STRUCTURAL PERFORMANCES, THERMAL INSULATING AND FIRE RESISTING ABILITIES OF RUBBERIZED CONCRETE WALL PANEL UTILIZING MAGNESIUM OXIDE BOARD AS THE SKIN LAYER

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

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

May 2023

DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STRUCTURAL PERFORMANCES, THERMAL INSULATING AND FIRE RESISTING ABILITIES OF RUBBERIZED CONCRETE WALL PANEL UTILIZING MAGNESIUM OXIDE BOARD AS THE SKIN LAYER"** was prepared by **MOK SHAO JUN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering with Honours at Universiti Tunku Abdul Rahman.

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Date : 28th APRIL2023

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ABSTRACT

The dramatic increase of waste tyres and rubber wastes has become a global environmental issue due to the rapid growth of the automobile industry. Further, population growth and urbanisation create a massive demand for raw construction materials. Over the past few decades, multiple researchers have distinguished the possibilities to utilise rubber waste and create its second value, such as partially replacing aggregates with rubber particles to produce rubberized concrete and apply it in the construction industry. Hence, this study aims to investigate the engineering properties of rubberized lightweight foamed concrete (RLFC) sandwiched wall panels. Flexural strength test, compressive strength test, thermal conductivity test, and flame exposure tests were conducted to determine the performance of rubberized lightweight foamed concrete (RLFC) sandwiched wall panels. The RLFC sandwiched wall panels were cast with RLFC inner core layer and magnesium oxide board as the skin layers. The inner core is produced by mixing foam and crumb rubber with concrete. Three different thicknesses of magnesium oxide board specimens were prepared, namely, 6MGO (6 mm), 9MGO (9 mm), and 12MGO (12 mm), respectively. All achieved a target density of 1150 kg/m^3 and an inner core thickness of 105 mm. Based on the results from lab experiments and the comparison between 6MGO and 12MGO, the changes in percentage for ultimate flexural strength and thermal conductivity are +24.05 % (18.13 kN to 22.49 kN) and -7.19 % (0.3904 Wm^{-1}K^{-1} to 0.3642 Wm^{-1}K^{-1}) respectively when the thickness of skin layer increase from 6 mm to 12 mm. Besides, no cracking or damage was found on the skin layer after exposure to direct flame for 60 minutes. The connection between both specimens' inner core and skin layer was in good condition. Based on the result, it can be concluded that the magnesium oxide board is suited as the skin layer of the RLFC sandwiched wall panel. According to the thermal insulation and fire-resisting performance, the sandwiched wall panel produced from this study may be ideally applied as a non-load-bearing wall system in the construction industry to reduce the effect of rubber waste on the environment. Further studies are needed to compare the results obtained from this study by using various types of sheathing material as skin layer and different mix proportions to cast the inner core.

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LIST OF SYMBOLS / ABBREVIATIONS

B	Average Width of Specimen, mm
D	Average Depth of Specimen, mm
L	Span Length, mm
P	Maximum Applied Load Indicated by The Testing Machine, kN
R	Modulus of Rupture, MPa

6MGO	Sandwiched Wall Panel Utilizing 6 mm Magnesium Oxide Board as Skin Layer
9MGO	Sandwiched Wall Panel Utilizing 9 mm Magnesium Oxide Board as Skin Layer
12MGO	Sandwiched Wall Panel Utilizing 12 mm Magnesium Oxide Board as Skin Layer
ASTM	American Society for Testing and Materials
BS	British Standard
CBPB	Cement Bonded Particle Board
CRC	Crumb Rubber Concrete
CSH	Calcium Silicate Hydrate
GB	Guojia Biaozhun
IBS	Industrialized Building System
ISO	International Organization for Standardization
LVDT	Linear Variable Differential Transducer
LVDTs	Linear Variable Differential Transducers
LWAC	Lightweight Aggregate Concrete
MDF	Medium-Density Fibreboard
MOR	Modulus of Rupture
MOT	Ministry of Transport
MS	Malaysia Standard
OPC	Ordinary Portland Cement
OSB	Oriented Strand Board
RCPT	Rapid Chloride Permeability Test
RCPT	Rapid Chloride Permeability Test

RLAC	Rubberized Lightweight Aggregate Concrete
RLFC	Rubberized Lightweight Foamed Concrete

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Concrete is the most common construction raw material used worldwide due to its structural properties and characteristics. The raw material of concrete is readily available, making it low-cost and easing the concrete production process by mixing all the raw materials. The excellent water and temperature resistance characteristics make concrete more durable and less maintenance for the extreme weather exposure. Based on the unit weight, the concrete can be classified into ultra-lightweight, lightweight, normal-weight, and heavyweight. The normal-weight concrete will be widely used to build infrastructure and buildings, while heavy-weight concrete will be applied for megastructures or special uses structures. The lightweight concrete, such as wall panels, will be used to build the non-structural and structural members. In order to achieve the Sustainable Development Goals by 2030, the industrialised building system (IBS) has been applied in the construction industry to reduce the wastage of building materials. Hence, the rubberized lightweight foamed concrete (RLFC) sandwiched wall panel will be studied in this research. The replacement of sand with crumb rubber was proposed a few decades ago to reduce solid waste disposal and pollution worldwide.

