THE FIRE RESISTANCE AND LOAD BEARING CAPACITY OF NON-LOAD BEARING LIGHTWEIGHT SANDWICHED RUBBERIZED CONCRETE WALL PANEL

Yu Tien Wan

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

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

April 2021

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	:	Yu Tien Wan
ID No.	:	1606939
Date	:	06/09/2021

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"THE FIRE RESISTANCE AND LOAD BEARING CAPACITY OF NON-LOAD BEARING SANDWICHED RUBBERIZED CONCRETE WALL PANEL."** was prepared by **YU TIEN WAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : 

Supervisor : Lee Foo Wei

Date : 06/09/2021

Signature :

Co-Supervisor :

Date :

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my sincere appreciation to my advisor Dr. Lee Foo Wei for the continuous support and guidance throughout my research. It was his borderless patience, enthusiasm, passion and motivation that motivates me to finish this project. I could not have imagined having a better advisor and mentor for my research study.

ABSTRACT

A constant increase in population growth rate has resulted in rapid urbanization, more development indicating more waste. The rising number of waste tyres disposal is a serious issue as the recycling of the waste tyres is extremely low, let alone reusing it for a beneficial purpose. Besides that, rising demand from the government of Malaysia to improve the wall partition aestheticism while replacing the conventional masonry walls to reduce the total deadweight of a building. This study is conducted to investigate the suitability of a lightweight experimentally, cost-effective and simple rubberized lightweight foamed concrete (RLFC) sandwich wall panel under load-bearing, load-deflection and flame-exposure test. Calcium silicate board is chosen to act as the outer skin, while rubberized lightweight foamed concrete is chosen to act as the inner core of the sandwich wall panel. Several mix trials were conducted, and a final composition of 0.55-P-80 was chosen. Calcium silicate boards are equipped mainly to resist harsh environmental conditions and extreme heat, while RFLC is responsible for holding structural load. Many researchers concluded that RFLC is sufficient to act as a non-load-bearing wall panel as it has sufficient load-bearing strength while having a low thermal conductivity that can improve the energy efficiency of buildings. For load-deflection and load-bearing tests, the test specimen suffered a crushing behaviour when subjected to an ultimate load of 1500 kN and 16.4 kN respectively. Only one main crack was observed for the flame exposure test when the test specimen was subjected to continuous flame exposure up to 60 minutes. The highest temperature recorded at the backside of the test specimen was 104 °C, which satisfies the ISO 834-1 requirement, which stated that the temperature recorded at the backside of the test specimen should not be more than 180 °C. The present study showed that calcium silicate board has high fireproof effectiveness while RFLC is suitable for the inner core of the sandwich wall panel.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

F_{ci}	compressive strength, Mpa
F_i	maximum load, N
A_{ci}	cross-sectional area which the load is applied, mm^2
R	modulus of rupture
P	maximum applied load. N
L	span length, mm
B	average width of the specimen, mm
D	average depth of specimen
W/C	water to cement ratio
RLFC	rubberized lightweight foamed concrete
OPC	ordinary portland cement

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The landfill had imposed a major environmental problem in the world. The irresponsible and responsible disposal of the waste tyre had been accumulated throughout the year and had raised environmental concerns. Hence, researchers had begun to search for good uses of the rubber tyre. Fortunately, the natural property of concrete being a volatile composite material made it possible to incorporate rubber aggregate as a substitute ingredient for the natural aggregate inside the concrete mixture. The final result of the composite mixture is also known as rubberized concrete. Although incorporating rubber aggregate inside the mixture of concrete sounds like a feasible solution, there are downfalls of mechanical properties that can be observed. The magnitude of the reduction in concrete compressive strength and tensile strength depends heavily on the rubber added. Moroney (2003) reported that adding rubber aggregate could increase fire resistance and also fire safety overall. The reason is that rubber aggregate had much lower thermal conductivity than the normal aggregate. There are many completed kinds of research regarding rubberized concrete, intending to discover the beneficial impact on society. This research aims to replace the aggregate inside the concrete by percentage and test for the load-bearing capacity and fire resistance of the non-load bearing sandwiched lightweight rubberized concrete wall-panel. The project expects to generate a composite skin panel and inner core material, which produce high fire resistance without compromising the load-bearing capacity.

1.2 Importance of the Study

The findings from numerous studies will redound to the benefit of the environment. Waste rubber can be utilized in concrete as rubberized concrete instead of being disposed of in the landfill. Stacks of waster rubber retain water after a rainfall, resulting as a potential mosquito breeding ground poses a major health hazard to the community as a deadly disease such as Malaria and dengue with mosquitoes as a carrier. Additionally, materials that cannot be recycled are usually incinerated in the landfill. Exposure of rubber tyres to high temperatures releases harmful gaseous emissions such as carbon monoxide, nitrogen dioxide and sulfur dioxide. Moreover, it was found that a high concentration of heavy metals such as zinc is released into the atmosphere, which poses harm to human health and the environment (Jimoda et al., 2017). Hence, modifying the concrete properties of rubber with a certain volumetric percentage to inherit its property is an alternative way to recycle and reuse waste rubber.

Typical concrete cannot fulfil certain aspects or requirements, especially in serviceability states, such as fire resistance. Because of that, rubberized concrete can increase both fire resistance and fire safety as it reduced the curvature and depth of the crack when exposed to a high level of heat (Hernández-Olivares and Barluenga, 2004). The addition of wall panels on both sides of the lightweight rubberized concrete enhances the overall fire-resistance and aesthetic appearance.

1.3 Problem Statement

It has been reported that more than two hundred and ninety million motor tyres in the United States alone are being disposed of every year (Zheng et al., 2008). These alarming numbers are still expected to increase and pose a significant environmental issue since tyres are non-biodegradable and composed of synthetic rubber. Although it is non-biodegradable, it can be decomposed. Based on the California Integrated Waste Management Board findings, chemicals inside the rubbers are mutagenic and carcinogenic when it undergoes decomposition. The chemicals released by improper disposal of the tyre could have leached into the soil and poisoned the groundwater, endangering the plants and animal in its vicinity.

Moreover, environmental problems are getting more severe as the landfill area in Malaysia is getting more limited. Besides that, the stockpile of used rubber was presented at the landfill. The excessively used rubbers presented at the landfill can undergo degradation processes to emit harmful gases and leachate, resulting in health catastrophe. (Sharifah, 2013).

Besides an environmental problem, it is the downfall of mechanical properties in rubberized concrete compared to normal concrete. Normal concrete is famous and wide-known material due to its high load-bearing capacity and durability. However, KEW and Kenny (2009) discovered a 60% reduction in compressive strength when more than 50% of 20mm coarse aggregate was replaced by rubber fillings, preventing market feasibility of rubberized concrete

Conventional concrete displayed a low-temperature threshold. When a fire event occurs, the concrete will experience significant degradation and ultimately to a failure state. Moreover, a conventional wall system imposes a significant dead-load on the total structural mass, resulting in an unnecessary steel reinforcement and foundation cost increment.

1.4 Aim and Objectives

This study aims to test and identify the contribution of rubber inside the concrete mixture. A few objectives are listed down as below:

1) To investigate the effect of rubber inside the concrete in terms of load-bearing.
2) To evaluate compressive strength and split tensile strength of rubberized lightweight foamed concrete
3) To determine the thermal conductivity and fire performance of rubberized concrete and calcium silicate wall panel respectively.

1.5 Scope and Limitation of the Study

The primary focus of this study is on the influence of the rubber aggregate on concrete properties. Besides that, it is aimed to compare the difference between unmodified concrete and rubberized concrete. The scope of this study comprises a comparison of slump test, compressive strength, tensile strength, concrete mass loss after curing, fire testing of concrete. However, the concerns of this study are the preparation of the size of rubber aggregate. It is challenging to prepare a group of rubber aggregates of consistent size. Furthermore, an adequate heat source that is to test for the fire resistance of the normal and rubberized concrete may be hard to find.

1.6 Contribution of the Study

The whole study demonstrates the feasibility of the sandwiched wall panel using rubber lightweight foamed concrete as the inner core and calcium silicate board as the wall panel. Results generated to obtain the optimum mix proportion of inner core can serve as a reference or benchmark for future researchers. On top of that, load-deflection test, load-bearing test, and flame exposure test are the three primary tests that were used to test the feasibility, adequacy, and suitability of calcium silicate wall panel and rubberized lightweight foamed concrete when integrated as a whole composite material in terms of durability, and serviceability performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter notes the previous studies from researchers regarding the utilization of recycled rubber aggregate in concrete and the changes in concrete material properties. The upcoming reviews display their methodologies, patterns and trends of the past researchers in their investigation of the properties of rubberized concrete, furthermore, displaying how the outcome of their experiment can validate the usage of recycled rubber in concrete is practical, effective, and having a positive potential effect in civil engineering application.

2.2 Introduction

Management issues of used rubbers lead to heaping piles, resulting in adverse environmental impact. The alarming accumulation of disposed of rubbers is a global issue. For instance, in India, approximately ten Million tyres are disposed of annually, leading to environmental problems as scrap tyres are considered non-degradable material harmful to the atmosphere (Rana and Yadav, 2020). Annually, the United Kingdom estimates forty million car and truck tyres are disposed of, which is projected to rise over 20 years. This alarming number of prohibitions from the government to dispose of used tyres in the UK forces professional engineers to discover an alternative solution (KEW and Kenny, 2009). Additionally, the pressing need to build more sustainable infrastructure with recycling waste, which can improve energy efficiency, has resulted in engineers conducting experiments and research on rubberized concrete (KEW and Kenny, 2009).

Apart from that, normal concrete does not fulfil well in serviceability states. To mitigate environmental harm, comprehensive researches on scrap rubber recycling are being carried out. Researchers have found benefits in incorporating recycled rubber tyres into concrete. It was suggested to take advantage of the natural property of low thermal conductivity of rubber and concrete as a composite material to develop a better heat-resistant product used in dwelling construction. This was because rubber aggregate is inferior in thermal conduction compared to stone aggregate (KEW and Kenny., 2009). Besides that, manufacturing rubberized concrete was easier, and the coating of rubber aggregate with cement paste had improved the distribution during mixing. The easier preparation reduced the production cost (KEW and Kenny., 2009). In addition, as compared to regular concrete, studies had shown that rubberized concrete was lighter, more durable when it came to chloride penetration and was more ductile (Muhammad et al., 2017).

Moreover, it had been proven that rubberized concrete had spalling resistance property when one percent of rubber particles had been incorporated inside the concrete mix (Muhammad et al., 2017). Likewise, a finding displays rubberized concrete has a lesser tendency of explosive spalling when exposed to high heat because rubber aggregate is quickly burned off, and the high pore pressure within it has escaped through the burnt rubber aggregate (Hernández-Olivares and Barluenga, 2004). On top of that, other researchers have displayed other superior properties regarding the addition of rubber in concrete. Adding rubber crumbs into asphaltic pavement layers displayed superior skid resistance, less fatigue cracking and a longer life-span (Ganjian et al., 2009). Similarly, rubberized concrete has an advantage, such as increased flexibility (Raju and Kumar, 2019). However, there is a contradiction statement between Raju and Kumar (2019) and KEW and Kenny (2009), where the former stated that rubberized concrete has higher abrasion resistance whereas the latter reported it had lower abrasion resistance.

Researchers had raised concern about the cost of production in the hope that rubberized concrete could be commercialized. Firstly, the utilization of rubber in concrete indicates that they will replace virgin materials with it and thus save money while protecting the environment. However, it was suggested that the making of rubberized concrete required additional surface treatment and additive resulting in incremental cost with a reduction of viability which makes it unsuitable overall (KEW and Kenny, 2009).

2.3 Fresh Rubberized Concrete Properties

A concrete mix before hardening is defined as fresh concrete. The properties in the fresh concrete will indicate the properties when it is in a hardened state. The hardened properties include compressive strength, tensile strength, crack development, water absorption, water penetration, and the likelihood of creep. Generally, there are two major properties to define the property of fresh concrete; the workability of the concrete and air content. An extended degree of workability of concrete is crucial as concrete must be adequately workable to encase the steel reinforcements fully.

On the other hand, sufficient air voids inside the concrete protect against freeze and thaw attacks as entrained air voids are noted as an empty chamber that allows water to enter, preventing crack formation to the concrete. The presence of various additives also directly affects the properties of the concrete. For instance, silica fume is an example of mineral admixture used to enhance the mechanical strength of concrete, whereas abietic acid salt or fatty acid salts are considered air-entraining admixtures that enhance adhesion between aggregate and cement. As for rubberized concrete, incorporating rubber aggregate inside the mixture will influence the concrete properties as described in a later context.

2.3.1 Slump Test

Workability refers to the ability of concrete to be cured or hardened without the presence of segregation or honeycombing. Slump test is used to test the consistency of fresh concrete and is mainly dependent on the water to cement ratio in normal concrete. Many studies discovered that adding rubber aggregate influenced the workability of the fresh concrete. One study showed that the amount of slump decreased as a higher percentage amount of rubber crumb was added; 0% of rubber crumb, contributing to 92mm of the slump, 5% of rubber crumb contributing to 60mm of slump drop, 10% of rubber crumb contributing to 29mm of a slump and 15% of rubber crumb contributing to 5mm of a slump. A dropped in slump value indicated a decrease in the workability of the concrete (Rana and Yadav, 2020). Another study reported a significant decrease of slump value when more than 12% replacement of rubber aggregate was added (Muhammad et al., 2017). Another study measured the workability of the rubberized concrete using the slump and the Ve-Be consistometer test, reported a decrease in workability with an increase of rubber fibre; However, it can be overcome with additive such as silica fume (Hernández-Olivares and Barluenga, 2004). Additionally, KEW and Kenny (2009) findings were in line with the previous finding, such that increasing the percentage of rubber up to 50% will result in a zero-slump value. On top of that, there was a finding stated that the rubber aggregate of smaller size displayed lower slump values when compared to coarser aggregate, and all concrete mixtures with rubber replacement ultimately produced lower slump value compared to the control mixture (Stallings, 2016).

