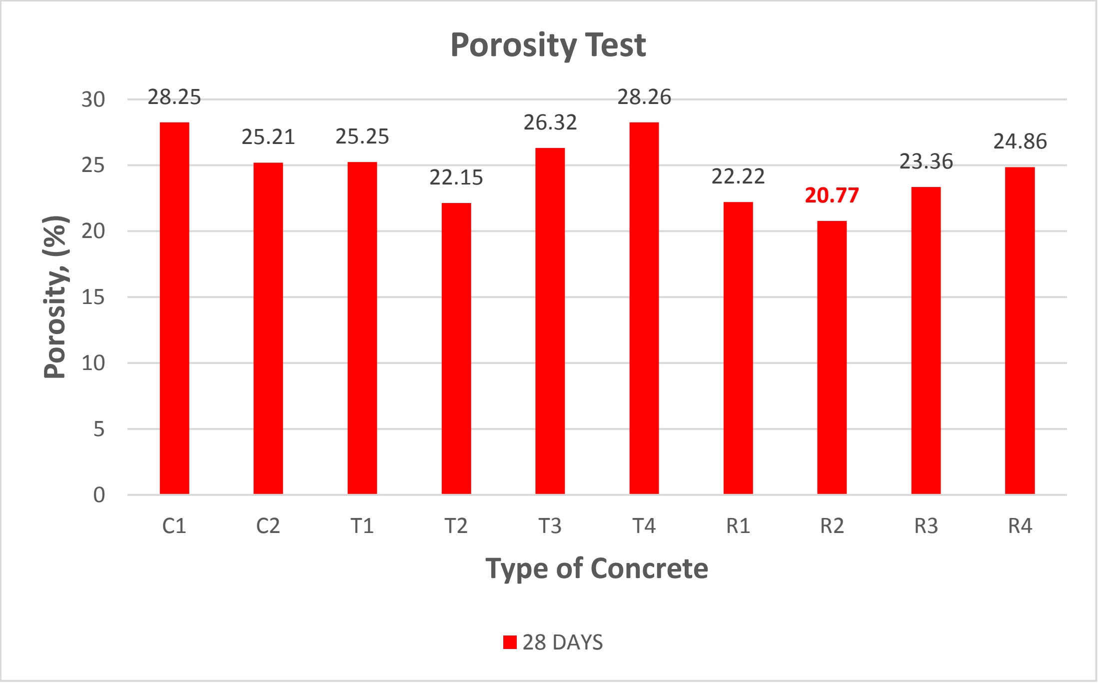

Figure 4.15: Porosity Test of Green Lightweight Concrete

4.8 Air permeability Test

Air permeability results are indicated in Table 4.7 and Figure 4.16. All the concrete specimen have the same decreasing trend in term of air permeability as the curing days increasing from 7 days to 28 days. This phenomenon is mainly due to the pozzolanic effects of the concrete, which lead to a reduction in pore structures and void as the curing ages increased

According the data showed on Figure 4.16, R2 concrete specimen has achieved the lowest air permeability value among all the concrete involved in the research study which is 5.10×10^{-6} m^2 at curing age of 28 days. The control concrete specimen is 12.28×10^{-6} m^2 at the curing age of 28 days with the difference of 7.18×10^{-6} m^2. This phenomenon is due to the 20% substitution portion of glass powder, and 1% substitution portion of titanium dioxide in R2 concrete specimen for partial replacement of cement have provided extra silica content to undergo a pozzolanic reaction to form more C-S-H gels to enhance the porosity of the concrete.

According to Table 4.2, T4 concrete specimen has the highest air permeability value at the curing age of 7 days, which is 26.16×10^{-6} m^2 than the control concrete specimen C1 which 25.11×10^{-6} m^2. This phenomenon is mainly due to the 3% substitution portion of titanium dioxide for partial cement replacement in the fabrication of T4 concrete specimen, the finer particles of titanium dioxide has increased the surface area and the water absorption ability which reduced the workability and fluidity of the concrete (Yu, Kang and Long, 2018). During the casting process, concrete with low workability is challenging to pour into the mould. Thus it will produce more pore structure than other excellent workability concrete. However, the air permeability of the T4 concrete specimen has reduced to 11.87×10^{-6} m^2 at curing age of 28 days, which is lower than the control concrete specimen C1, which is 12.28×10^{-6} m^2. This phenomenon is due to the titanium dioxide has produced extra C-S-H gels than the control concrete specimen C1, and also it has significant filling effects which can fill up the minor pore structures which helped to reduce the porosity of the concrete, thus reduced the air permeability of the concrete (Wang, Zhang and Gao, 2018).