Rubberized concrete is mixing concrete and rubber particles in which the rubber particles partially replace coarse or fine aggregate. Most rubber particles added to rubberized concrete will be the small particles ground from recycled tyres. The study on rubber particles in ordinary concrete was conducted in the early 1990s due to the recycling and reuse of tyre waste as a priority in Arizona, United States. Rubber plays an essential role in the past industrial revolution, especially the blooming of the automobile industry, leading to higher annual manufacture and disposal of rubber products such as rubber tyres. One billion tyre waste is generated globally and annually at the end of its lifetime (Halsband et al., 2020). Another statistic shows that global rubber production reached 13.9 million metric tonnes, while the Asia Pacific occupies 91 % of global rubber production (Tiseo, 2021). Another concern will be the nonbiodegradable characteristics of rubber, even under long-term biological treatment. Therefore, the conventional waste management method, such as burning waste, will not be recommended because it will severely affect the environment and humans. Hence, one of the most effective ways to reduce rubber waste will be to utilise the rubber waste, create its second value and be helpful in the generation of economic value in different industries (Shahidan, Isham and Jamaluddin, 2016). The rubber waste passes through physical and mechanical treatment, such as the grinding of rubber waste to produce several rubber particles. The ground rubber particles can apply in different industries, such as partially replacing aggregate to produce rubberized concrete. The partial replacement of aggregates with rubber particles will cause the reduction of tyre waste and the demand for natural aggregates in the construction industry. Hence, rubberized concrete is not considered an especially novel technology, but the properties of rubberized concrete need more verification for widespread use as an environmentally friendly construction material.

According to a recent research report, rubberized lightweight concrete is low in density and thermal conductivity while having a greater sound absorption coefficient after replacing crumb rubber with sand (Pongsopha et al., 2022). The consequences of low unit weight and density result in low compressive and flexural strength. Therefore, the primary design consideration of the non-structural members, such as partition walls and wall panels, are thermal insulation, acoustic insulation, and fire-resisting performance will be the primary consideration. Hence, the rubberized lightweight foamed concrete will focus on non-load bearing study in this study. In this research, a study on structural performance, thermally insulating, and fire-resisting abilities of RLFC sandwiched wall panels with magnesium oxide skin layer will be carried out.

1.2 Importance of the Study

This study may devote a better insight into the rubberized concrete wall panel's structural performance, thermally insulating, and fire-resisting abilities with a skin layer of magnesium oxide board. The concrete core will mainly affect the structural performance, while the skin layer will affect the thermal insulating and fire-resisting abilities.

The dramatic increase of waste tyres and rubber waste worldwide has become one of the primary concerns due to the rise in demand and supply worldwide. The conventional waste management method typically will lead to several environmental impacts such as air pollution caused by burning, water pollution, reducing the vegetation of soil, and health issues brought to nearby residents due to the breeding of mosquitoes. The most effective ways will be recovering or recycling rubber waste or waste tyres into reclaimed rubber or crumb rubber through grinding processes (Secretariat of the Basel Convention, 2002). The crumb rubber typically will be added to replace the aggregate partially. Another study shows that adding rubber particles to the concrete mix reduces the density (Fawzy, Mustafa and Elshazly, 2020). The lower density characteristic will affect the strength properties of the concrete. Most of the research is done on how the rubberized concrete properties are affected by the rubber particle content. Using crumb rubber for partial aggregate replacement will help reduce the disposal of rubber waste or waste tyres and reduce the shortage and depletion of natural aggregate resources due to higher demand from new development worldwide. Hence, this study is carried out and provides insight into how the replacement of crumb rubber in RLFC sandwiched wall panels affect its structural, thermal insulation, and fire resistance performance.

This study may explain more explicitly how the rubber replacement and different thicknesses affect the thermal insulation performance of the RLFC sandwiched wall panel. The wall panel with good thermal insulation performance will reduce the heat gain and loss in summer and winter, which means less energy is required to maintain the interior building temperature. There are several significant impacts on the environment caused by energy consumption: climate change, air pollution, habitat destruction, etc.

Low density and self-weight will reduce the loading transfer to the building components: column, beam, and foundation. The structural member's design will be based on the smaller loading and reduce the total construction cost. Due to the rubberized concrete's low strength properties, such as compressive and flexural, the wall panel suggested applying on the non-load bearing wall, which only carries its self-weight. By comparing the lightweight concrete and conventional wall systems, the conventional wall systems will generate more loading, which acts on the structural member; hence, a stronger structural member is needed to support the loading. This will increase the volume or size of the structural member, which requires more raw material and reinforcement for the structural member. The extraction of aggregate and steel production will increase the carbon footprint, which might oppose the 2030 Agenda of Sustainable Development adopted by the Malaysian Government. Therefore, this study is vital to be carried out for several reasons, such as reducing construction costs and raw materials usage by applying the lightweight concrete wall system instead of conventional wall systems and promoting the replacement of crumb rubber in lightweight concrete.

1.3 Problem Statement

Several researchers stated that large quantities of waste tyres during the end of their lives have become one of the major concerns around the world (Siddika et al., 2019). The rapid growth of the global automobile industry further promotes the number of waste tyres, which could pose environmental issues such as substantial landfill areas needed to dispose of waste tyres. The waterproof property and vulcanisation process of rubber makes the rubber products unable to biodegrade under normal conditions. There are several ways to manage waste tyres, such as open dumping, landfills, burning, and pyrolysis, which might lead to serious environmental, social, and economic problems such as pollution and health issues. Disposing of waste tyres and reuse in the household might lead to the breeding of mosquitoes and several diseases. Hence, this increases the difficulty of reducing waste tyres and other rubber waste and leads to a large dumping area needed to dispose of the trash. Disposing waste tyres at landfill areas will result in uncontrolled fire, which causes toxic gas emissions and reduces soil fertility. The measures used to recycle and dispose of the waste tyres or rubber waste mentioned above might not be efficient and environmentally friendly. Hence, the circular economy of waste tyres and rubber waste will be considered to create and extend the value of rubber waste or waste tyres to apply the different waste management methods to make the process more efficient. Nowadays, most rubber waste or waste tyres will be disposed of, and only around 5 % of it will be applied in the construction industry (Kara De Maeijer et al., 2021). One of the possible ways will be to reuse the waste rubber, grind it into tiny particles, take it as a partial replacement for fine or coarse aggregate and add it into cement paste to form rubberized concrete.