2.3.2 Air Content

Many researchers agreed that mixing the rubber aggregate inside the concrete mixture had produced higher air content than a normal concrete without an air-entraining admixture. This study reported that the rubber has better air entrainment ability due to its contribution from its capillarity on its surface (Muhammad et al., 2017). Another study suggested that due to its onerous process in cutting the rubber, the rough surface contributed to the air-entraining mechanical property, acting as an air-entraining agent, which enhances the mechanical property of the concrete (Hernández-Olivares and Barluenga, 2004). The size of the rubber aggregate highly influenced the air entrainment. This was because fine rubber aggregate contributed to a larger surface area under the same volume, which can entrain more air than coarse rubber aggregate. It was also reported that the nature of rubber properties was able to reject the water molecules but allow the air bubbles to adhere to the surface of the rubber due to its non-polar nature (Stallings, 2016).

2.3.3 Summary of Fresh Concrete Properties

In conclusion, researchers had concluded that the rubberized concrete displayed the following trends as a fresh concrete:

- The trend of workability of the fresh concrete decrease with an increase of rubber content.
- The slump value was reported to be minimum when the rubber content replacement is at 50%.
- Finer rubber aggregate was reported to have a lower slump value than coarser rubber aggregate.
- Rubber particles were able to entrap air due to its rough finishes

- Rubber aggregates are hydrophobic, which allow air entrainment on its surface.

2.4 Hardened Concrete Properties

Researchers had displayed how the rubber aggregates had affected many mechanical properties. The properties include density, compressive strength, water permeability, water absorption, split tensile strength, flexural strength, chloride penetration, modulus of elasticity and fire performance.

2.4.1 Density

The study conducted by Muhammad et al. (2017) shows that the value of dry density of the coarse aggregate and fine aggregate was 167 kg/m^3 and 1552 kg/$m^{3,}$ whereas the average density of the rubber aggregate is 677 kg/m^3. The result directly indicated that a higher replacement of rubber aggregate inside the concrete mixture would reduce the density of the concrete. The reason was that rubber has more void that can entrain air, resulting in lower mass per unit volume (Muhammad et al., 2017). This point was further proven to be accurate as researchers such as Hernández-Olivares and Barluenga (2004) had a similar founding. In another research, it was reported that the lower density of the concrete is directly related to the thermal conductivity. The higher the amount of rubber content, the higher the total thermal resistance. The total thermal resistance for 0% of the rubber content was 3.96 (m^2K/w) compared to 100% of rubber content was 5.02 (m^2K/w) (KEW and Kenny, 2009).

2.4.2 Compressive strength

Concrete compressive strength was reduced when the aggregate was replaced with material such as rubber, which had higher elasticity and lower density. One study reported that rubberized concrete would have a significant decrease in compressive strength regardless of it being exposed to fire or not. In the absence of fire, the compressive strength was at 57MPa with 0% replacement of rubber aggregate, whereas the compressive strength was at 29 MPa with 24% replacement of rubber aggregate. In the presence of fire, it was reported that for the same amount of the rubber replacement, the highest amount of 60% reduction in compressive strength was noted at 20 minutes, and the compressive strength was further reduced when it was left burning in the fire. The finding stated that due to its inferiority in stiffness of rubberized concrete when exposed to fire, cracks were more easily formed, speeding up the concrete's failure (Muhammad et al., 2017).

In this study, the researcher ensured the normal concrete and rubberized concrete was cured under saltwater. It was reported that the compressive strength of rubberized concrete was inferior to the normal concrete regardless of the curing environment (Yusof and Ramli, 2008). In another research, rubber aggregate of different sizes was separated into three groups: fine rubber with an average diameter of 9.5 mm, coarse rubber with an average diameter of 19 mm, and crumb rubber with an average diameter of 25 mm. The result showed that a lesser amount of rubber aggregate replacement had a lesser reduction of compressive strength. However, although fine rubber had a significant reduction in strength, it was relatively lower than the replacement of coarse rubber aggregate (Yasin, 2012). Table 2.1 showed the design mix ratios proposed for the tests, whereas Figure 2.1 to Figure 2.6 displayed the compressive strength of a different type of mix of concrete

Table 2.1: Design mix ratios proposed for the test (Yasin 2012).

Mix No.	Cement	Water	Sand	Fine Aggregate	Coarse Aggregate	Fine Rubber	Coarse Rubber	Crumb Rubber
1	1	1	2	2	2	-	-	-
2	1	1	2	-	2	2	-	-
3	1	1	2	2	-	-	2	-
4	1	1	2	1	1	1	1	-
5	1	1	2	-	-	1	1	-
6	1	1	-	1	1	1	1	2

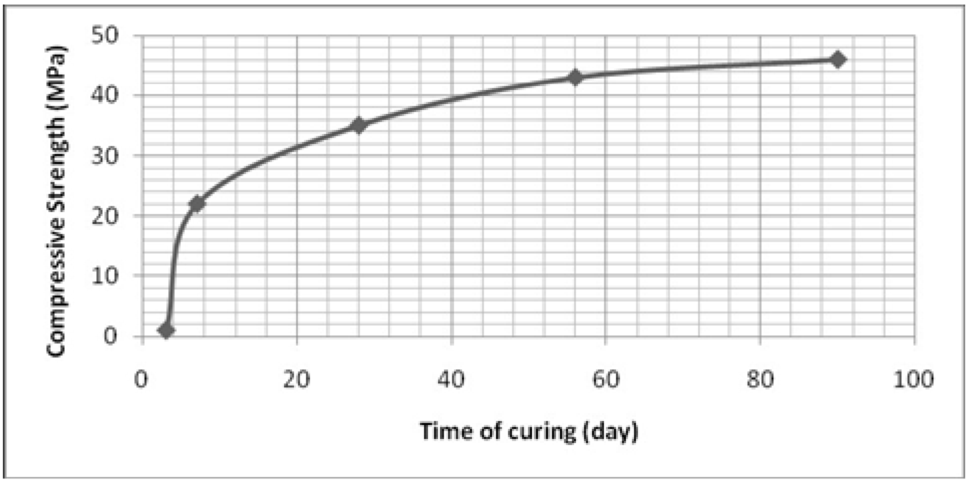

Figure 2.1: Compressive strength vs time of curing for design mix No. 1 (Yasin 2012).

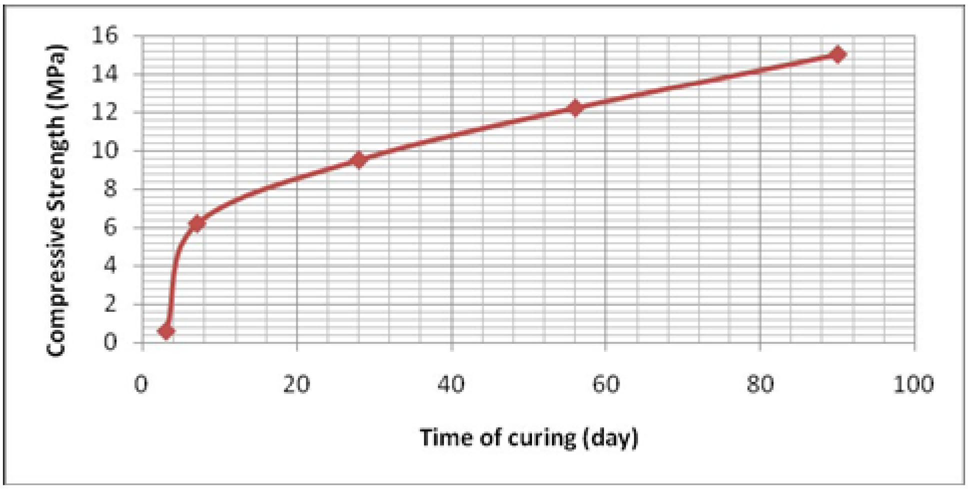

Figure 2.2: Compressive strength vs time of curing for design mix No. 2 (Yasin 2012).

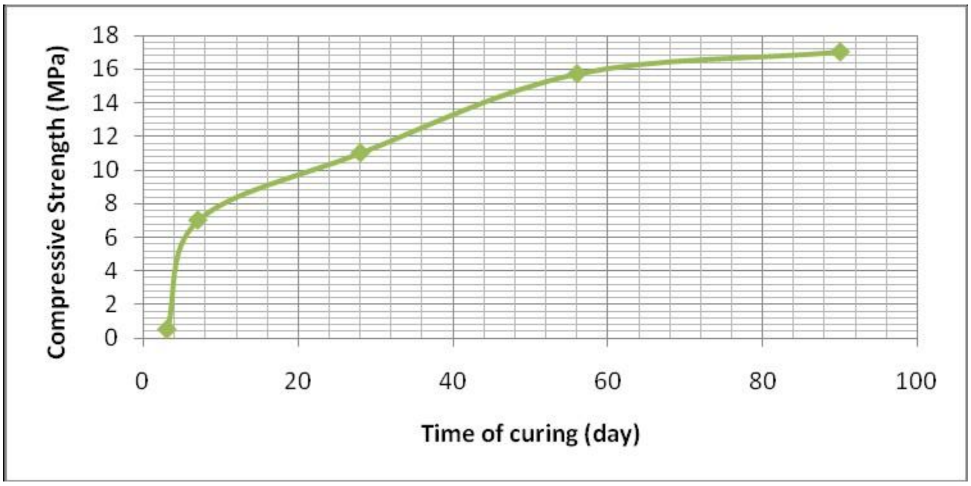

Figure 2.3: Compressive strength vs time of curing for design mix No. 3 (Yasin 2012).

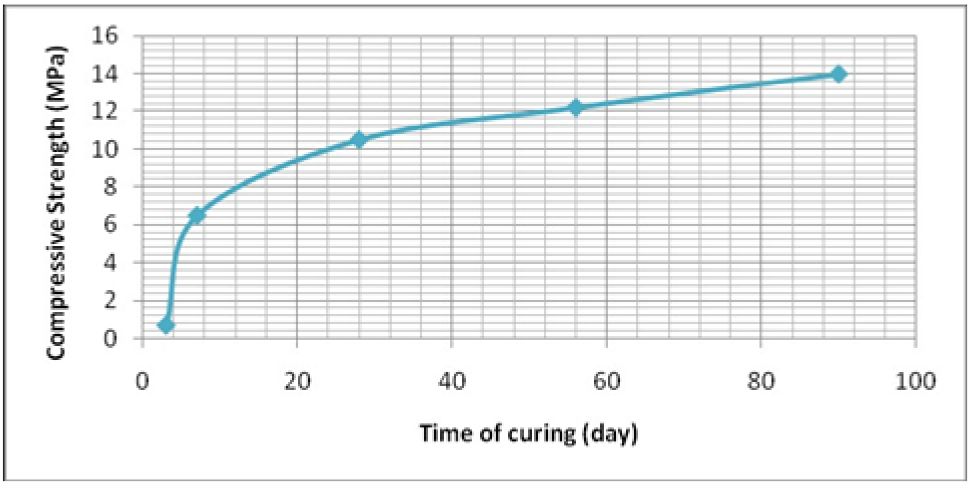

Figure 2.4: Compressive strength vs time of curing for design mix No. 4 (Yasin 2012).

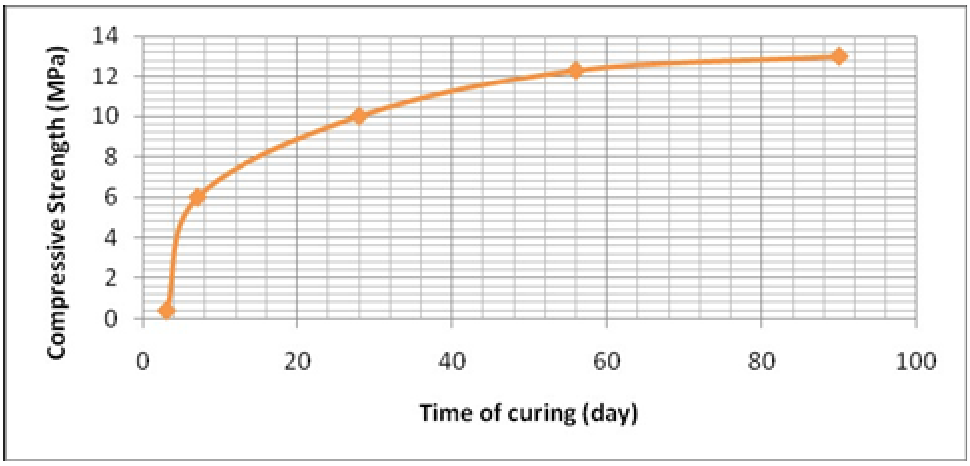

Figure 2.5: Compressive strength vs time of curing for design mix No. 5 (Yasin 2012).