Table 4.7: Air Permeability Test of Green Lightweight Concrete

Concrete Specimen	Permeability x 10^{-6}, K (m^2)		
	7 Days	14 Days	28 Days
C1	25.11	18.76	12.28
C2	22.00	16.83	11.10
T1	23.52	15.25	9.73
T2	22.22	13.20	8.80
T3	24.16	15.87	10.52
T4	26.16	17.53	11.87
R1	19.57	13.52	6.57
R2	17.37	10.20	5.10
R3	20.40	13.87	6.51
R4	23.23	14.53	7.60

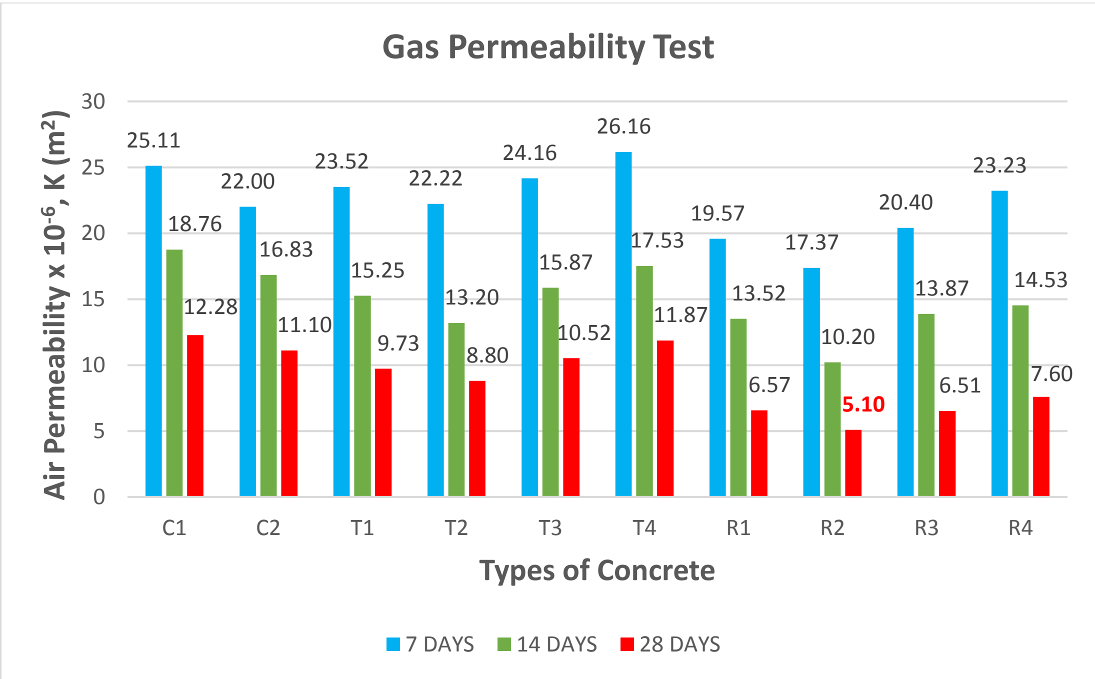

Figure 4.16: Gas Permeability Test of Green Lightweight Concrete

4.9 Chloride Penetration Test

Chloride penetration analysis is shown in Table 4.8 and Figure 4.17. The chloride penetration test is essential testing for the durability properties of concrete as the chloride water can attack the reinforcement of the concrete, which affected the performance of concrete.