Furthermore, the shortage of raw materials for aggregate resources such as sand and gravel has become the primary concern in certain countries. Many countries now face the depletion of natural aggregate resources, leading to increasing transportation for exporting the aggregate to other countries. Aggregate is the primary building material needed for construction and reduces the concrete mix cost. In the typical concrete mix, aggregate becomes the main composition, contributing to the strength properties of concrete. The aggregates within the cement paste provide a rigid skeletal structure and act as a filler to reduce the space occupied by the cement paste. Aggregate is becoming a prominent and typical building material on construction sites after only a few decades. The higher aggregate demand around the world leads to higher aggregate extraction worldwide. Aggregate extraction cannot prevent the environmental impact mainly caused by aggregate mining and its process. One of the typical impacts will be the change of land use, usually the conversion from undeveloped or agricultural land. Aggregate extraction has several effects, including habitat extinction, slope failure that causes landslides, groundwater pollution, sedimentation, and changes in flow patterns (Langer and Arbogast, 2002). Hence, the partial replacement of aggregate using the crumb rubber has been applied, and the properties of rubberized concrete have been identified.

Besides, the researcher suggests that future studies on the fire performance of rubberized concrete must be done (Kumaran, Mushule and Lakshmipathy, 2008). Due to the lack of reflection on the rubberized concrete wall panel's fire performance, the rubberized concrete wall panel's fire-resisting abilities have been carried out. The increased rubber particle content in the concrete mix will reduce strength and mechanical properties. Hence, more studies focus on the functional properties typically considered for the non-load-bearing structure. For the high-strength concrete filled with rubber, the fire test of the concrete shows the reduction of curvature and risk of explosive spalling (Hernández-Olivares and Barluenga, 2004). Furthermore, the study shows that the sized-down rubberized concrete wall panel, which utilized calcium silicate board as the skin layer, fulfils the ISO 834-1: 1999 (Tien, 2021). Hence, the rubberized concrete wall panel covered with a magnesium oxide board on both layers will be carried out in this study to identify further the structural performance, thermally insulating, and fire-resisting abilities.

1.4 Aim and Objectives

The aim of this study is to evaluate the engineering properties of sandwiched wall panels made of rubberized lightweight foamed concrete with a density of 1150 kg/m^3 as an inner core material and magnesium oxide board as an outer skin layer. The specific objectives of this research are as below:

(i) To investigate the structural performance of rubberized lightweight foamed concrete sandwiched wall panels in flexural and load bearing.

(ii) To determine the thermal insulation performance of rubberized lightweight foamed concrete sandwiched wall panels with different skin layer thicknesses.

(iii) To investigate the fire-resisting properties of the proposed rubberized lightweight foamed concrete sandwiched wall panel.

1.5 Scope and Limitation of the Study

The current study focuses on the structural performance, thermal insulation, and fire-resisting abilities of sandwiched wall panels which utilised rubberized lightweight foamed concrete (RLFC) as the inner core and magnesium oxide board as its skin layer. The density required for the RLFC to be used as the inner core will be 1150 kg/m^3.

Apart from that, several scopes are set before the research. The water-to-cement ratio of the RLFC inner core will be 0.55. Besides, the powdered form of crumb rubber will be used to replace the fine aggregate with a crumb rubber proportion of 80 %. The wall panel with the size of 300 mm × 300 mm × 105 mm, including the skin layer, will be studied in this research. The skin layer will be the magnesium oxide layer 6 mm, 9 mm, and 12 mm thick, and the thickness of RLFC will be 87 mm, 81 mm, and 75 mm, respectively. The adhesiveness between RLFC and magnesium oxide board will be provided by the TPS Thin Bed Adhesive Premium 668, and the thickness of this adhesive agent will be around 3 mm for both sides. The total thickness of the RLFC sandwiched wall panel will be 105 mm.

The laboratory test, the load-bearing, and the flexural strength test will be carried out to identify the structural performance of this RLFC sandwiched wall panel. After the curing duration of 28 days, both tests will be carried out. Another test, the flame exposure test, will be carried out to determine the fire-resisting abilities of RLFC concrete wall panels. The thermal insulation will be identified through the thermal conductivity test. The dimension of this RLFC sandwiched wall panel that will be tested to achieve the objective of this study is 300 mm × 300 mm × 105 mm.

The limitation of this study will be that the flexural strength and load-bearing tests only get the maximum loading that can be applied to the specimen with the size of 300 mm × 300 mm. The fire-resisting abilities are only be tested by continuously heating at 600 °C for 60 minutes.

1.6 Contribution of the Study

This study provides guidance and reference for future research on rubberized lightweight foamed concrete (RLFC) sandwiched wall panels. It determines the practicality of RLFC sandwiched wall panels cast with RLFC inner core and magnesium oxide board as the skin layers. The flexural strength test, load bearing test, thermal conductivity test, and flame exposure test will be conducted to test the practicality of this wall panel and provide an insight into how the replacement of crumb rubber in RLFC sandwiched wall panel affects its structural, thermal insulation and fire resisting performance. Further, this study promotes the utilisation and creates the second value of rubber waste. It helps reduce the disposal of rubber waste and the depletion of aggregate natural resources, which are global environmental issues. Based on the wall panel's structural, thermal insulation, and fire-resisting performance, this provides an insight into the practicality of this wall panel. It can be further studied and tested using a full-scale sample before being applied in a non-load-bearing wall system. The wall panel with good thermal insulation will help achieve energy efficiency. Moreover, this RLFC sandwiched wall panel's lightweight characteristic will reduce the loading on the structural component compared with conventional concrete. This is the first finding utilizing magnesium oxide board as the skin layer of RLFC sandwiched wall panel. Hence, it has served as a starting point in examining the practicality before it has been applied in industry and promoting green materials and technology products in the market that are helpful to reduce cost and impact on the environment caused by human activities.

1.7 Outline of the Report

This thesis is made up of five chapters in total. The first chapter provides a clear vision of the general knowledge and application of concrete and rubberized concrete. Further, Chapter One also includes the study’s significance, problem statement, aims and objectives to be achieved, and concludes with the scope and limitations of this study.