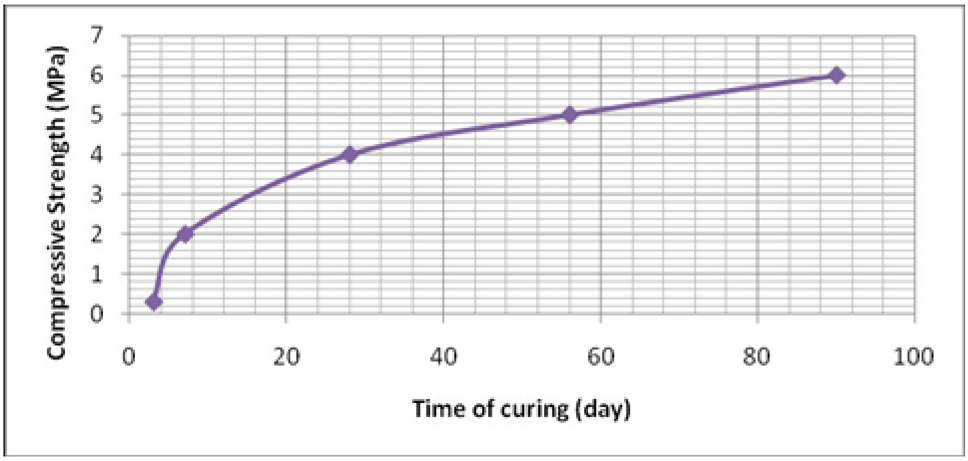

Figure 2.6: Compressive strength vs time of curing for design mix No. 6 (Yasin 2012).

In another test, the result produced from chipped rubber and powder rubber as an aggregate replacement was in line with other researchers. The reason was due to the softer texture of rubber aggregate in comparison with the normal aggregate. During loading, the area around the rubber particle was found to crack first, which accelerated the rupture process progressively. Besides that, cracks were formed around the concrete part that had the least resisting force due to inadequate or insufficient bonding between rubber particles and the cement paste, which result in a non-uniform distribution in the paste. Rubber particles were lighter and had a lower specific gravity. It tended to float to the top during casting and vibrating, which also resulted in non-uniform distribution.

The rubber had inferior stiffness compared to the stone aggregate and reduced the concrete mass stiffness according to the percentage of replacement; the studies showed that replacement of less than 5 percent was favourable. (Ganjian et al., 2009). It was observed by KEW and Kenny (2009) that during compression failure, the test specimen did not display typical compressive failure such as spalling due to the presence of rubber aggregate that tends to grasp the sample fragments at failure state.

2.4.3 Water Permeability Depth and Water Absorption

Permeability is one of the crucial factors to determine the durability of the concrete. Concrete with high permeability will result in water flowing through the concrete. The water will cause a freeze-thaw phenomenon and induce stress inside the concrete; Water and air will ingress into the reinforced concrete and result in corrosion of the reinforcement, leading to concrete cracking, expansion, and ultimately failure.

In this study, Ganjian, et al., (2009) reported that incorporating rubber inside the concrete mixture increased the water permeability depth. The depth of permeability increases with a higher percentage of replacement. The concrete's water permeability with 5% and 7.5% replacement was still favourable under the DIN 1048 standard. However, it is classified as medium with 10% tyre rubber replacement. Rubber aggregate replacement increased both the water absorption rate and water permeability depth. This was noted when the specimen with rubber aggregate replacement formed a crack during oven drying, which denoted a high water absorption result. However, it was also reported that the replacement of cement with tyre powder reduced the water absorption and the reduction increased with increased usage of tyre powder. Although powdered tyres improved the resistance in water absorption, it was also reported that they increased the depth of the water permeability of the concrete. The reason is due to the lack of adequate bonding and the existence of capillaries inside the rubber that could entrain water (Ganjian et al., 2009). Figure 2.7 displayed the relationship between the amount of replacement in material and water absorption.

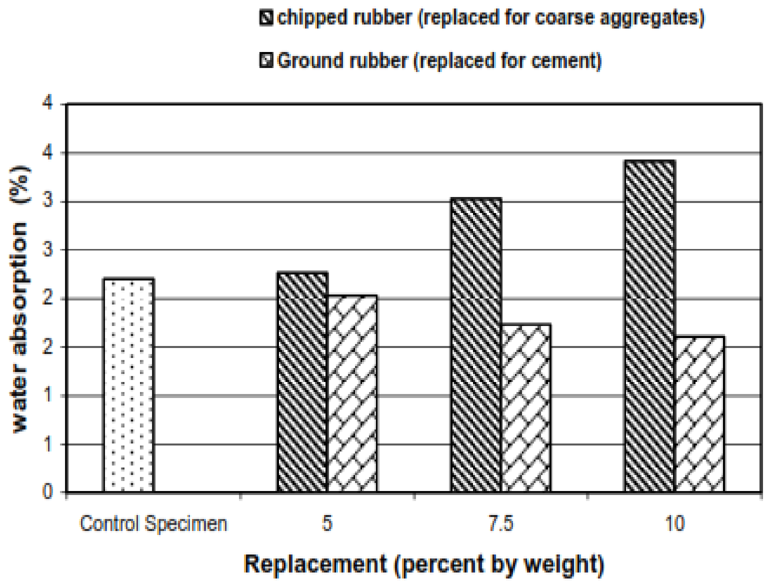

Figure 2.7: Result of water absorption test. (Ganjian et al., 2009)

Another study reported that concrete cured under salt and acid solution displayed a better water absorption resistance for concrete with natural rubber replacement. The result reported an improvement of 2.44% in the water absorption resistance. However, the reason for the improvement was not stated (Yusof and Ramli, 2008).

2.4.4 Split Tensile Strength

This experiment discovered that replacing the coarse aggregate with rubber aggregate or replacing the cement paste with tyre powder reduced the tensile strength, and the reduction increased with the gradual replacement of the rubber aggregate. Replacement of cement paste with tyre powder displayed a reduction of 24%, and coarse aggregate replacement with crumb rubber displayed a reduction of 44%. The result opposed the hypothesis that rubber should be superior in tensile strength due to its capability of sustaining high deformation load, and the reason deduced was due to weak bonding inside the concrete mixture, and it can form cracks relatively easy when a load was applied. After the tensile test, it was reported that they were fallen chipped rubber which proved that segregation of cement paste and rubber aggregate happened at the area of stress (Ganjian, et al., 2009). Another result from the research was in line with other researchers finding that incorporating rubber aggregate resulted in weaker tensile strength of concrete. However, the report discovered that coating the rubber aggregate with cement paste generated smaller strength reduction due to better adhesion between rubber chips and the cement paste. Additionally, the rubber aggregate coating increased the chip's unit weight and prevented the likelihood of floating on top, which results in an extra uniform mix (KEW and Kenny, 2009). Figure 2.8 and Figure 2.9 are shown for better clarification.

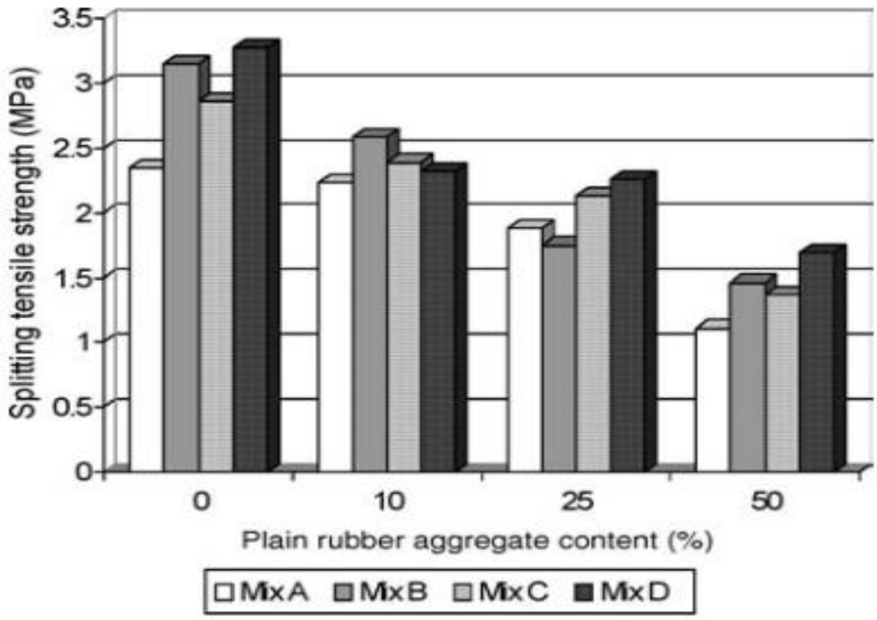

Figure 2.8: Splitting tensile strength with plain rubber aggregate replacement (KEW and Kenny, 2009).

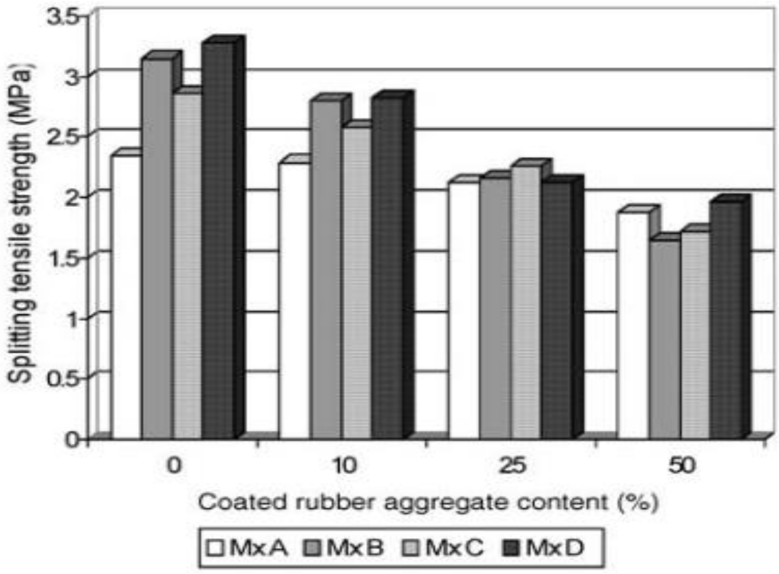

Figure 2.9: Splitting tensile strength with coated rubber aggregate replacement (KEW and Kenny, 2009).

However, another study reported that the replacement of rubber aggregates up to 6% produced better tensile strength where at 0% replacement of rubber aggregate, tensile strength was at 4.5 MPa, which was inferior to that of 6% replacement (6.6 MPa). The report suggested that it could be due to the rubber filling up the cracks in its vicinity as soon as a crack was formed around it. Additionally, exposure of the specimen to fire reduced the split tensile strength, and the reduction increased with a longer period of fire exposures. It is observed that for a longer period of concrete in the fire exposure, the rubbers inside it were easily burnt off, which resulted in more voids in the concrete, creating a higher reduction in both tensile and compressive strength (Muhammad et al., 2017).

2.4.5 Flexural Strength

Flexural strength and tensile strength are almost similar as they identified the nature of tensile resistance of a material. The main difference is that the tensile strength test applied maximum tensile force that can be experienced throughout the entire volume of the concrete specimen, whereas for the flexural strength test, the maximum tensile force was only experienced at the edge of the concrete test piece located at the bottom of the neutral axis; The crack will form at the weakest fibre detected. Hence, due to a smaller total volume of concrete specimen experiencing maximum tensile force in flexural test, the probability of detecting a defected fibre is lower. Thus, the flexural strength of a material is typically higher unless the material of the concrete is homogenous.

Numerous findings by the researchers were in line with the statement that flexural strength is higher than tensile strength. In this research conducted by Ganjian, et al., (2009) reported that a mixture of 10% chipped rubber (replacement for coarse aggregate) was 3.15 MPa in flexural strength, and the replacement for ground grubber (replacement for cement) was 3.55 MPa, comparing to 0% replacement was 5.3 MPa; A total reduction of 37% and 29% respectively. The reason deduced was the poor bonding between the rubber aggregate and the mixture when chipped rubber could be effortlessly removed. The bonding can be improved if the magnesium oxychloride cement was used. When the concrete was cracked, more rubber chips were found dropping to the ground compared to the rubber powder. However, it was noted that up to 5% percent replacement of chipped rubber displays the least reduction in flexural strength of 5%. The researcher did not present the reasons for it to have the least strength reduction and display superiority over powder rubber.

In another study, the flexural strength of the rubberized concrete increase when 20% replacement of the aggregate contents was made. The improvement in the flexural strength increased when the rubber aggregate was coated with cement (KEW and Kenny, 2009).

2.4.6 Surface Treatment of Rubber Particles

This study showed that surface treatment of rubber particles with sodium hydroxide solution displayed a reduction of 33% in compressive strength. Other mechanical properties such as flexural strength were also improved. The treatment method was submerging the rubber particles in a sodium hydroxide solution for 20 minutes before utilizing them. The reason was that sodium hydroxide improved the adhesion and bond of the rubber particles to cement paste (Ganjian et al., 2009).

In another study, Stallings (2016) reported that submerging rubber particles in the water alone had resulted in an increase of 16% in the compressive strength compared to the rubber particles left untreated. Moreover, submerging the rubber aggregate in the admixture of water and tetrachloride resulted in an increase of 57% in compressive strength. Besides that, compressive strength improved in the rubberized concrete mixture when it was coated with a silane coupling agent. For the same mixture, the one with 30% coated displays 25% extra strength than the 30% uncoated rubberized concrete. Moreover, the coating had averted the rubberized concrete mixture from losing the compressive strength compared to the controlled mixture. On day 28, a loss of 10% in compressive strength was noted compared to a 10% coated rubber mixture and controlled specimen, whereas a loss of 23% in compressive strength when it was 30% coated. A reduction of 32% and 38% in compressive strength with the controlled specimen when it was left uncoated respectively.