According to Figure 4.17, the penetration length of the R series concrete has a shorter length compared to the T series of concrete. The chloride penetration length of R series concrete, which are R1, R2, R3, and R4 are 3.3 cm, 2.9 cm, 3.2 cm, and 3.6 cm respectively. The chloride penetration length of the T series, which are T1, T2, T3, and T4 are 3.6 cm, 3.1 cm, 4.7 cm, and 5.2 cm. This phenomenon is mainly due to the presence of 20% substitution portion of glass powder as partial replacement of cement for the R series concrete, the glass powder which known as pozzolans are improved the resistance of concrete toward chloride penetration by reducing the amount of CH bond during the pozzolanic reaction, it increased the nucleation sites for precipitation of hydration products and lessening the capacity of chloride entrance (Matos and Sousa-Coutinho, 2012).

In conclusion, the optimum reading of the chloride penetration test is R2 concrete specimen, which is 2.9 cm. The 20% substitution portion of glass powder and 1% substitution portion of titanium dioxide for the partial replacement of cement have successfully enhance the resistance of the concrete towards the chloride penetration as it can produce more C-S-H gels and significant filling effects which make the arrangement of the particle in the concrete more compacted and fewer pore structures and void.

Table 4.8: Chloride Penetration Test of Green Lightweight Concrete

Concrete Specimen	Penetration Length (cm)
C1	6.0
C2	4.5
T1	3.6
T2	3.1

Table 4.8: Continue

Concrete Specimen	Penetration Length (cm)
T3	4.7
T4	5.2
R1	3.3
R2	2.9
R3	3.2
R4	3.6

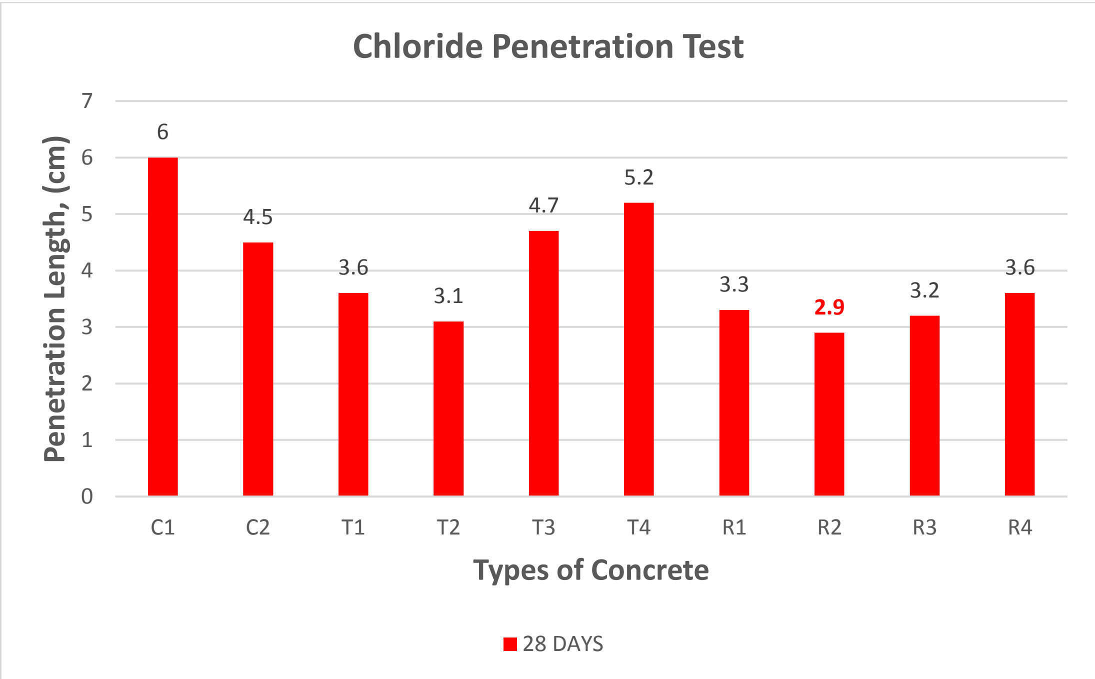

Figure 4.17: Chloride Penetration Test of Green Lightweight Concrete

4.10 Economical Appraisal

Table 4.9: Cost Estimation for Fabrication of 1 m^3 of Ordinary Concrete

Materials	Unit (kg)	Price per unit (RM)	Total (RM)
Cement	500	0.50	250
Sand	1300	0.02	29.75

Table 4.9: Continue

Materials	Unit (kg)	Price per unit (RM)	Total (RM)
Waste Glass	-	-	
Titanium Dioxide	-	6.00	
Total			279.75

Table 4.10: Cost Estimation for Fabrication of 1 m^3 of Green Lightweight Concrete by incorporating with 20% of Waste Glass and 1% if TiO_2.