For Chapter Two, the literature review will review the findings related to the rubberized lightweight foamed concrete (RLFC) and sandwiched wall panel from existing case studies and research. First, the study on the fresh and hardened properties of rubberized lightweight concrete from previous researches have been reviewed further to compare the result at the end of this study. Furthermore, this chapter will review and discuss the study on the rubberized lightweight foamed concrete's advantages, disadvantages, and applications. A detailed discussion of sandwiched wall panels will be included and discussed based on previous studies. Some key findings from past research have also been identified and included in this chapter.

Chapter Three discusses the detailed methodology and work plan for producing the RLFC sandwiched wall panel using magnesium oxide board as a skin layer. The mix proportion for different thickness specimens will be shown in this chapter. Moreover, this chapter will also discuss the types of tests, the standard used, and the method of conducting the tests.

Chapter Four presents all results obtained from the tests used to investigate the engineering properties of this wall panel specimen. The result will be tabulated and analysed. A detailed discussion of the result obtained will be done by comparing the result obtained from the tests.

Lastly, Chapter Five will summarise all the findings with conclusive remarks based on this study's aim and objectives. Besides, some of the recommendations will be provided and proposed for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Lightweight Concrete

The lightweight concrete will have a density range of 290 kg/m^3 to a maximum of 1900 kg/m^3. Cube strength range of 1 to 65 MPa and thermal conductivities of 0.3 to 1.0 W/mK are lower than normal concrete (Newman and Choo, 2003). The lightweight concrete can be produced through three techniques: no fine aggregate used for the concrete mixture, entrain bubbles in the concrete mixture and partially or fully replace the natural aggregate with low specific gravity aggregate in the concrete mixture.

2.1.1 Types and Application of Lightweight Concrete

Three types of lightweight concrete are found in the market: no-fines concrete, aerated lightweight concrete, and lightweight aggregate concrete.

2.1.1.1 No-Fines Concrete

The no-fines concrete is concrete with only cement, water, and coarse aggregate. The lack of fine aggregate within the concrete will lead to more voids in the hardened concrete. During the mixing and handling of no-fines concrete, the shape of coarse aggregate and water content must be considered to reduce the chances for local crushing to occur and prevent a lack of cohesion due to the lack of water for cement hydration (Elbaset, 2003). The no-fines concrete typically will be applied for load-bearing and non-load-bearing structures, which support the external walls and partition, retaining walls on a small scale, and act as a damp proofing subbase material. The advantages of no-fines concrete will be low density, which leads to lower cement content, lower cost, good thermal conductivity, and low drying shrinkage, which may cause by insufficient water for cement hydration (Alam et al., 2012).

2.1.1.2 Aerated Lightweight Concrete

Aerated concrete consists of two main categories: autoclaved and non-autoclaved aerated concrete. The autoclaved aerated concrete is made of cement, fine aggregates, water, and aluminium powder or other alternatives, the expanding chemical agent. The added aluminium powder will produce gases during mixing and contain many bubbles once it sets (Mosleh Salman, Akram Hassan, and Abed Al-wahab Ali, 2010). The aerated concrete can be made by injecting the gases during mixing more suitable for precast factories, mixing in stable foam, or using the entraining air agent suitable for on-site casting (Fathi, Manaf and Mohd.Ismail, 2020). Furthermore, the foamed concrete is made up by adding foam during mixing. The foam added can be pre-formed in the foam generator and mix the foam with the concrete mix or the mixed foaming method, in which the agent adds and mix with the raw material. Other than pre-formed foam, synthetic or protein-based admixture can be added to produce foam concrete. The amount of foam added will be based on the expected density needed to be achieved. The aerated concrete consists of structural and insulation properties and fire resistance behaviour, which can be applied and used for walls, floors, and roofs. The cellular properties of aerated concrete make it easier to shape and cut; hence, the adjustment can be made on-site, providing flexibility in the design of the concrete structures.

2.1.1.3 Lightweight Aggregate Concrete

For lightweight aggregate concrete, aggregate with a void structure will be used instead of natural aggregate to produce this type of concrete. There are many sources to obtain lightweight aggregate, whether it is natural sources or artificial sources. The primary purpose of applying lightweight aggregate concrete will be to reduce the total construction cost by considering this type of concrete before selecting the normal concrete with a higher price per cubic meter (Mehta and Monteiro, 2001). Reducing the total cost needed for concrete will help reduce the loading transfer to the foundation and lower the foundation cost. There are two types of lightweight aggregate concrete (LWAC): partially compacted LWAC and structural LWAC. The partially compacted concrete will be commonly used and applied for the precast concrete blocks, panels, roofs, and walls, which must be cast on-site. The criteria for this concrete need to be fulfilled are concrete with proper strength and low density, which can maintain high thermal insulation and low drying shrinkage (Samidi, 1997). The lightweight structural aggregate can be applied with steel reinforcement, and a proper concrete cover must be provided to prevent steel corrosion.

2.2 Rubberized Lightweight Foamed Concrete

The rubber particles will be mixed into the concrete as a partial replacement for fine and coarse aggregate, forming the rubberized concrete as the final product. Since rubber waste has become a significant environmental issue, recycled rubber particles have been proposed to be added to the concrete mixture as a partial replacement. Researchers must identify several fresh and hardened properties before applying rubberized concrete in construction. The partial replacement by rubber particles can affect the mechanical, physical, durability, and functional properties. Some studies prove that adding rubber particles increases resilience, durability, and elasticity (Kumaran, Mushule and Lakshmipathy, 2008).