2.4.7 Modulus of Elasticity

Many researchers had raised concern over how rubber affects the modulus of elasticity of the concrete. The important property that governs the serviceability and performance of concrete structures is the modulus of elasticity, and this property was governed by the cement paste and the toughness of the selected aggregate (Zheng et al., 2008).

In this journal, the study was conducted on how rubber affected the modulus of elasticity in the concrete mix. Two tests were performed by Zheng, et al., (2008), which are the dynamic and static modulus of elasticity tests. Regarding static modulus of elasticity, it was reported that the modulus of elasticity decreased with higher use of both crushed and ground rubberized concrete. Replacement content varied from 15 to 45% for both crushed and ground rubberized concrete. Reduction of 14.8 to 29.9% for ground rubberized concrete and 27.4 to 49.4% for crushed rubberized concrete as compared to controlled concrete with a modulus elasticity of 31.8 GPa. Regarding the dynamic modulus of elasticity, the trend was the same as the result of the static modulus of elasticity. Decrease in dynamic modulus values at 5.7 to 28.6% in correlation with 15 to 45% rubber replacement for ground rubber content. The reduction of crushed rubberized concrete was 16.5 to 25.0% for a similar rubber replacement.

In another study, the result displayed a similar trend for replacement of the rubberized concrete in terms of chipped rubber. 5 to 10% of replacement contribute to 17 to 25% reduction in the modulus of elasticity respectively. In contrast, the same amount of replacement for powdered rubber had 18 to 36% reduction in modulus of elasticity. It was noted that the lower modulus of elasticity leads to higher ductility of a material. Rubberized concrete could absorb more force when compared to a normal concrete mixture (Stallings, 2016).

2.4.8 Fire Performance

Research regarding fire resistance in rubberized concrete had been done to find its viability. This study conducted by Hernández-Olivares and Barluenga (2004) concluded a significant improvement in the fire performance when the specimen of a concrete mixture had rubber aggregate replacement compared to another one without rubber aggregate replacement. The researchers made the rubber replacement in 4 batches, 0%, 3%, 5% and 8%. It was reported that when exposed to a high temperature of 1000 °C, the controlled specimen displayed an explosive spalling effect, whereas 3% did not. Figure 2-10 and Figure 2-11 show the result for better clarification.

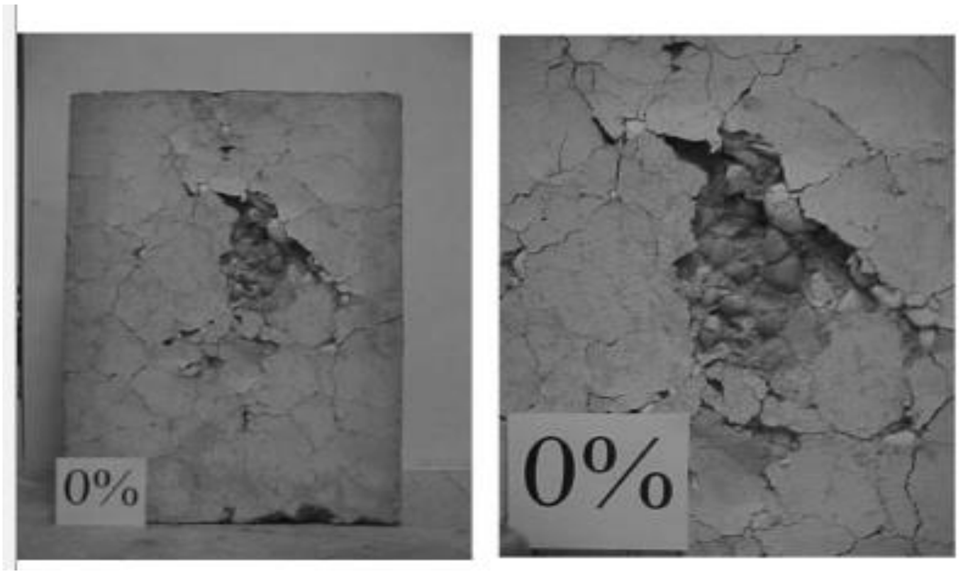

Figure 2.10: The exposed surface of 0% rubber aggregate replacement after fire test (Hernández-Olivares and Barluenga, 2004).

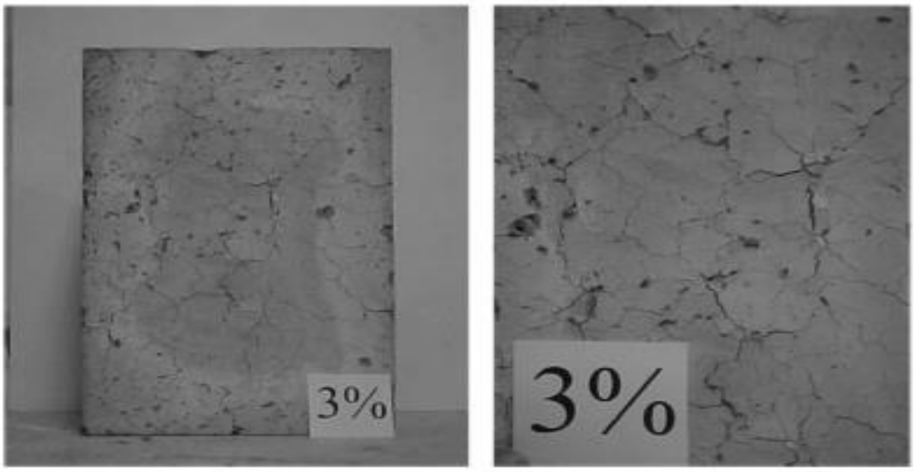

Figure 2.11: The exposed surface of 3% rubber aggregate replacement after fire test (Hernández-Olivares and Barluenga, 2004).

Besides that, it was reported that there was a visible curvature after the concrete specimens had been exposed to a high temperature of heat. The reduction of the curvature is directly related to the amount of rubber replacement in the concrete mixture; Replacement of 8% displayed a small degree of curvature, whereas 0% replacement displayed a high degree of curvature. The reason deduced was that the vapour built up during exposure to high heat can escape through the burnt rubber, reducing the stress inside the concrete.

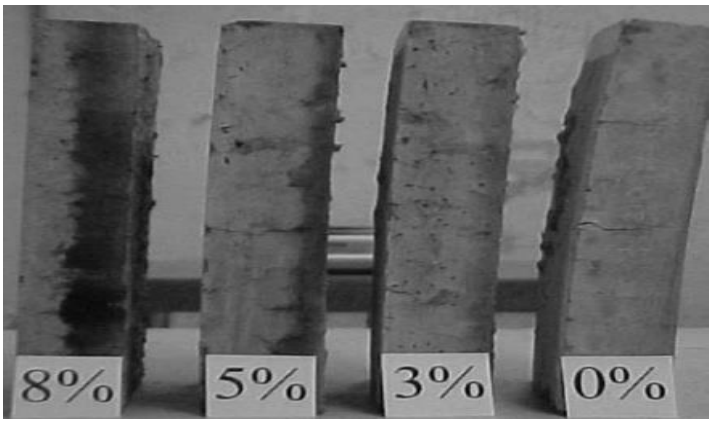

Figure 2.12: Curvature of a test specimen after fire exposure (Hernández-Olivares and Barluenga, 2004).

Another study showed that a large volume of smoke was produced when the rubber aggregate presented in the concrete mixture had been burned in high temperatures. For 24% of the rubber aggregate replacement, the specimen was found flashing with the flame for 15 minutes continuously when exposed to the fire for an hour. Besides that, explosive spalling had been reported for concrete mixture with 0 to 6% rubber aggregate replacement, but little to no explosive spalling for replacement more than 6%. Moreover, the mass loss increased linearly to the amount of rubber aggregate replacement when exposed to fire. Longer concrete exposure in fire specimens led to a higher mass loss as all the mass loss belonged to the entrapped rubber aggregate and water inside the concrete mixture (Muhammad et al., 2017).

2.4.9 Hardened Concrete Properties Summary

In conclusion, the following properties of the hardened concrete discovered by the researchers are summarised as shown below:

- Rubberized concrete has a lower density due to its lower unit weight and higher porosity inside the rubber.
- Rubber aggregate replacement affects the compressive strength significantly.
- Finer rubber aggregate replacement has a lower reduction in strength compared to the coarse rubber aggregate replacement.

- An additive such as silica fume enhances the mechanical strength of the concrete, whereas abietic acid salt or fatty acid salts are considered an air-entraining agent.
- The split tensile test and flexural strength test reported that the rubberized concrete experiences failure in lower magnitude. However, the formation of cracks was significantly reduced.
- Rubberized concrete decreases the modulus of elasticity of the material but improves the ductility of the material.
- Replacement of the aggregate or cement paste with rubber aggregate or powdered rubber increases the permeability of water.
- Pre-treatment of the rubber aggregate with water, sodium hydroxide or silane coupling agent enhanced the mechanical strength of the concrete.
- Rubberized concrete did not display spalling effect, and it shows a lesser curvature under the exposure of intense heat, whereas the normal concrete explodes and displays a visible curve under a high temperature.

2.4.10 Summary of Rubberized Concrete.

A complete and comprehensive literature review was completed on the utilization of used rubber in concrete mixture and its effects on concrete properties. A brief description is given as shown in Table 2.2.

Table 2.2: Summary of Literature Review

Properties	Effects/Result	Authors
Slump Test	Decrease	(Rana, A. and Yadav, K., 2020), (Muhammad, M.A. et al., 2017), (KEW, H.Y. and Kenny, M., 2009), (Stallings, K.A., 2016)

Table 2.2 (Continued)

Air Content	Increase	(Muhammad, M.A. et al., 2017), (Hernández-Olivares, F and Barluenga, G., 2004), (Stallings, K.A., 2016)
Density	Decrease	(Muhammad, M.A. et al., 2017), (Hernández-Olivares, F and Barluenga, G., 2004), (KEW, H.Y. and Kenny, M., 2009)
Compressive Strength	Decrease	(Muhammad, M.A. et al., 2017), (Yusof. M. Z and Ramli. M., 2008), (Yasin, A.A., 2012), (Ganjian, et al., 2009), (KEW, H.Y. and Kenny, M., 2009)
Water Permeability	Increase	(Ganjian, et al., 2009)
Water Absorption	Decrease	(Ganjian, et al., 2009), (Yusof. M. Z and Ramli. M., 2008)
Split Tensile Strength	Decrease	(Ganjian, et al., 2009), (KEW, H.Y. and Kenny, M., 2009), (Muhammad, M.A. et al., 2017)
Flexural Strength	Decrease	(Ganjian, et al., 2009), (KEW, H.Y. and Kenny, M., 2009),
Modulus of Elasticity	Decrease	(Zheng. L et al., 2008), (Stallings, K.A., 2016)

Table 2.2 (Continued)

Fire Performance (Explosive Spalling)	Increase	(Hernández-Olivares, F and Barluenga, G., 2004), (Muhammad, M.A. et al., 2017)
Fire Performance (Curvature)	Increase	(Hernández-Olivares, F and Barluenga, G., 2004)

2.5 Sandwiched Wall Panel

The increasing demand for raw construction materials will lead to an environmental problem. Furthermore, many households favour masonry walls and wooden floor panels, which will increase the additional deadweight for the entire structural building (Lakshmikandhan, et al., 2017).

Sandwiched wall panel comprises two or more materials, one material for the outer part of the wall panel that is relatively thin, another material that acts as an infill inner core material that is relatively thick. The combination of the two materials with a connector will result in a superior composite structural component. Generally, there are two types of sandwiched wall panels. The first type, the outer skin, is mainly responsible for acoustic and thermal insulation, whereas the inner core carries the structural load. The second type is the opposite of the first type. The outer layer is mainly responsible for carrying the structural weight, and the inner core is responsible for thermal and sound insulation. Kumar, et al. (2021) states that sandwiched wall panels can provide thermal insulation, reducing the energy required for heating or cooling the interior building space.

Researches had displayed interest in the potential of sandwiched wall panels due to their superior structural performance, lower dead load, and higher energy-efficient construction.

Lakshmikandhan, et al. (2017) realized the potential of deploying alternative recyclable lightweight materials such as bamboo, rice straw and reed as suitable infill material. The primary purpose of the inner core lightweight material is not just to fill the gap between the skin but to increase the sound and heat resistance of the overall sandwiched wall panel. Moreover, the cost to construct a lightweight sandwiched wall panel is lower compared to a conventional wall. The author suggested adding a ferrocement wall panel as the skin and having lightweight inner core material will have higher strength, improved ductility, and better crack resistance than the conventional masonry wall.

According to a study, Ng, et al. (2011) mentioned that newspaper sandwiched aerated lightweight concrete could be the new trend in the construction industry as sandwiched wall panels had the potential of enhancing and optimizing the thermal performance. The thermal performance of a building is dependent on two parameters which are time lag and decrement factor. The author experimented by erecting the model on a prototype house exposed to ambient temperature and discovered that the use of sandwiched wall panel increases the time lag and decreases the decrement factor. Equation 2.1 governed the decrement factor is as shown below.

$$Decrement\ factor, \lambda = \frac{A_i}{A_e} = \frac{T_{i(\max\ )} - T_{i(ave)}}{(T_{e(\max\ )} - T_{e(ave)}} \qquad (2.1)$$

where

A_i = interior surface temperature, °C

A_e = external surface temperature, °C

$T_{i(max)}$ = maximum interior surface temperature, °C

$T_{e(max)}$ = maximum external surface temperature, °C

According to Kumar, et al., (2021), given the same load and span conditions, the overall thickness of the designed sandwiched wall panel can reduce up to one-thirds compare to the conventional non-composite wall. The reduction in self-weight, in turn, reduced the seismic effect. In the author's studies, crushing failure is dependent on three parameters for the sandwiched wall panel, namely slenderness ratio, spacing of the connector and thickness of the insulator.