Materials	Unit (kg)	Price per unit (RM)	Total (RM)
Cement	395	0.50	197.50
GGBS	1300	-	-
Waste Glass	100	-	-
Titanium Dioxide	5	6.00	30.00
Total			227.50

In the economical appraisal, the cost estimation for the production of 1 m^3 of the ordinary concrete is RM 279.75/ m^3. Besides, the cost estimation for the production of 1 m^3 of the lightweight green concrete is RM 227.50/ m^3. There reduction of cost is estimated as RM 52.25/ m^3 which is 18.7%.

4.11 Estimation of Carbon Dioxide (CO_2) Emission

Table 4.11: Carbon Dioxide (CO_2) Emission of Ordinary Concrete and Green Lightweight Concrete.

Concrete Specimen	Cement (kg)	Carbon Dioxide (m^2)
Ordinary Concrete	500	275.32
R2 Green Concrete	395	217.50

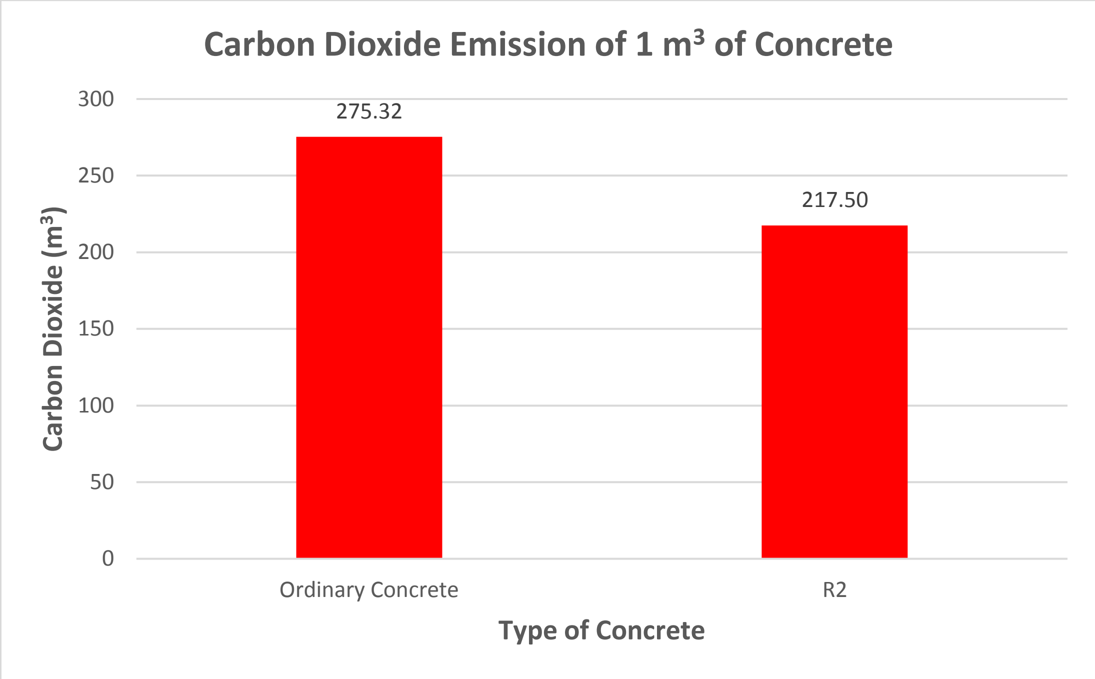

Figure 4.18: Carbon Dioxide Emission of Various Type of Concrete.