2.3 Fresh Properties of Rubberized Lightweight Foamed Concrete

2.3.1 Workability

Workability is the energy needed to counter friction between the fresh cement paste particles. The workability also represents how easily the concrete can be mixed, handled, and compacted. In a fresh state, the workability of concrete enables the concrete mix to pour and shape into any shape. Besides, the factors that will affect the concrete workability have been identified: the admixture type and content, grading and condition of aggregate, aggregate type, aggregate-to-cement ratio, water-to-cement ratio, admixture type and content, and cement fineness. Based on the previous study by another researcher, the rubberized concrete will have lower workability than normal concrete due to the crumb rubber's ability to absorb the free water compared with the normal aggregate (Arafa et al., 2022). The partial replacement of aggregate with rubber particles will affect the workability, but it depends on the type of rubber particles and the content added. The crumb rubber concrete (CRC) slump values decrease during the increase of the crumb rubber grade and proportions (Holmes, Browne and Montague, 2014). The concrete mixture with fine ground rubber has higher workability than the coarse tyre chips concrete mixture (Zheng, Huo and Yuan, 2008b). The coarse rubber particle increases the friction between the particles in the concrete mix. It shows that adding different types of rubber particles will affect the workability differently. Furthermore, the content and proportions of rubber particles within the concrete mix will impact the fresh mix differently. Based on the research done by other researchers, replacing rubber particles with up to 10 % will not result in a significant effect on workability.

In comparison, 30 % of replacements need mechanical vibration to make the concrete mix workable again (Moustafa and Elgawady, 2015). Most of the studies found that the workability of rubberized concrete will reduce. It can be solved by adequately adding admixture, leading to higher workability of rubberized concrete than normal concrete. An adequate and proper addition of admixture into a fresh mix with rubber particles will result in good workability compared with normal concrete (Elchalakani, 2015). Adding a super-plasticizer around one to three per cent of cement weight can control the workability of rubberized concrete mix (Youssf et al., 2014).

2.4 Hardened Properties of Rubberized Lightweight Foamed Concrete

2.4.1 Density

The density of concrete mix can be classified into two, which are fresh and dry density. The fresh density is determined to prepare the actual volume needed for the concrete mix and have good control during casting. In contrast, the dry density is determined to manage foamed concrete's mechanical, physical, and durability properties after hardening (Ramamurthy, Kunhanandan Nambiar and Indu Siva Ranjani, 2009). According to ASTM C 330, the density range for lightweight concrete is between 1120 and 1920 kg/m^3. The rubberized concrete with which the rubber particle partially replaces the aggregate will have a lower density or weight than the normal concrete without rubber particles. The rubber particles added will cause the reduction of the density of concrete due to the low specific gravity of rubber particles than the sand. In Figure 2.1, the density of lightweight aggregate concrete without rubber particles is 1765 kg/m^{3,} while the volume replacement of 50 % is 1588 kg/m^3 (Pongsopha et al., 2022). The density of rubberized concrete with recycled rubber is lower than that of ordinary concrete, while adding silica fume into the mix will slightly increase the density of rubberized concrete (Pelisser et al., 2011). In addition, the density of rubberized concrete will be affected by the sizes of rubber particles. The finer the rubber particles, the higher the concrete density because the fine rubber particles can fill the gap and reduce the possibility of void structure without affecting the permeability constant (Gesoğlu et al., 2014). Besides, the mixture with crumb rubber and tyre chips had the slightest reduction in concrete density, while the mixture with only tyre chips had the most significant reduction (Pacheco-Torgal, Ding and Jalali, 2012).

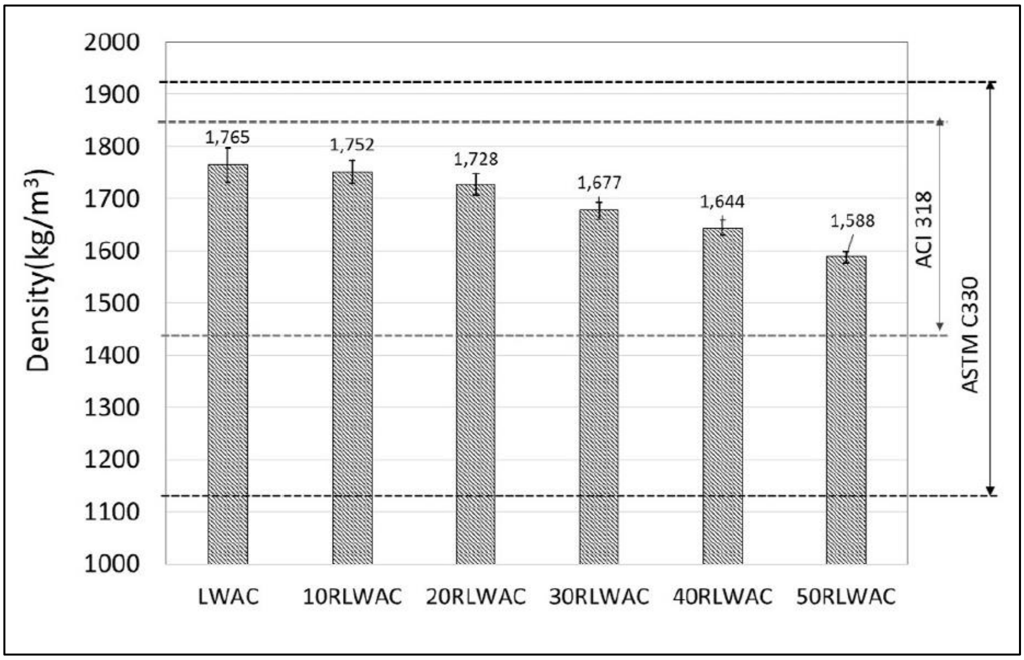


Figure 2.1: Density of Lightweight Aggregate Concrete (LWAC) and Rubberized Lightweight Aggregate Concrete (RLAC) (Pongsopha et al., 2022).