2.5.1 Connection System for the Sandwiched Wall Panel

The vital factor in ensuring the full function of a composite structure is the connection system. In the sandwiched wall panel, the connector is vital in ensuring the skin panel and inner core act as a whole. Different types of connection systems will affect the performance of the sandwiched wall panel.

According to this study, Lakshmikandhan, et al. (2017) had used a shear stud as the connection system for his sandwiched wall panel. The picture is illustrated in Figure 2.13

Figure 2.13: Shear Connectors Tied with Skin Reinforcement (Lakshmikandhan, et al., 2017)

The experiment demonstrated the importance of the connection system in sandwiched wall panels because the cracking pattern observed at the opening of the model after the compressive load test indicates the lack of shear interaction between the skin concrete layer.

Kumar, et al., (2021) composed a sandwiched wall panel with geopolymer concrete wythes as the skin panel and insulation layer as the inner core. The connector used to connect these both materials is hollow tubular glass fiber reinforced polymer connectors. Figure 2.14 below described the setup of the sandwiched wall panel.

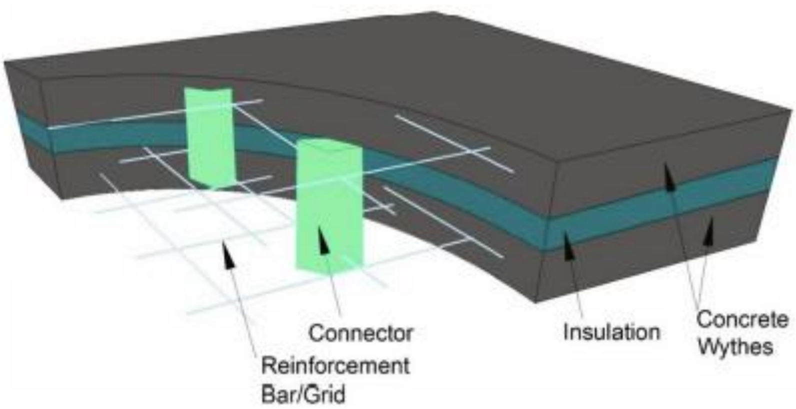

Figure 2.14: Sandwiched Wall Panel with Hollow Tubular Glass FRP Connectors (Kumar, et al., 2021).

It was mentioned that the connectors are subjected to pre-tensioning to prevent the lateral separation of the insulation layer and concrete wythes. Moreover, the lateral or transverse spacing or the connector did not significantly affect the ultimate axial load. 1168 kN ultimate axial loads for 200 mm spacing between the connector and 1181 kN ultimate axial load for 600 mm spacing between connector. However, it was emphasized that the casting and curing stage was essential to ensure the whole structure was monolithic.

Adhesive glue is another connection system used to integrate the different layers of the sandwich wall panel. Polyurethane (PU) adhesive glue is an excellent example of bonding material. The adhesive material must have mechanical properties similar or better than the core material (Pereira and Fernandes, 2019).

2.5.2 Type of Sheathing Material

The benefit of sandwiched wall panel is the flexibility in choosing the sheathing material. The type of sheathing material used also affects the choice of the connection system.

There are sandwiched wall panel designs having the skin panel responsible for carrying the structural load, Lakshmikandhan, et al. (2017) developed a ferrocement outer skin layer and lightweight concrete as the inner core. The lightweight concrete was developed by mixing concrete mixture and expanded polystyrene beads. On the other hand, Kumar, et al. (2021) construct two reinforced geopolymer concrete wythes as the sheathing material whereas using an insulation layer as the inner core.

The design of the sandwiched wall panel can be interchanged where the inner core is designed for load sustaining purposes, whereas the sheathing material is responsible for corrosion, heat and sound resistance. Many sheathing materials can be used compositely with the inner core. Few examples include calcium silicate board, gypsum board and asbestos cement board. Unfortunately, gypsum board is not suitable for exterior buildings as it can dissolve in water. Asbestos cement board emits toxic dust into the air, which is detrimental to human health. A calcium silicate board is chosen as it is cheaper than lightweight concrete, and it has moderately good water, heat and fire resistance (Kristanto, L., 2017). The study showed that the thicker calcium silicate board had high flexural strength, 6mm displayed 7 MPa ultimate flexural strength, whereas 8 mm displayed 13 MPa flexural strength. It did not display crack under the soak-dry and warm-water tests, indicating good material resistance towards external weather.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The primary purpose of this chapter is to develop a complete work plan from the beginning stage of the study to the completion of the project. The overall working plan is presented in Figure 3.1.

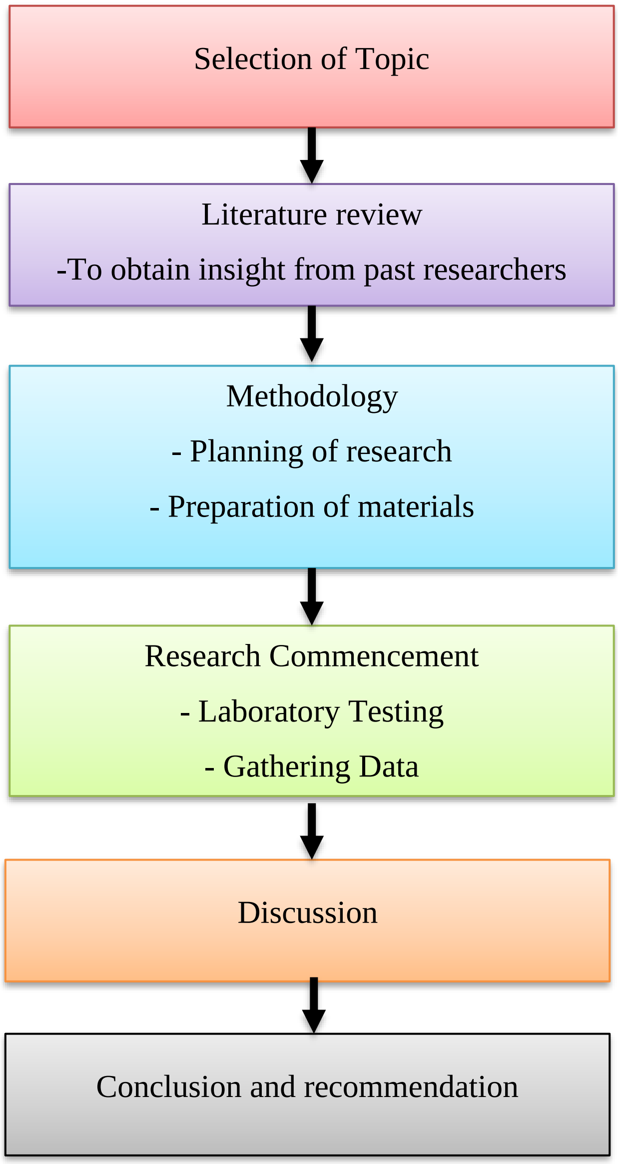

Figure 3.1: Overall Workflow Process

3.2 Raw Materials and Equipment

Rubber aggregate, Ordinary Portland Cement (OPC), powdered rubber, crumb rubber, fine aggregate (sand), water and foaming agent are the raw materials required to produce lightweight rubberized concrete as the inner core for the sandwiched wall panel. Equipment such as a furnace, concrete mould, slump cone, rod, concrete vibrator and thermocouple are used for this project.

3.2.1 Ordinary Portland Cement (OPC)

An OPC brand chosen for this study is named ‘Orang Kuat’ cement from YTL Cement Bhd is chosen for this project. The content will then sieve through a 600 μm screen to remove the hydrated clinker in the cement. The leftover is appropriately stored in an air-tight container to prevent the hydration process of the cement. Figure 3.2 illustrates the type of cement used in this experiment.

Figure 3.2: The Ordinary Portland Cement, ‘Orang Kuat’ brand from YTL Sdn Bhd.

3.2.2 Fine Aggregate

Sand will be used as fine aggregate throughout this project. The sand will be oven-dried at 105 °C to remove the moisture content inside it. After that, the sand will pass through the sieving apparatus, and the aggregate that can pass through at least the No.30 sieve size of 600 μm will be collected with a clean container and store in a dry place. Figure 3.3 present the sieved sand in a container.

Figure 3.3: Sieved Sand in a Container

3.2.3 Crumb Rubber

Rubber will be shredded to form two groups. The first group will represent ground rubber powder where the size must not exceed 40 mesh; It will replace the fine aggregate by weight percentage. The second group will be named crushed rubber, with sizes ranging from 0.075 mm to 4.75 mm. Size of No.4 and No.200 sieve will ensure the crushed rubber size is within the specified range. The crushed rubber will be used to replace coarse aggregate in weight percentage. Figure 3.3 and 3.4 presents granular and powdered crumb rubber.

Figure 3.4: Granular Crumb Rubber Particles

Figure 3.5: Powdered Crumb Rubber Particles

3.2.4 Foaming Agent

SikaAER@- 50/50 is selected as an air-entraining agent due to its strong air-entraining properties. The mixture of SikaAER@-50/50 with water inside the foam generator will produce foam of desired quantity. Figure 3.6 shows the foaming agent.

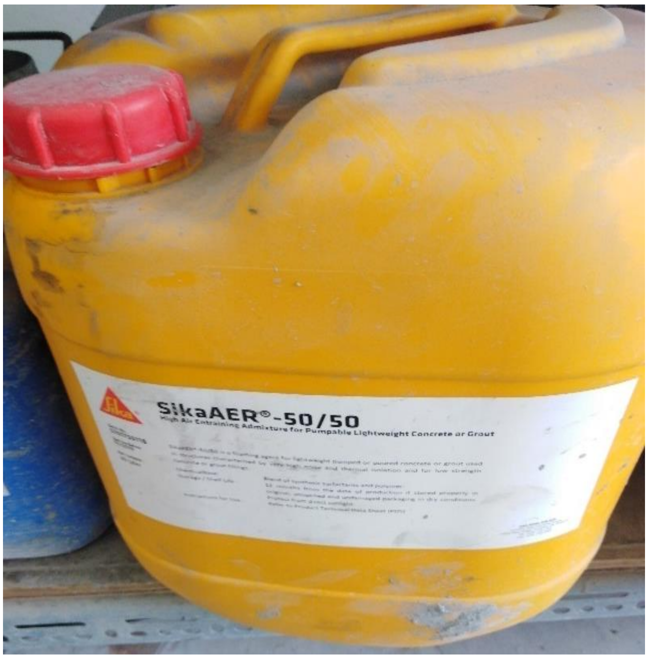

Figure 3.6: The Foaming Agent- SikaAER@- 50/50

The goal is to acquire a density of approximately 45 kg/m^3 for foam. The volume ratio for a foaming agent to water is approximately 1:20, and the mixture will be directed into the foam generator under the pressure of 0.5 MPa to produce foam that will be dispensed out through the nozzle. Figure 3.7 and Figure 3.8 display the foam generator and foam produced, respectively.

Figure 3.7: Foam Generator

Figure 3.8: Foam Generated

3.2.5 Water

According to ASTM C1602, tap water will be used throughout the research to produce a consistent result. The water to cement ratio will be set to 0.55 for all specimens to ensure consistent results. Moreover, tap water is used due to its relatively consistent pH of 7.5.

3.3 Mix Proportioning

In this study, there will be mainly three mixtures. The water to cement ratio will be set to 0.55.

The first mixture, mixture A, will have a proportion of its weight of fine aggregate (FA) replaced by powdered rubber by 0, 10, 20, 30, 40, 50, 60, 70, 80 percent. The code used for this mixture is 0.55-P-X; 0.55 stands for water to cement ratio, ‘X’ stands for rubber replacement in terms of percentage, and ‘P’ stands for powdered rubber.

The second mixture, mixture B, will have a proportion of its weight of coarse aggregate (CA) replaced by crumb rubber by 0, 10, 20, 30, 40, 50, 60, 70, 80 percent. The code used for this mixture is 0.55-C-X; ‘C’ stands for crumb rubber. Table 3.1 below shows the powdered and granular crumb rubber replacement.

Table 3.1: Powdered Rubberized Concrete (PRC)

Designation	**Rubber Particles Replacement (%)**	**Water/Cement Ratio**
0.55-P-0	0	0.55
0.55-P-10	10	0.55
0.55-P-20	20	0.55
0.55-P-30	30	0.55
0.55-P-40	40	0.55
0.55-P-50	50	0.55
0.55-P-60	60	0.55
0.55-P-70	70	0.55
0.55-P-80	80	0.55

Table 3.2: Granular Crumb Rubberized Concrete (GCRC)

Designation	**Rubber Particles Replacement (%)**	**Water/Cement Ratio**
0.55-C-10	10	0.55
0.55-C-20	20	0.55
0.55-C-30	30	0.55
0.55-C-40	40	0.55
0.55-C-50	50	0.55
0.55-C-60	60	0.55
0.55-C-70	70	0.55
0.55-C-80	80	0.55

The abundant mix proportion will be shown in Table 3.3. The purpose of having a variation in density of cement, sand, water, powdered rubber, crumb rubber and foam is to choose the highest compressive strength and tensile strength. Even though the density of water and cement might differ from one specimen to another, the water to cement ratio must be adjusted to 0.55. Although there were various compositions for the lightweight rubberized concrete, the total density of 1150 kg/m^3 was acquired in all mixes. The mix that exhibited the highest compressive strength and flexural strength will be used to cast the inner core of the sandwiched wall panel with the dimension of 300 mm x 300mm x 75 mm. Table 3.3 shows the composition and the actual density of materials.