Table 4.11 and Figure 4.18 are indicating the carbon dioxide emission of the production of 1 m^3 concrete. The 1 m^3 of ordinary concrete production will release 275.32 m^3 of carbon dioxide, the 1 m^3 of the R2 lightweight green concrete production will release 217.50 m^3 of carbon dioxide with the difference 57.82 m^3 of carbon dioxide which is known as 21% of reduction.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The fabrication of lightweight green concrete by incorporating with ground granulated blast furnace slag, green colored waste glass and titanium dioxide has successfully improved the mechanical properties and durability properties of the concrete. The optimum concrete in this research study is R2 which is concrete incorporating with ground granulated blast furnace slag, 20% substitution portion of green coloured waste glass and 1% substitution portion of titanium dioxide for partial replacement of cement. The optimum concrete has achieved excellent result in compressive strength test and flexural strength test, which are 104 N/mm^2 and 14.96 N/mm^2 respectively. Besides, the optimum concrete has great improvement on the durability of the concrete such as air permeability, water absorption, porosity and chloride penetration and the result of the optimum concrete in these testing are 5.10×10^{-6} m^2, 3.60 %, 20.77 %, and 2.9 cm. Besides, the production of the optimum concrete is RM 227.50/m^3 compared to the production of ordinary concrete is RM 279.75/m^3 which can help to save 18.7% of the cost of production of concrete. Furthermore, the carbon dioxide emission of the optimum concrete is reduced by about 21% compared to the ordinary concrete.

In a nutshell, the use of ground granulated blast furnace slag, waste glass and titanium dioxide in fabricating lightweight green concrete has successfully improved the properties of the concrete. Also, the optimum lightweight green concrete reduced several environmental problems and met the criteria of conservation of materials.

Hence, this new findings will create a new pathway for fabricating green and sustainable construction material in the future.

5.2 Recommendation

There are some recommendations to consider for future studies.

i) Incorporating with other waste materials such as paper sludge, gypsum and etc to investigate the mechanical properties and durability properties of the concrete.

ii) Determine the effect of the lightweight green concrete by adding any admixture, for example water reducers, air-entraining agents, water-reducing retarders and accelerator.

iii) Determine the effect of using other lightweight aggregates such as expanded clay, pumice and others.

REFERENCES

Abdul Hafiz, S. B. and Prakash, K. B., 2017. An Experimental Investigation on The Effect of Nano-TiO_2 Particle on The Properties of Concrete. *International Research Journal of Engineering and technology (IRJET)*, pp.2621-2626.

Abdul Kadir, A., Ismail, M., Al Bakri Abdullah, M., Sarani, N. and Hassan, M., 2016.The Usage of Glass Waste as Cement Replacement. *Key Engineering Materials*, 673, pp.95-104.

Abu-Allaban, M. and Abu-Qudais, H., 2011. Impact Assessment of Ambient Air Quality by Cement Industry: A Case Study in Jordan. *Aerosol and Air Quality Research*, pp.802-810.

Afshinnia, K. and Rangaraju, P. R., 2016. Sustainable use of recycled glass in Portland cement concrete. *The journal of solid waste technology and management*, pp.16-24.

Ali, N. and Shadi, R., 2011. TiO2 nanoparticles' effects on properties of concrete using ground granulated blast furnace slag as binder. *Science China Technological Sciences*, pp.3109-3118.

Aliabdo, A., Abd Elmoaty, A. and Aboshama, A., 2016. Utilization of waste glass powder in the production of cement and concrete. *Construction and Building Materials*, 124, pp.866-877.

Allahverdi, A., Maleki, A. and Mahinroosta, M., 2018. Chemical activation of slag-blended Portland cement. *Journal of Building Engineering*, 18, pp.76-83.

AL-Zubaid, A., Shabeeb, K. and Ali, A., 2017. Study The Effect of Recycled Glass on The Mechanical Properties of Green Concrete. *Energy Procedia*, 119, pp.680-692.

Andrew, R., 2018. Global CO2 emissions from cement production. *Earth System Earth System Science Data*, 10(1), pp.195-217.

Bhargavi, P., Revathi,Bh. And Kumar, M, L., 2019. Experimental Analysis of Workability and Characteristic Strength of M40 and M60 Grade of Concrete by Partial Replacement of Cement with Nano TiO2. *International Journal for Innovative Research in Science and Technology*, pp. 43-47.

Blengini, G. A., Busto, M., Fantoni, M., & Fino, D., 2012. Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA. *Waste Management*, pp.1000–1008.