2.4.2 Compressive Strength

The compressive strength of rubberized concrete is always one of the main concerns due to the partial replacement of the aggregate with rubber particles. Several factors will affect the concrete compressive strength: the voids ratio, the bonding between the particles in the mixture, and the toughness of the raw material. Based on ASTM C330, the minimum compressive strength needed for structural lightweight aggregate concrete is 17.2 MPa. According to Kaloush, Way and Han (2005), the compressive rubberized concrete with crumb rubber will reduce compared with ordinary concrete due to the air voids. The added de-airing material can reduce the effect on compressive strength. The air void will be created and generated due to the accumulation of crumb rubber around aggregates (Bisht and Ramana, 2017). Other than air void, the soft cement particles around rubber particles, lack of bonding, raw material properties, and low specific gravity of rubber particles which cause the top of concrete to be full of rubber content, will also affect the concrete compressive strength (Ganjian, Khorami and Maghsoudi, 2009). The partial replacement of aggregate with rubber particles will reduce the compressive strength of the concrete. Figure 2.2 shows that the compressive strength reduces consistently for the replacement volume of crumb rubber from 0 % to 50 %. The reduction will be based on the concrete mixture's rubber particle content and proportion replacement. The replacement of rubber particles not only reduces the compressive strength but also reduces the splitting tensile strength at the same time. It also depends on the rubber particle content percentage in the concrete mix (Nell Eldin, Senouci and Member, 1993). The lower rubber particle content will not significantly affect the mechanical properties of concrete.

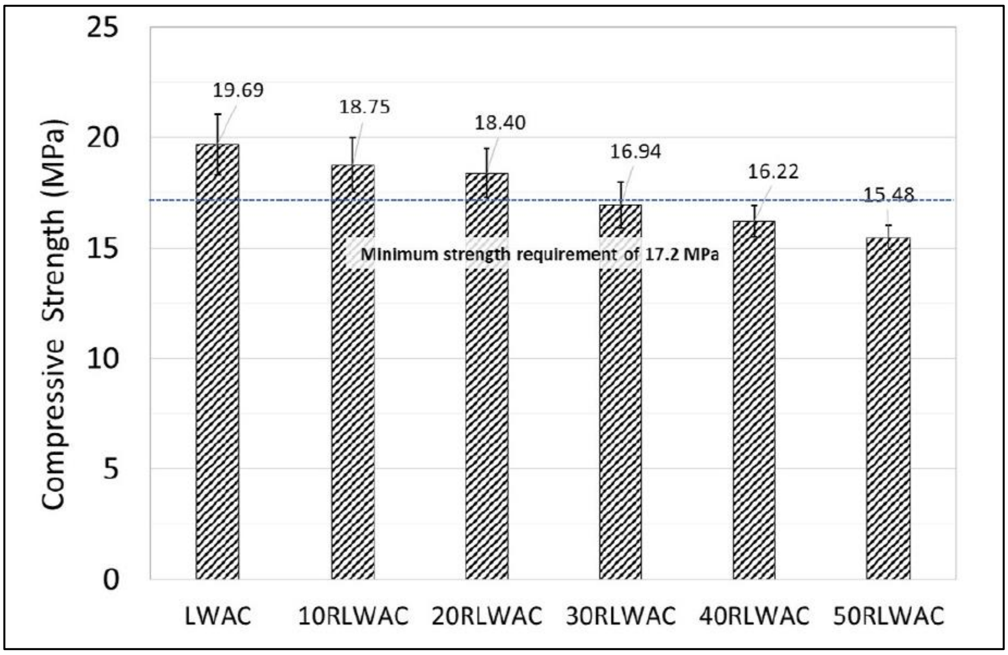


Figure 2.2: Compressive Strength of Lightweight Aggregate Concrete (LWAC) and Rubberized Lightweight Aggregate Concrete (RLAC) (Pongsopha et al., 2022).

In contrast, the increase in the rubber content will reduce the concrete strength, and the strength will reduce significantly if the rubber content exceeds 20 %. In addition, the addition of the admixture will also affect the compressive strength. According to Onuaguluchi and Panesar (2014), the concrete mixture with rubber particles and silica fume will improve compressive and tensile strength due to the pozzolanic reaction between limestone and silica fume. Furthermore, in some of the studies, the researchers found that the size of the rubber particles' treatment method will have different impacts on concrete compressive strength. The sodium hydroxide solution added during the treatment process of rubber particles will slightly increase the bonding between cement and rubber particles, resulting in higher compressive strength. The smaller and more refined the rubber particles added, the higher the compressive strength of rubberized concrete. The finer particles can explain that this will fill the gaps and strengthen the concrete.

2.4.3 Splitting Tensile Strength

The partial replacement by rubber particles in concrete mixture reduces tensile strength due to the weak bonding between the cement and rubber particles and eases the gaps between them (Kumar, Dev and Verma, 2022). The higher the aggregate replacement with rubber particles, the more significant the reduction of the tensile strength of concrete. Concrete failure under the tensile loading has been accelerated due to the concentrated loading applied along rubberized concrete's weak interfacial transition zone (Arafa et al., 2022). The finer rubber particles slightly reduce splitting tensile strength (Liu et al., 2009). In contrast, the fine rubber particles, such as the fine crumb rubber with different rubber content in the concrete mixture, will have a higher average splitting tensile strength (Gesoğlu et al., 2014). Both studies prove that adding rubber particles will reduce the splitting tensile strength. This is because the finer particles will fill the gaps between the cement and rubber particles (Su et al., 2015).

2.4.4 Flexural Strength and Flexural Stiffness

The addition of rubber particles will reduce the flexural strength of concrete, but it will vary for different sizes of rubber particles. The finer the rubber particles added, the lower the loss in flexural stiffness of rubberized concrete (Su et al., 2015). In Table 2.1, the Modulus of Rupture (MOR) obtained from the flexural strength test will reduce the increased replacement volume of crumb rubber. One weakness of rubber particles is the reduction of concrete's tensile strength. During post-peak behaviour, several properties have been found that significantly increase the toughness and ductility of concrete (Farhan, 2016). The weak bonding between the particles in the fresh mix leads to a significant initial reduction rate for flexural strength compared to compressive strength (Aslani, 2016). Besides, the proportion of rubber particles will result in different flexural strength outcomes. The combination or mix of crumb rubber and rubber fibres will further increase the flexural strength of concrete with an aspect ratio of eight to ten (Gupta, Chaudhary and Sharma, 2014). Usually, the fine aggregate will be replaced by the rubber particles, and the research found that fine rubber particles will bring a minor effect on the rubberized concrete flexural strength (Aiello and Leuzzi, 2010). Adjusting the water-to-cement ratio and adding admixtures such as silica fume can enhance the bonding of particles (Elchalakani, 2015). The flexural strength will slightly increase when the emulsified asphalt-to-cement ratio increase due to the bonding between the particles becoming stronger (Bing and Ning, 2014). The rubberized concrete that partially replaces the coarse aggregate will have higher flexural strength reduction than the rubberized concrete that partially replaces the fine aggregate (Arafa et al., 2022).