Table 3.3 The composition and the actual density of materials.

Designation	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Powdered Crumb Rubber (kg/m^3)	Granular Crumb Rubber (kg/m^3)	Foam (kg/m^3)
0.55-P-0	443.07	443.07	243.69	0.00	0.00	20.18
0.55-P-10	453.71	408.34	249.54	18.83	0.00	19.58
0.55-P-20	464.87	371.90	255.68	38.59	0.00	18.96
0.55-P-30	476.60	333.62	262.13	59.35	0.00	18.30
0.55-P-40	488.93	293.36	268.91	81.18	0.00	17.61
0.55-P-50	501.92	250.96	276.06	104.17	0.00	16.88
0.55-P-60	515.62	206.25	283.59	128.42	0.00	16.12
0.55-P-70	530.09	159.03	291.55	154.03	0.00	15.31
0.55-P-80	**545.39**	**109.08**	**299.97**	**181.11**	**0.00**	**14.45**

Table 3.3 (Continued)

0.55-C-10	453.71	408.34	249.54	0.00	18.83	19.58
0.55-C-20	464.87	371.90	255.68	0.00	38.59	18.96
0.55-C-30	476.60	333.62	262.13	0.00	59.35	18.30
0.55-C-40	488.93	293.36	268.91	0.00	81.18	17.61
0.55-C-50	501.92	250.96	276.06	0.00	104.17	16.88
0.55-C-60	515.62	206.25	283.59	0.00	128.42	16.12
0.55-C-70	530.09	159.03	291.55	0.00	154.03	15.31
0.55-C-80	545.39	109.08	299.97	0.00	181.11	14.45

3.3.1 Specimen Preparation

Before commencement of this experiment, all materials are weighted with an electric scale to ensure the mixing proportion is according to specification. Firstly, aggregates and crumb rubber were completely dry mixed to achieve a uniform mixture. After that, OPC was added and mixed continuously until it can be visually seen that all the ingredients were spread evenly, closely followed by water. Lastly, adding the desired amount of foam into the mixture gives it a thorough mix until the white foam is not visible. The casting of fresh concrete was commenced after the mixing was properly carried out and weighed to the desired density of 1150 kg/m^3. All the batches were produced according to the various proportion specified in Table 3.3. A step-by-step procedure is presented as shown in Figure 3.9 below.

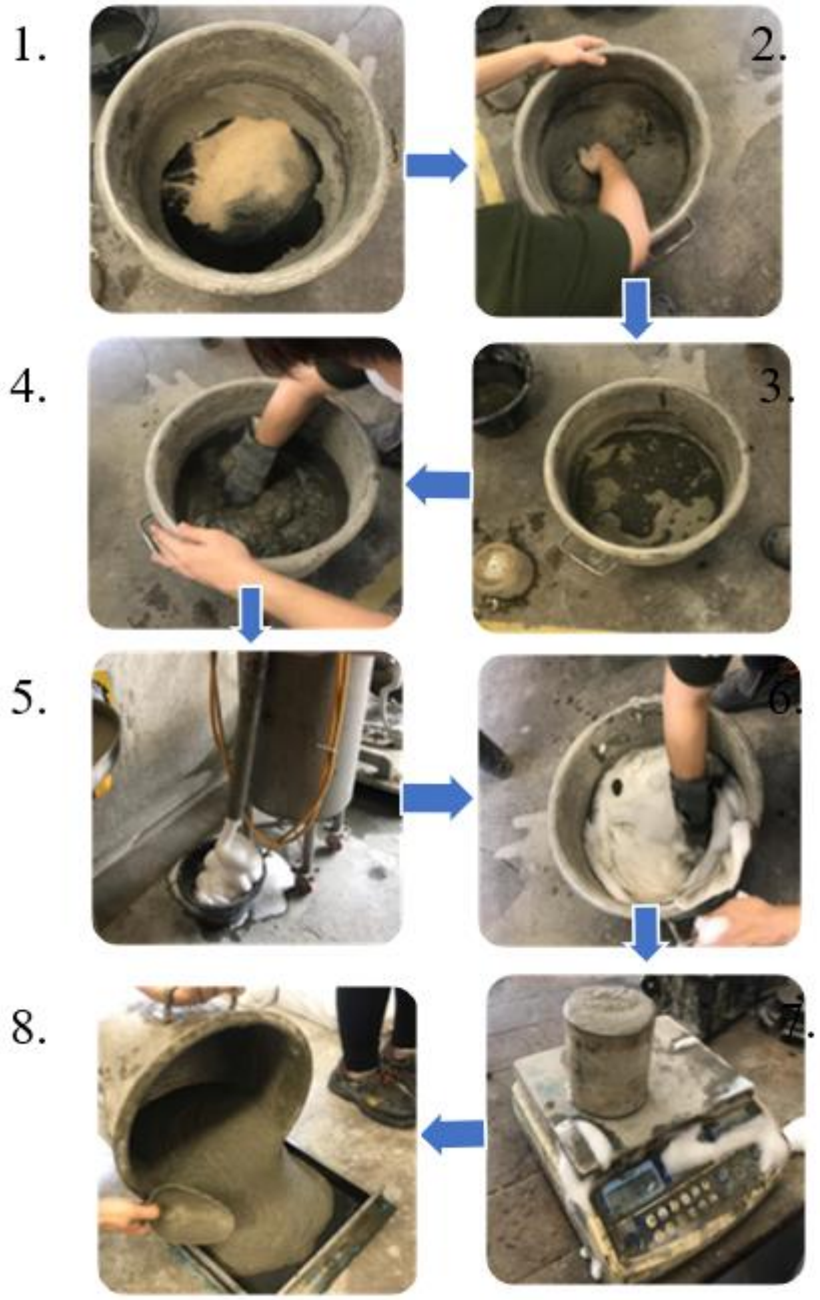

Figure 3.9: Step by step mixing procedure

3.3.2 Sheathing Material for Lightweight Rubberized Concrete Sandwiched Panel

In this experiment, calcium silicate board will be chosen as the wall panel for the lightweight rubberized concrete since it has strong fire resisting properties, which can further enhance or strengthen the fire resistance capacity of the rubberized concrete when integrated. The calcium silicate board was commercially purchased. Figure 3.10 illustrates the calcium silicate board.

Figure 3.10: Calcium Silicate Board

3.3.3 Casting and Curing Condition for Concrete, Cylinder, and Wall Panel Specimen

After thoroughly mixing the concrete mixture, the mixture will be cast into the mould. There are two different types of concrete moulds to be prepared. The first is a concrete cube mould with 100 mm x 100 mm x 100 mm for compression test. The next is a cylindrical mould with a dimension of 100 mm of diameter x 200mm (H); Its purpose is to test its tensile strength under the splitting tensile strength test. The last mould is the wall panel mould with a dimension of 300 mm x 300 mm x 75 mm. The mix chosen to cast in the wall panel mould will be 0.55-P-80, because the mix exhibits the highest compressive strength and flexural strength. The moulds were cleaned and oiled before the casting of the concrete. After completion of the concrete casting, the excess will be removed, and the surface was levelled. After 24 hours, the specimens were removed from the mould and stored in the water tank for curing purposes. Once the concrete specimens were cured for 28 days, they were removed from the water storage and placed inside the oven for 24 hours to remove excess moisture content.

3.3.4 Connection of Calcium Silicate Board and Rubberized Concrete.

This experiment will choose calcium silicate as the sheathing material for the lightweight rubberized concrete sandwich panel. A suitable bonding material must be introduced to ensure a strong connection between the inner core with the calcium silicate board. In this experiment, Polyurethane Glue will be used due to its strong adhesive properties and is highly resistant to most forms of degradation. The brand chosen was called Collano Semparoc Polyurethane Adhesives. Figure 3.11 illustrates the types of adhesive gel used in this experiment.

Figure 3.11: Collano Semparoc Polyurethane Adhesives

The adhesive glue was applied in such a way that one surface of the two calcium silicate boards was covered with evenly distributed adhesive gel, the cured lightweight foamed rubberized concrete was planted onto one of the calcium silicate boards, and the other calcium silicate board was incorporated on top of the lightweight foamed rubberized concrete.

3.3.5 Production of The Sized-Down Wall Panel Specimen

Rubberized lightweight foamed concrete sandwiched panels are composite structures composed of two materials with distinct properties. The outer skin layer will be a calcium silicate board, and the inner layer will be rubberized lightweight foamed concrete. These two layers were bounded with adhesives polyurethane glue to produce a final structure with superior properties that can fulfil the building code of practice. This experiment constructed a wall panel specimen with 300 mm x 300 mm x 75 mm dimensions. The purpose of scaling down the dimension is to determine the suitable thickness of the inner core concrete beforehand. Figure 3.12 depicts the sized down wall panel specimen.

Figure 3.12: Sized-down Wall Panel Specimen

3.4 Laboratory Testing

There are many specimens with different proportions of crumb rubber replacement. Compressive and flexural strength tests were executed to select the strongest composition from the lots to fill in as the inner core for the sandwiched wall panel. Every designated specimen was tested three times to obtain the average compressive index. The strongest composition after the testing was ‘0.55-P-80’, and this composition will be reproduced as the core structure for the wall specimen. Once the sandwiched wall panel has been set up, three tests were executed. The tests being flame exposure test, load-deflection test, and load-bearing capacity test.

3.4.1 Compressive Strength Test for Concrete Cube Specimen

The test was carried out in accordance with BS 1881: Part 116. The cured concrete specimen was placed in the centre of the machine. The instrument was adjusted such that the plate touches the top surface of the specimen. The load was applied gradually with a rate of 0.2 kN/s until the first fracture point occurred. After that, the procedure was repeated with another specimen, and the recordings were recorded. The compressive strength of the concrete cube was calculated with formula 3.1.

$$fci = Fi/Aci \tag{3.1}$$

where

fci = the compressive strength, MPa

Fi = the maximum load, N

Aci = The cross-sectional area which the load is applied, mm^2

3.4.2 Flexural Strength for Concrete Cylinder Specimen

A flexural strength test was carried out in accordance with ASTM C 78. The flexural strength of concrete is determined by either centre point loading or four-point load. Centre point loading will be used in this test. The specimen was carefully placed on the rollers and centred with the longitudinal axis of the specimen. A continuous loading was applied at a rate of 0.2 kN/s. The recording was recorded when the specimen failed by developing cracks. The procedure was repeated with the other specimen. Equation 3.2 was used to calculate the modulus of rupture.

$$R = \frac{3PL}{2BD^2} \tag{3.2}$$

where

R= Modulus of Rupture

P= Maximum applied load indicated by the testing machine, kN

L= span length, mm

B= average width of the specimen, mm

D= average depth of specimen, mm

3.4.3 Flame Exposure Test

The objective of this test was to determine the behaviour of the sized down sandwiched wall panel towards continuous exposure of flame. The surface was heated up to 600 °C for 60 minutes. ISO 834-1 mentioned that the weakest spot would be at its centre for a test specimen. Hence, a thermocouple was placed at the centre of the wall panel not facing the fire; it was used to take the temperature of the calcium silicate every minute. After completing the test, observations regarding the integrity of the structure and the formation of cracks on the wall panel surface are observed. Figure 3.13 illustrated the complete setup for the test. The test was carried out in accordance with ISO- 834-1.

Figure 3.13: Flame Exposure Test Being Conducted on a Sized-Down Wall Panel Sample

3.4.4 Load Deflection Test.

The load-deflection test was implemented to determine the out-of-plane ultimate flexural strength of the sized down rubberized lightweight foamed concrete sandwiched panel. The support was loaded 10 mm away from the edge of the specimen. A linear voltage displacement transducer (LVDT) is mounted at the midspan of the specimen, and it is connected to a data logger to produce the load-deflection reading during the test. The increasing load was applied from an I-beam at a constant rate onto the specimen, and the failure of the specimen will serve as an indication of ultimate flexural strength. Figure 3.14 illustrates the complete setup for the load-deflection test.

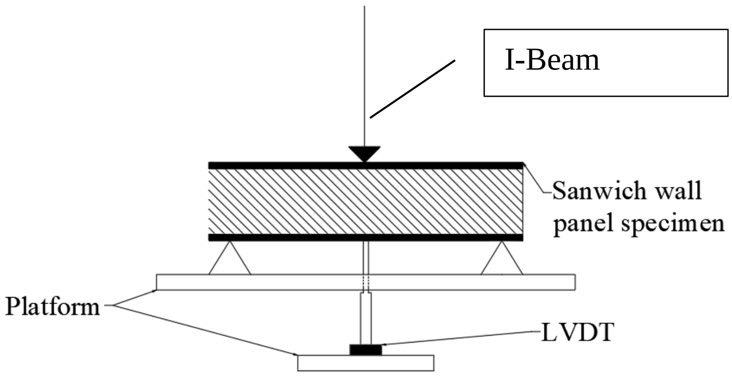

Figure 3.14: Load-Deflection Test

3.4.5 Load Bearing Capacity Test.

The sandwiched wall panel is set up vertically, and two steel plates were placed at the top and the bottom of the specimen. The purpose of having the steel plate was to distribute the load coming from the I-Beam evenly. An I-beam was placed along the longitudinal axis of the wall panel. The constant rate of the compressive load is applied to the specimen. Four compressometers are installed on every near corner of the surface of the specimen. The compressor meter is to help determine the deformation of the specimen surface upon loading. Two LVDTs are also installed on each centre of the calcium silicate board to determine the lateral deflection of the specimen. The lateral deflection versus load readings is generated in a data logger for interpretation. The load at which the sandwich wall panel specimen fractures indicate the wall panel's ultimate load capacity. Figure 3.15 illustrates the complete setup for the load-bearing capacity test.