Braganca, M. O. G. P., Portella, K. F., Gobi, C. M., Silva, E. M. and Alberti, E., 2017. The Use of 1% Nano- Fe_3O_4 and 1% Nano-TiO_2 as Partial Replacement of Cement to Enhance the Chemical Performance of Reinforced Concrete Structures. *Athens Journal of Technology and Engineering*, pp.97-107.

Bremner, T. W., 2008. Lightweight concrete. *Developments in the Formulation and Reinforcement of Concrete*, pp.167.

Cha, B. J., Saqlain, S. and Seo, H. O., 2019. Hydrophilic surface modification of TIO2 to produce highly sustainable photocatalyst for outdoor air purification. *Applied surface* science, pp.1-28.

Chaipanich, A. and Chindaprasirt, P., 2015. The properties and durability of autoclaved aerated concrete masonry blocks. *Eco-Efficient Masonry Bricks and Blocks*, pp.215-230.

Chen, J., Kou, S, C. and Poon, C, S., Hydration and properties of nano-TiO_2 blended cment composites. *Cement and Concrete Composites*, 34, pp.642-649.

Davis, D. and Divya, C. R., 2015. Reduction of air pollution from vehicles using titanium dioxide. *International research journal of engineering and technology (IRJET)*, pp.1308-1314.

Du, H. and Tan, K., 2014. Waste Glass Powder as Cement Replacement in Concrete. *Journal of Advanced Concrete Technology*, 12(11), pp.468-477.

Du, H. and Tan, K., 2017. Properties of high volume glass powder concrete. *Cement and Concrete Composites*, 75, pp.22-29.

Elaqra, H. and Rustom, R., 2018. Effect of using glass powder as cement replacement on rheological and mechanical properties of cement paste. Construction and Building Materials, 179, pp.326-335.

Elia, H., 2018. Using Nano- and Micro-Titanium Dioxide (TiO_2) in Concrete to Reduce Air Pollution. *J Nanomed Nanotechnol* 9, pp.1-3.

Flower, D. J. M. and Sanjayan, J. G., 2007. Green House Gas Emissions due to Concrete Manufacture. *The International Journal of Life Cycle Assessment*, pp.282-288.

Gesoglu, M., Ozturan, T., & Guneyisi, E., 2004. Shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates. *Cement and Concrete Research*, pp.1121–1130.

Ibrahim, S. and Meawad, A., 2018. Assessment of waste packaging glass bottles as supplementary cementitious materials. *Construction and Building Materials*, 182, pp.451-458.

Islam, G., Rahman, M. and Kazi, N., 2017. Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*, 6(1), pp.37-44.

Jacobsen, S., Marchand, J., & Boisvert, L., 1996. Effect of cracking and healing on chloride transport in OPC concrete. *Cement and Concrete Research*, pp.869–881.

Jani, Y. and Hogland, W., 2014. Waste glass in the production of cement and concrete – A review. *Journal of Environmental Chemical Engineering*, 2(3), pp.1767-1775.

John, F., 1929. The story of Portland cement. *Chemical education*, pp.1854.

Joshaghani, A., 2018. Evaluating the Effects of Titanium Dioxide (TiO2) and Carbon-Nanofibers (CNF) as Cement Partial Replacement on Concrete Properties. *MOJ Civil Engineering*, pp.1-10.

Karri, S. K., Rao, G. V. R., Raju, P. M., 2015. Strength and Durability Studies on GGBS Concrete. *SSRG International Journal of Civil Engineering (SSrG-IJCE)*, pp.34-41.

Kosmatka, S., 2011. Design and control of concrete mixtures. *15th ed. Ottawa: Cement Association of Canada*, pp.1-12.

Kumar, S., Muthu, K, U., Sagar, A. and Yadav, D, T., 2018. Experimental investigation of Mechanical properties of Geo polymer concrete with GGBS and Hybrid Fibers. *International Journal of Applied Engineering Research*, pp. 292-298.

Lu, L., He, Y., Ping, B., Wang, F. and Hu, S., 2016. TiO_2 Containing Electromagnetic Wave Absorbing Aggregate and its Application in Concrete. *Construction and Building Materials*, pp.603-609.