Table 2.1: Modulus of Rupture Lightweight Aggregate Concrete (LWAC) and Rubberized Lightweight Aggregate Concrete (RLAC) (Pongsopha et al., 2022).

Type	Replacement Volume of Crumb Rubber (%)	MOR (MPa)
LWAC	0	3.41
10RLWAC	10	2.87
20RLWAC	20	2.59
30RLWAC	30	2.48
40RLWAC	40	2.28
50RLWAC	50	2.20

2.4.5 Abrasion Resistance

Abrasion resistance can be defined as the ability of a material or the resistance of a structure's surface to be worn away by rubbing or friction. The structures' abrasion resistance can protect the structures and elongate their service life. Concrete with good abrasion resistance will be suitable for constructing road pavement and hydraulic structures such as dam spillways and tunnels where friction is applied on the surface along its service life. Adding rubber particles to the concrete improves abrasion resistance and reduces the concrete's wear depth (Senin et al., 2016). Different types of rubber particles added will affect the rubberized concrete properties differently. Compared with rubber powder, more effective abrasion resistance and wear depth reduction will be found in rubber fibre (Gupta, Chaudhary and Sharma, 2014). The addition of rubber particles will impact the compressive strength while increasing the abrasion resistance but adding silica fume can increase both abrasion resistance and compressive strength (Kang, Zhang and Li, 2012).

2.4.6 Modulus of Elasticity

The modulus of elasticity of concrete will be used to measure the stiffness of concrete. The higher the concrete grade, the higher the modulus of elasticity. Replacing aggregate with rubber particles or rubber powder reduces the modulus of elasticity of concrete. One of the reasons is the reduction of compressive strength (Haryanto et al., 2017). The lower elastic modulus of rubber particles will result in low stiffness and less brittleness of concrete, ensuring high deformability and ductility. The rubberized concrete results in low compressive strength, elastic modulus, and rigidity compared with normal concrete (Pelisser et al., 2011). The type of rubber particles will affect the elastic modulus of concrete, such as the crumb rubber will have lower static and dynamic elastic modulus than the ground rubber when the replacement amount increases (Zheng, Huo and Yuan, 2008a).

2.4.7 Thermal and Acoustic Properties

The thermal properties will be studied to know the thermal conductivity, the specific heat capacity of concrete, and how the temperature affects other concrete properties. Increasing the concrete's exposed temperature will cause evaporation of free water content after the hardening process and shrink concrete (Topçu and Bilir, 2009). Replacing coarse aggregate with rubber particles will reduce thermal conductivity and specific heat capacity and increase thermal resistance. In Table 2.2, the thermal conductivity of concrete with powdered crumb rubber decrease by around 17.95 %, and the relation between the proportion of crumb rubber and thermal conductivity is linear (Lim et al., 2020). The partial replacement of rubber particles will have a good and well sound absorption compared with ordinary concrete (Holmes, Browne and Montague, 2014). The sound absorption of rubberized concrete will be more excellent due to the larger volume and higher grade of rubber particles, as shown in Figure 2.3. Density is one factor affecting sound absorption, which means that the higher the density, the higher the sound absorption rate. Besides, crumb rubber has been found to produce rubberized concrete with lower void content (Sukontasukkul, 2009). For sound insulation, the performance of rubberized concrete will be lower than ordinary concrete because of the larger size and no-uniform distribution of air void in the concrete. One of the researches shows that the replacement of fine aggregate with crumb rubber show micro-cracks at 400 °C, while no cracking was found between 70 °C to 200 °C (Fawzy, Mustafa and Abd El Badie, 2020).

Table 2.2: Thermal Conductivity of Lightweight Aggregate Concrete (LWAC) (Heng Lim et al., 2020).

Type	**Thermal Conductivity (W.k^{-1}.m^{-1})**	**Percentage of Reduction (%)**
CR0	1.1863	0
CR15	1.0737	9.49
CR30	0.9969	15.97
CR45	0.9733	17.95