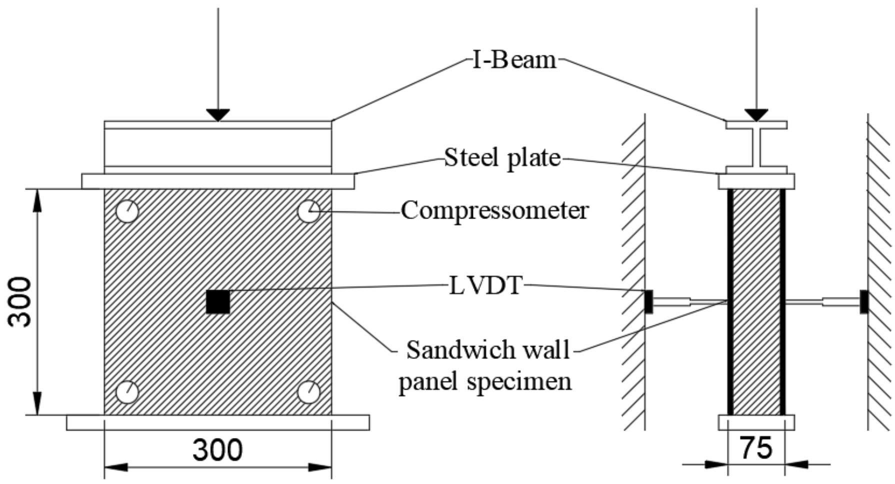

Figure 3.15: Complete Set-Up of Load-Bearing Capacity Test.

3.5 Summary

This chapter includes the methodology in preparing rubberized lightweight foamed concrete sandwich wall panels. Many specimens with various crumb rubber replace were set up. The compressive and flexural strength were used to determine the most substantial composition out of all the specimens. ‘0.55-P-80’ composition was selected at the end as the inner-core material due to its highest tensile and compressive strength. A calcium silicate board was chosen as the sheathing material for the sandwiched wall panel due to its strong resistance to fire and high durability. After the sandwiched wall panel was set up, the specimen was subjected to three tests to determine its fire resistance, load-bearing capacity, and out-of-plane bending strength.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter mainly comprises the behaviour and performance of non-load bearing sandwiched lightweight rubberized concrete wall-panel under various tests. The tests included flame exposure test, load-deflection test and load-bearing capacity test. The test will give an insight regarding the suitability of calcium silicate board as the skin for the sandwiched wall panel and lightweight rubberized concrete as the inner core for the sandwiched wall panel. Before the commencement of the wall-panel tests thereof, an optimum mix to produce the best lightweight rubberized concrete had been determined. The tests were conducted to determine the optimum mixes were the compressive strength test and flexural strength test. The function of lightweight rubberized concrete was to act as an inner fill for the sandwiched wall panel.

4.2 Characteristic strength of RLFC with optimal mix proportions.

The main objective in this subsection is to get the ideal mix that can produce the highest compressive strength. The reason is that the ASTM building code has mentioned that the minimum load-bearing strength requirement for a non-load-bearing wall panel is 3.45 MPa. Different mix proportions with different values of fresh density for cement, sand, water, powdered crumb rubber was mixed to produce various mix specimen. Bear in mind that the resultant fresh density shall not differ more than 50 kg/m^3 compared with the targeted fresh density (1150 kg/m^3).

Due to human error, the resultant fresh density of the mixed specimen may differ positively or negatively from the targeted fresh density, which will affect the compressive strength and produce a biased result. The way to amend this problem was by introducing a dimensionless parameter, compressive strength index, and producing three similar mix proportions to obtain an average compressive strength index for a more consistent result. The compressive strength index is the thousands of quotients after the characteristic strength is divided by the fresh density. The summary of the characteristic strength of the concrete cube specimen is presented in Table 4.1.

Table 4.1: Characteristic Compressive Strength of RLFC Cube Specimens

Designation	**Specimen**	**Fresh Density (kg/m^3)**	**Characteristic Strength (MPa)**	**Compressive Strength Index**	**Average Compressive Strength Index**
0.55-P-0	1	1134	3.37	2.9718	3.2764
	2	1175	4.33	3.6851	
	3	1138	3.61	3.1722	
0.55-P-10	1	1122	2.97	2.6471	2.9179
	2	1130	3.35	2.9646	
	3	1133	3.56	3.1421	
0.55-P-20	1	1107	3.20	2.8907	3.0891
	2	1102	3.60	3.2668	
	3	1119	3.48	3.1099	
0.55-P-30	1	1139	3.46	3.0378	3.0318
	2	1127	3.32	2.9459	
	3	1128	3.51	3.1117	
0.55-P-40	1	1148	3.57	3.1098	3.1487
	2	1105	3.43	3.1041	
	3	1120	3.62	3.2321	
0.55-P-50	1	1155	4.05	3.5065	3.7198
	2	1165	4.18	3.5880	
	3	1203	4.89	4.0648	

Table 4.1 (Continued)

0.55-P-60	1	1165	4.85	4.1631	3.9185
	2	1149	4.35	3.7859	
	3	1148	4.37	3.8066	
0.55-P-70	1	1137	4.94	4.3448	4.2105
	2	1136	4.75	4.1813	
	3	1140	4.68	4.1053	
0.55-P-80	**1**	**1130**	**4.84**	**4.2832**	**4.3062**
	2	**1136**	**4.91**	**4.3222**	
	3	**1143**	**4.93**	**4.3132**	
0.55-C-10	1	1142	3.32	2.9072	3.1433
	2	1135	3.50	3.0837	
	3	1134	3.90	3.4392	
0.55-C-20	1	1108	3.86	3.4838	3.2028
	2	1110	3.39	3.0541	
	3	1117	3.43	3.0707	
0.55-C-30	1	1091	2.91	2.6673	2.7437
	2	1093	2.89	2.6441	
	3	1096	3.20	2.9197	
0.55-C-40	1	1104	2.63	2.3822	2.5427
	2	1129	3.04	2.6926	
	3	1128	2.88	2.5532	
0.55-C-50	1	1102	2.35	2.1325	2.1960
	2	1102	2.40	2.1779	
	3	1102	2.51	2.2777	

Table 4.1 (Continued)

0.55-C-60	1	1097	2.56	2.3336	2.3341
	2	1094	2.47	2.2578	
	3	1095	2.64	2.4110	
0.55-C-70	1	1128	2.75	2.4379	2.4763
	2	1132	2.75	2.4293	
	3	1136	2.91	2.5616	
0.55-C-80	1	1128	3.08	2.7305	2.8271
	2	1132	3.24	2.8622	
	3	1139	3.29	2.8885	

As can be seen from Table 4.2, 80 % sand replacement with powdered rubber had displayed the highest compressive strength. On top of that, a large amount of powdered rubber replacement reduced the required foam, which explained the increase in compressive strength. Since coarse aggregate is the main strength contributor, hence, coarse aggregate replacement with granular crumb will reduce the strength properties comparing with another specimen.

Based on physical observation, all the specimens displayed cracks when oven-dried for 24 hours, at 105 °C. The reason is that crumb rubber particles weaken the bond in the mix, and rubber loses its strength when exposes to high heat, making it unsuitable as a sheathing material for the wall panel. Hence, the rubberized lightweight foamed concrete will only act as a load bearer.

4.3 Splitting Tensile Strength of RLFC with Optimal Mix Proportions.

The sheathing material does not contribute to tensile resistance; hence, the rubberized lightweight foamed concrete will resist tensile strength.

Naturally, concrete is weak in tensile strength. Hence, reinforcing with crumb rubber aims to increase the tensile strength of the concrete. The splitting tensile strengths of the cylinder specimen are tabulated in Table 4.2.

Table 4.2: Characteristic Splitting Tensile Strength of RLFC Cylinder Specimen

Designation	**Specimen**	**Fresh Density (kg/m^3)**	**Splitting Tensile Strength (MPa)**	**Average Splitting Tensile Strength (MPa)**
0.55-P-0	1	1136	0.598	0.585
	2	1125	0.572	
	3	1101	0.584	
0.55-P-10	1	1122	0.539	0.564
	2	1136	0.519	
	3	1162	0.634	
0.55-P-20	1	1168	0.621	0.554
	2	1119	0.518	
	3	1136	0.522	
0.55-P-30	1	1154	0.493	0.492
	2	1141	0.500	
	3	1108	0.484	
0.55-P-40	1	1085	0.576	0.578
	2	1135	0.516	
	3	1124	0.643	

Table 4.2 (Continued)

0.55-P-50	1	1125	0.638	0.633
	2	1108	0.617	
	3	1120	0.644	
0.55-P-60	1	1163	0.688	0.623
	2	1149	0.583	
	3	1082	0.598	
0.55-P-70	1	1154	0.637	0.673
	2	1130	0.605	
	3	1116	0.777	
0.55-P-80	**1**	**1113**	**0.694**	**0.703**
	2	**1129**	**0.761**	
	3	**1110**	**0.656**	
0.55-C-10	1	1145	0.627	0.597
	2	1129	0.605	
	3	1111	0.560	
0.55-C-20	1	1128	0.538	0.540
	2	1138	0.598	
	3	1111	0.484	
0.55-C-30	1	1106	0.560	0.536
	2	1113	0.554	
	3	1117	0.493	
0.55-C-40	1	1141	0.401	0.422
	2	1166	0.500	
	3	1169	0.366	

Table 4.2 (Continued)

0.55-C-50	1	1087	0.242	0.286
	2	1098	0.312	
	3	1138	0.306	
0.55-C-60	1	1091	0.245	0.262
	2	1103	0.312	
	3	1098	0.229	
0.55-C-70	1	1145	0.321	0.360
	2	1176	0.379	
	3	1199	0.379	
0.55-C-80	1	1143	0.312	0.299
	2	1100	0.334	
	3	1103	0.251	

Based on Table 4.2, 80 % replacement of powdered rubber displayed the greatest splitting tensile strength. This is because rubber has a low modulus of elasticity and is more capable of sustaining deformation than fine sand.

4.4 Thermal Conductivity of RLFC with Optimal Mix Proportion

It is vital to take note that thermal conductivity is different from fire resistance. Thermal conductivity strongly relates to time lag and decrement factor, and low thermal conductivity indicates comfortable indoor temperature. This test is set up to determine the specimen with the lowest thermal conductivity. The thermal conductivity of the concrete with optimum mix proportions is tabulated in Table 4.3.

Table 4.3: Thermal Conductivity of RLFC

Designation	**Thermal Conductivity ($Wm^{-1}K^{-1}$)**
0.55-P-0	0.4858
0.55-P-10	0.4902
0.55-P-20	0.4772
0.55-P-30	0.4602
0.55-P-40	0.3906
0.55-P-50	0.3688
0.55-P-60	0.3700
0.55-P-70	0.4122
0.55-P-80	**0.3415**
0.55-C-10	0.4882
0.55-C-20	0.4664
0.55-C-30	0.4549
0.55-C-40	0.4271
0.55-C-50	0.3781
0.55-C-60	0.3823
0.55-C-70	0.3518
0.55-C-80	**0.3391**

According to Table 4.3, it is evident that the thermal insulator of RLFC increases regardless of powdered or crumb rubber replacement. The higher replacement of rubber increases the thermal conductivity of the RLFC sample. This is because rubber possesses better insulating properties comparing with fine sand or coarse aggregate. Although 0.55-C-80 displayed lower thermal conductivity than 0.55-P-80, it was not suggested to be used as inner core material due to its poor mechanical properties. 0.55-C-80 is proposed as the inner core of the sandwich wall panel for further study.

4.5 Load Deflection Test Result

The test was commenced after 28 days of curing the test specimen. The test specimens were cleaned and set up prior to the load-deflection test. After that, the sandwich wall panel was placed in a horizontal position for testing. The constant load was applied until the sandwich wall panel failed, and LVDT generated the load-deflection reading for interpretation. Figure 4.1 represents the load-deflection curves for the sandwich wall panel.

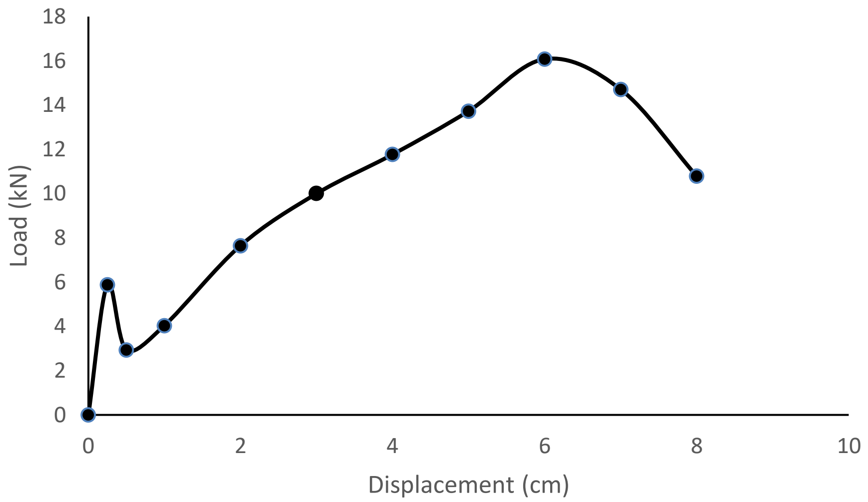

Figure 4.1: Flexural Strength of Rubberized Lightweight Sandwiched Wall Panel

Figure 4.1 shows the load-deflection curve for the sandwiched wall panel. Based on this figure, the sustained load rises to 6 kN before a sharp drop. This sudden drop does not indicate failure but cracks the calcium silicate wall panel, which results in a redistribution of the panel force directly into the surrounding panel. The cracking of the calcium silicate wall panel indicates a probability of a concentrated load failure. A possible amendment to avoid localized failure is by increasing the width of the I-beam to reduce the pressure acting on the test specimen.