Ma, R., Li, H., Mei, J., Li, X. and Chen, F., 2015. Effects of Nano-TiO_2 on the Toughness and Durability of Cement-Based Material. *Advances in Materials Science and Engineering*, pp.1-10.

Malagavelli, V. and Rao, P, N., 2010 High performance concrete with GGBS and ROBO sand. *International Journal of Engineering Science and Technology*, pp. 5170-5113.

Mali, J. R., Bagul, P., Biyani, Y., Pandhare, P., Bafna, H. and Joshi, M., 2017. Partial Replacement of Fine Aggregate with GGBS. *International Journal of Advance Research, Ideas and Innovations in Technology*, pp.113-117.

Matos, A. and Sousa-Coutinho, J., 2012. Durability of mortar using waste glass powder as cement replacement. *Construction and Building Materials*, 36, pp. 205-215.

Mindess, S., Young, J. F. and Drawin, D., 2003. *Concrete for special application. Concrete,* pp.547-562.

Mohamed, O., 2018. Durability and Compressive Strength of High Cement Replacement Ratio Self-Consolidating Concrete. *Building 8(11),* pp.153-155.

Nazari, A. and Riahi, S., 2010. The effect of TiO2 nanoparticles on water permeability and thermal and mechanical properties of high strength self-compacting concrete. *Materials Science and Engineering*: A, 528(2), pp. 756–763.

Nazari, A. and Riahi, S., 2011. Corrigendum to "The effect of TiO_2 nanoparticles on water permeability and thermal and mechanical properties of high strength self-compacting concrete. *Material Science and Engineering*, pp.756-763.

Oner, A. and Akyuz, S., 2007. An experimental study on optimum usage of GGBS for the compressive strength of concrete. *Cement and Concrete Composites*, pp. 505-514.

Pepin, R., 2017, *The History of Concrete*[Online]. Available at: https://www.giatecscientific.com/education/the-history-of-concrete/?fbclid=IwAR0c1DOEx7i0f7VB7wtYuNZSD75EBbLpIWz6lbsUiNXmyvKGr-Mm8VVOjag [Accessed: 3 April 2019].

Praveenkumar, T, R., Vijayalakshmi, M, M. and Meddah, M, S., 2019. Strengths and durability performances of blended cement concrete with TiO_2 nanoparticles and rice husk ash. *Construction and Building Materials*, pp. 343-351.

Rao, S, K., Sravana, P. and Rao, T, C., 2016. Abrasion resistance and mechanical properties of Roller Compacted Concrete with GGBS. *Construction and Building Materials*, pp. 925-933.

Richard, W., 1995. From prehistoric rubble mixes to Roman cement. *The history of concrete*, pp.1-8.

Sakthivel, R., Kitcha, T, A., Dhanabal, M., Aravindan, V. and Aravindh, S., 2018. Experimental Study of Photocatalytic Concrete using Titanium Dioxide. *International Journal for Innovative Research in Science and Technology*, pp. 117-123..

Senff, L., Hotza, D., Lucas, S., Ferreira, V, M. and Labrincha, J, A., 2012. Effect of nano-SiO2 and nano-TiO2 addition on the rheological behavior and the hardened properties of cement mortars. *Materials Science and Engineering*, pp. 354-361.

Shilpa, R. and Dr. Kumar, P. R., 2014. Effect of using glass powder in concrete. *International Journal of Innovative Research in Science, Engineering and Technology*, pp.421-427.

Sorathiya, J., Shah, S. and Kacha, S., 2017. Effect on Addition of Nano “Titanium Dioxide” (TiO2) on Compressive Strength of Cementitious Concrete. *Kalpa Publications in Civil Engineering*, pp. 219-225.

Sorathiya, J., Shah, S. and Smit, K., 2017. Effect on Addition of Nano “Titanium Dioxide” TiO_2 on Compressive Strength of Cementitious Concrete. *International Conference on Research and Innovations in Science, Engineering and Technology*, pp.220-225.

Stanley, C., 1999.*Concrete through the ages*. Crowthorne, Berkshire: *British Cement Association*, pp.2-30.

Suresh, D. and Nagaraju, K., 2015. Ground granulated blast slag (GGBS) in concrete. *IOSR journal of mechanical and civil engineering (IOSR-JMCE)*, pp.76-82.

Tiew, K.-G., Ahmad Basri, N. E., Watanabe, K., Abushammala, M. F. M. and Bin Ibrahim, M. T., 2014. Assessment of the sustainability level of community waste recycling program in Malaysia. *Journal of Material Cycles and Waste Management*, pp.598–605.

Vandhiyan, R., Ramkumar, K. and Ramya, R., 2013. Experimental Study on Replacement of Cement by Glass Powder. *International Journal of Engineering Research & Technology (IJERT)*, pp.234-238.

Wang, L., Zhang, H. and Gao, Y., 2018. Effect of TiO_2 Nanoparticles on Physical and Mechanical Properties of Cement at Low Temperatures. *Advances in Materials Science and Engineering*, pp.1-12.

Wongkeo, W., Thongsanitgarn, P. and Chaipanich, A., 2012. Compressive strength and drying shrinkage of fly ash-bottom ash-silica fume multi-blended cement mortars. *Materials and Design*, pp.655-662.

Yu, X, M., Kang, S, B. and Long, X., 2018. Compressive strength of concrete reinforced by TiO_2 nanoparticles. *AIP Conference Proceedings 2036*, pp. 1-5

Yurtoglu, N., 2018. Manufacture of Titanium Dioxide. *History Studies International Journal of History*, 10(7), pp.241-264.

Zhang, R., Cheng, X., Hou, P. and Ye, Z., 2015. Influences of Nano-TiO2 on the Properties of Cement-based Materials: Hydration and Drying Shrinkage. *Construction and Building Materials*, pp.35-41.

STANDARDS

ASTM International, 2013. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. *West Conshohocken*, PA, ASTM C618 - 17a. www.astm.org.

ASTM International, 2016. Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy. *West Conshohocken*, PA, ASTM C1723-16.www.astm.org.

British Standard 12350, 2009. *Testing fresh concrete Part 5: Flow table test*. London, BS EN 12350-1:2009

British Standard Institution, 1999. *Methods of test for mortar for masonry. Determination of workable life and correction time of fresh mortar*. London, BS EN 1015-2:1999

British Standard Institution, 2000. *Test sieves - technical requirements and testing. Test sieves of metal wire cloth*. London, BS 410-1:2000.

British Standard Institution, 2004. Testing Concrete. *Determination of ultrasonic pulse velocity*. London, BS EN 12504-4:2004.

British Standard Institution, 2006. *Ground granulated blast furnace slag for use in concrete, mortar and grout. Definitions, specifications and conformity criteria. London*, BS EN 15167-1:2006

British Standard Institution, 2009. *Testing hardened concrete. Compressive strength of test specimens. London*, BS EN 12390-3:2009

British Standard Institution, 2009. *Testing hardened concrete. Flexural strength of test specimens*. London, BS EN 12390-5:2009

British Standard Institution, 2009. *Testing hardened concrete. Making and curing specimens for strength tests*. London, BS EN 12390-2:2009

British Standard Institution, 2009. *Testing hardened concrete. Shape, dimensions and other requirements for specimens and moulds*. London, BS EN 12390-1:2009.

British Standard Institution, 2010. *Methods of testing cement. Determination of fineness*. London, BS EN 196-6:2010

British Standard Institution, 2011. *Cement. Composition, specifications and conformity criteria for common cements*. London, BS EN 197-1:2011

British Standard Institution, 2011. *Testing concrete. Method for determination of water absorption*. London, BS 1881-122:2011.

British Standard Institution, 2012. *Testing hardened concrete. Shape, dimensions and other requirements for specimens and moulds*. London, BS EN 12390-1:2012.

British Standard Institution, 2015. *Testing hardened concrete. Determination of the chloride resistance of concrete, unidirectional diffusion*. London, BS EN 12390-11:2015

Cabrera, J.G. and Lynsdale, C.J., 1988. A new gas permeameter for measuring the permeability of mortar and concrete. *Magazine of Concrete Research*, 40, pp. 77-82. BS 1881-122:2011

RILEM Recommendations, 1984. Absorption of water by concrete by immersion under vacuum. *Materials and Structures*.