After axial force redistribution, the gradient of the load-displacement graph had been reduced to half. This can be explained by the weak adhesive bond between the calcium silicate wall panel and the RLFC after the crack. The ultimate load of the sandwich wall panel is 16.4 kN, where the tension side of the test specimen experiences a large crack in the middle, quickly followed by the crushing and collapse of the whole specimen. The maximum lateral deflection before crushing is 80mm.

4.6 Load Bearing Capacity Test Result

Figure 4.2 presents the load and the vertical deflections graph of the sandwich wall panel. A marker pen is used to mark the crack surface, and the failure pattern is observed for interpretation.

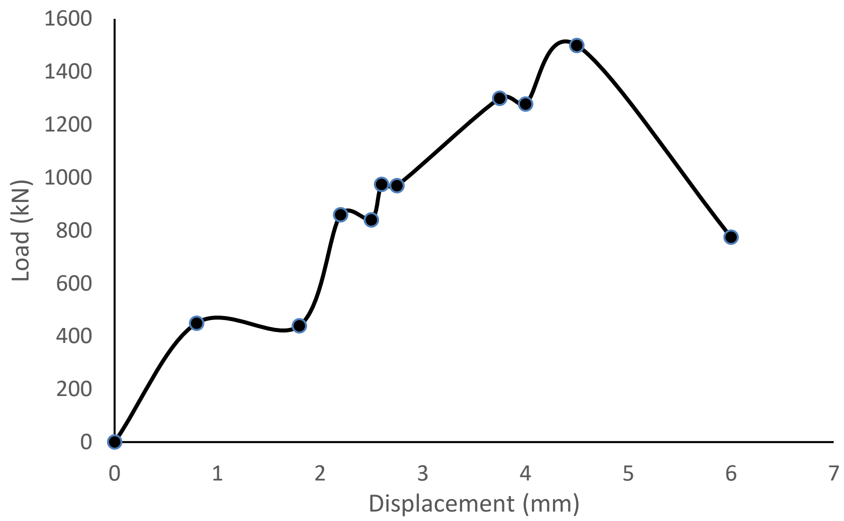

Figure 4.2: Load Bearing Capacity of Rubberized Lightweight Sandwiched Wall Panel.

Based on Figure 4.2, the first crack appears when a sudden load drop at 450 kN. The crack indicates redistribution of the applied load. The load is progressively applied until the second load drop after it reaches 860 kN. In this part, the existed crack diameter has increased, and many micro-cracks are spotted on the surface of the wall panel. The third drop at 1300 is due to a macro crack appearing at the panel edge beam. The slight separation between the calcium silicate board and RLFC is spotted at the fourth drop about 1270 kN. When the load increased to 1500 kN, many main cracks have begun to enlarge in size, followed by small spalling of the calcium silicate wall panel and RLFC. The ultimate load of the test specimen is at 1500 kN, where crushing and spalling of the test specimen occur.

4.7 Flame Exposure Test Result

The utilization of the calcium silicate wall panel must possess firefighting performance. Figure 4.3 presents the time-temperature chart when an RLFC sandwiched wall panel is exposed to a direct flame up to 600 °C for 60 minutes.

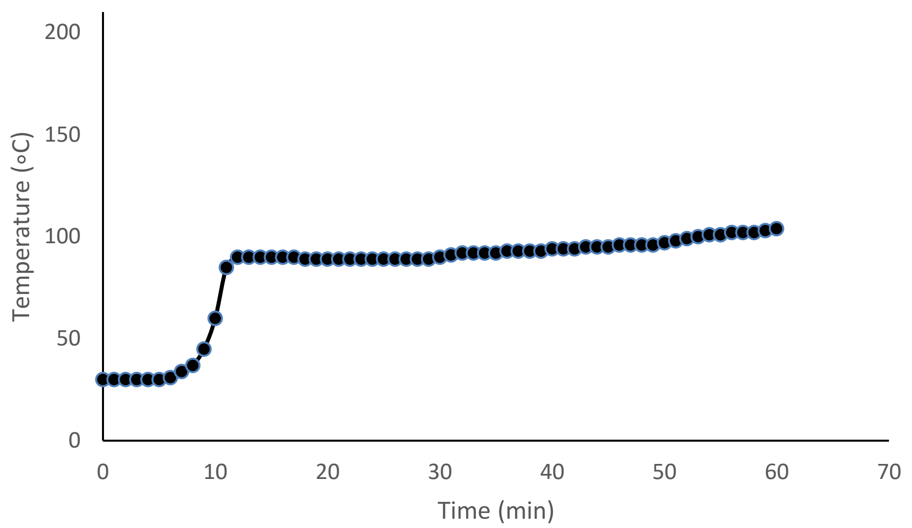

Figure 4.3: Temperature vs Time for Calcium Silicate Board

The temperature of the calcium silicate panel starts at 30 °C, in synchronization with the room temperature. After around 8 minutes mark, the colour of the calcium silicate board begins to change from white to milky brown; the graph displayed a drastic uptrend behaviour until the 12th-minute mark, where the reading of the temperature seems to be stabilized. At this point, the colour of the calcium silicate board starting to turn dark brown. A crack is starting to form at the middle-upper portion of the test specimen. From the 12th-minute mark to the 37th-minute mark, the same crack extends towards the centre, and there is no sign of other cracks. After the 60th minute mark, the highest temperature reading is 104 °C, which satisfies the ISO 834-1 requirement, which states that the temperature recorded at the backside of the test specimen should not be more than 180 °C. After 60th minutes mark, other than a visible crack and a blackish appearance on the side exposed to flame, there is no sign of structural failure, which indicates that calcium silicate board is suitable and effective as a fireproof material.

4.8 Summary

This chapter presents the result obtained from the concrete cube compressive test, concrete cylinder flexural strength test, RLFC sandwich wall panel flame exposure test, RLFC sandwich wall panel load-deflection, RLFC sandwich wall panel load-bearing capacity. 80 % replacement of fine sand with powdered rubber is chosen as a solution for infilling the inner core for the sandwiched wall panel. The average compressive strength is 4.3062 MPa, and the average flexural strength is 0.703 MPa.

From the load-deflection test, the load-deflection behaviour shows that failure occurs due to weak bonding between the wall panel and the inner-core. The ultimate load is 16.4 kN, and the specimen failed in a crushing manner.

From the load-bearing test, the experimental investigation revealed that the failure of the test specimen is not because of the connection system between the wall panel and the inner-core, unlike the load-deflection test. The first crack occurs at 30% of the ultimate load. Plentiful minor cracks are observed when the load is gradually applied, mainly at the surface centre and the edge of the sandwich wall panel. The ultimate compressive strength of the sandwiched wall panel is 1500 kN.

From the flame exposure test, the wall panel has met the demand of the 60 minutes fire rating test. There is only one crack present for the entire experiment. There is no sign of spalling or crushing of the wall panel specimen. After 60 minutes, the highest temperature recorded by the thermocouple is 104 °C. However, there is no strict regulation as to how the calcium silicate panel are produced, and hence, calcium silicate boards from different manufacturers might produce a different result.

In a nutshell, the result confirms the suitability of the RLFC sandwiched wall panel as a non-load-bearing wall with good fire performance.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Numerous tests were conducted to determine the feasibility of RLFC as the inner core and calcium silicate board as the skin wall panel in a composite sandwich wall panel.

The purpose of integrating foam into the concrete mix is to reduce the dead loads of the whole structural building, saving costs in reinforcement and foundation. Volumetric percentage of fine and coarse aggregates were replaced by powdered and granular crumb rubber respectively, and the optimum mix discovered was 0.55-P-80. The mix displayed a compressive strength of 4.3062 MPa, which is higher than the minimum requirement of 3.45 MPa set by the ASTM building code of practice. The mix presented a flexural strength of 0.703 MPa. Although 0.55-C-80 shows an improvement in thermal conductivity over 0.55-P-80, the improvement is negligible and is not enough to compensate for the inferiority in compressive and flexural strength compared with 0.55-P-80.

The sandwich wall panel is used as the connection system of adhesive bonding. The adhesive glue was named Collano Semparoc Polyurethane Adhesive. It was commercially purchased.

From the load-deflection test result, the connection system displayed high importance. When the test specimen was subjected to concentrated load, it was observed that minor tearing occurred along with the connection system, and the midspan of the test specimen exhibited brittle failure mode. However, brittle failure mode indicating higher stiffness. The ultimate flexural strength recorded was 16.4 kN

From the load-bearing test result, it was observed that the test specimen failed gradually. Numerous micro-crack was detected during the loading, which indicates the sandwich wall panel exhibits ductile behaviour. The ultimate compressive strength recorded was 1500 kN.

From the flame exposure test, after 60 minutes of continuous exposure of direct fire to 600 °C, the highest temperature recorded by the thermocouple was 104 °C, indicating that calcium silicate was suitable as a firefighting material, according to ISO 834-1.

5.2 Recommended Solutions

The study of load-bearing and fire performance of non-load bearing lightweight rubberized sandwiched wall panels is still limited in this field. Some considerations have to be accounted for improve the result. The recommendations are suggested below:

1. The connection system for the sandwiched wall panel plays a vital role to ensure the wall panel and inner core act as a composite system. Advance connection systems such as shear studs can be proposed to enhance the connection system.
2. For load-deflection tests, the loading area must be increased to prevent concentrated failure of the test specimen.
3. Investigate the mechanical properties of sandwich wall panels when admixture such as silica fume is added in the RLFC to enhance its compressive strength.
4. Considering adding chicken mesh during the casting of RLFC to prevent spalling out of the inner core during crushing failure.
5. During fire testing, ensuring a consistent composition of the test panel is very important. Consider conducting more tests with a different model of calcium silicate board to investigate the difference in fire performance.

REFERENCES

Ganjian, E., Khorami, M. and Maghsoudi, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and building materials*, 23(5), pp.1828-1836.

Hernández-Olivares, F. and Barluenga, G., 2004. Fire performance of recycled rubber-filled high-strength concrete. *Cement and concrete research*, 34(1), pp.109-117.

KEW, H.Y. and Kenny, M., 2009. Developing viable products using recycled rubber tyres in concrete. *In International Conference on Concrete Construction* pp. 523-531.

Kew, H.Y., Etebar, K., Limbachiya, M.C. and Kenny, M., 2009. Investigation into the potential of rubberized concrete products. *In International Conference on Concrete Construction*, pp. 533-543.

Kristanto, L., Sugiharto, H., Agus, S. D., & Pratama, S. A. (2017). Calcium silicate board as wall-façade. *Procedia engineering*, *171*, 679-688.

Kumar, S., Chen, B., Xu, Y., & Dai, J. G. (2021). Structural behavior of FRP grid reinforced geopolymer concrete sandwich wall panels subjected to concentric axial loading. *Composite Structures*, *270*, 114117.

Lakshmikandhan, K. N., Harshavardhan, B. S., Prabakar, J., & Saibabu, S. (2017, August). Investigation on wall panel sandwiched with lightweight concrete. In *IOP Conference Series: Materials Science and Engineering* (Vol. 225, No. 1, p. 012275). IOP Publishing.

Muhammad, M.A., Abdullah, W.A. and Abdul-Kadir, M.R., 2017. Post-fire mechanical properties of concrete made with recycled tire rubber as fine aggregate replacement. *Sulaimania Journal for Engineering Sciences*, 4(5).

Ng, S. C., Low, K. S., & Tioh, N. H. (2011). Thermal inertia of newspaper sandwiched aerated lightweight concrete wall panels: Experimental study. *Energy and buildings*, *43*(10), 2956-2960.

Raju, Y.K. and Kumar, N.H., 2019. Strength Performance of Crumb Rubber Concrete. Volume, 7, pp.2007-2010.

Rana, A. and Yadav, K., 2020. A study on Rubberized Concrete. International *Journal of Engineering Research & Technology*, 9(9).

Stallings, K.A., 2016. *Investigation of Recycled Tire Chips for use in Gdot Concrete Used to Construct Barrier Walls and other application*. Bachelor thesis, The University of Georgia, Georgia.

Wang, Y., Chuang, Y. J., & Lin, C. Y. (2015). The performance of calcium silicate board partition fireproof drywall assembly with junction box under fire. *Advances in Materials Science and Engineering*, *2015*.

Yasin, A.A., 2012. Using Shredded Tires as an Aggregate in Concrete. *Contemporary Engineering Sciences*, 5(10), pp.473-480.

Yusof, M.Z. and Ramli, M., 2008, September. Experimental studies of the effectiveness of mortar modified with latexes. *In Excellence in Concrete Construction through Innovation: Proceedings of the conference held at the Kingston University, United Kingdom*, 9-10 September 2008, pp. 263. CRC Press.

Zheng, L., Huo, X.S. and Yuan, Y., 2008. Strength, modulus of elasticity, and brittleness index of rubberized concrete. *Journal of Materials in Civil Engineering*, 20(11), pp.692-699.