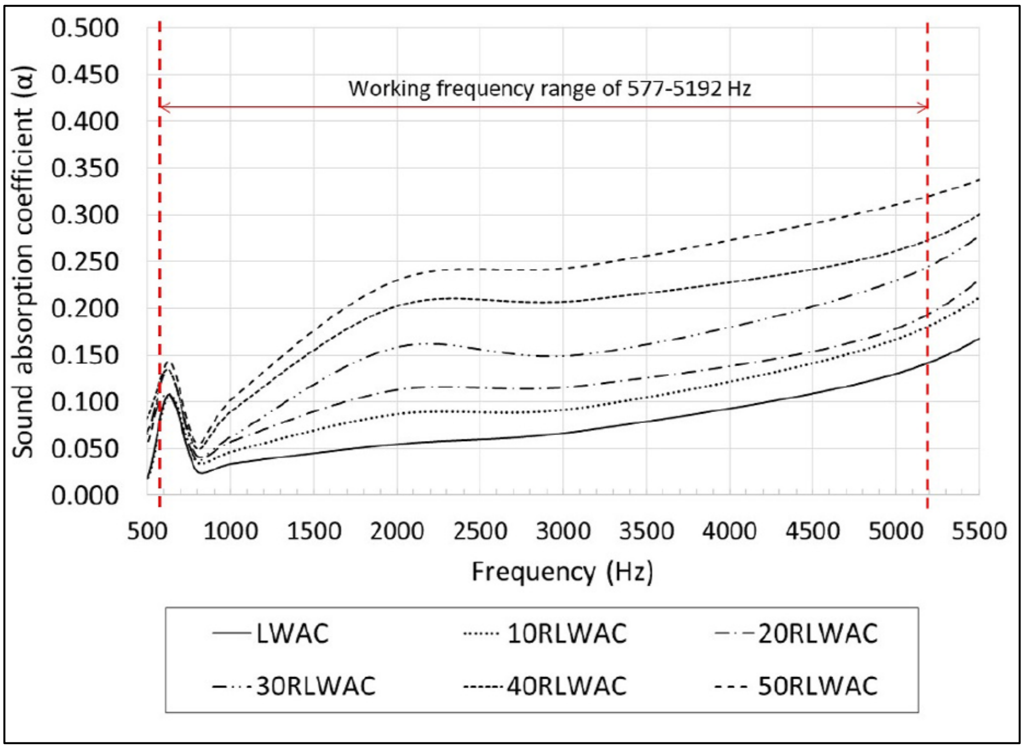


Figure 2.3: Sound Absorption of Lightweight Aggregate Concrete (LWAC) and Rubberized Lightweight Aggregate Concrete (RLAC) (Pongsopha et al., 2022).

2.4.8 Freeze-Thaw Resistance

The rubber particles replacing the aggregate in concrete will increase the freeze-thaw resistance. The freeze-thaw resistance increases when the rubber particles' fineness increases or the rubber particles' size reduces (Zhu et al., 2012). Air entrainment is one of the most widely applied methods for freeze-thaw resistance (Richardson et al., 2012). Using crumb rubber can be one of the alternative methods to entrain air, and it can become one of the freezes thaws resisting agents due to its non-polar rough surface, which can entrain air (Paine, Dhir, Moroney and Kopasakis, 2002). Based on the research done by Al-Akhras and Smadi (2004), rubberized concrete with powdered rubber can achieve 55 % of the dynamic modulus of elasticity by using one hundred and fifty cycles of freezing and thawing. In contrast, normal concrete uses fifty cycles of freezing and thawing. The study concludes that normal concrete will exhibit low resistance to the freezing and thawing caused by the surrounding.

2.4.9 Fire Performance

The higher the rubber content in the rubberized concrete, the lower the strength of the rubberized concrete. High temperatures also cause concrete cracking, reducing strength (Topçu and Bilir, 2007). When the concrete is exposed to a specific temperature, the decomposition of rubber particles in the concrete will lead to mass loss, compressive strength reduction in dynamic and static elastic modulus, and increased concrete permeability (Gupta et al., 2017). Adding crumb rubber reduces the cracking and explosive spalling found after exposure to an elevated temperature. Less cracking will be found for the rubberized concrete with higher crumb rubber content. Based on the experiment, the concrete exposed to a higher temperature will reduce compressive strength, splitting tensile strength, and flexural strength (Fawzy, Mustafa and Abd El Badie, 2020). The compressive strength increases for the rubberized concrete with zero to one per cent of crumb rubber due to the heat curing effect (Mohammed et al., 2020). The higher the exposed temperature for concrete, the greater the mass losses when the temperature exceeds 260 °C, where the rubber and water evaporate. The elevated temperature will also lead to the decrease of modulus of elasticity because of the decomposition of rubber and cause the forming of a void, which leads to cracking (Wrya A. Abdullah, Mohamed R. AbdulKadir and Muhammad A. Muhammad, 2018).

2.5 Advantages of Rubberized Lightweight Foamed Concrete

Adding rubber particles to concrete will reduce the gross density of concrete, reducing the concrete weight (Mohammed et al., 2012). The increased rubber content in concrete will result in a good sound absorption characteristic and a considerable reduction in ultrasonic modulus due to more void structure within concrete (Khaloo, Dehestani and Rahmatabadi, 2008). The partial replacement of rubber particles in concrete has improved acid resistance due to the quick reaction of crumb rubber toward acid penetration (Bisht and Ramana, 2019). The rapid chloride permeability test (RCPT) shows that the charge transmitted in rubberized concrete samples is lower than that of ordinary concrete samples. It means that the addition of rubber particles results in the improvement of chloride penetration resistance (Onuaguluchi and Panesar, 2014). The increased rubber content enhances the toughness, resistance to impact energy to failure and dampness ratio of concrete. The increased resistance to impact energy makes the concrete absorb the high kinetic energy, and the high dampness ratio enables the rubberized concrete to withstand the dynamic load (Hamdi, Abdelaziz and Farhan, 2021).

2.6 Disadvantages of Rubberized Lightweight Foamed Concrete

Adding rubber particles to concrete reduces compressive strength because of the formation of a void structure in the concrete and poor adhesion (Li et al., 2019). The reduction of modulus of elasticity has been found due to the poor linkage between cement and rubber particles. Due to the lower elastic modulus of rubber aggregate, it does not have sufficient resistance toward the loading acted on the concrete (Nell Eldin, Senouci and Member, 1993). Even though the smaller particle size will lower the reduction of compressive strength, overall compressive strength will reduce compared to ordinary concrete. Furthermore, increased rubber content in concrete from 10 % to 50 % leads to an 18 % to 32 % reduction of concrete flexural strength. (da Silva et al., 2015). Hence, rubberized concrete has been proposed for non-structural structures (Zaher Khatib and Bayomy, 1999). Based on the study by other researchers, adding rubber particles to concrete will reduce slump value, reducing workability (Zaher Khatib and Bayomy, 1999). The lower workability of concrete will increase the total construction time and the difficulty of finishing work. The rubber particles need further research, laboratory test, and treatment before they add to the concrete mixture (Bravo and de Brito, 2012). This result in extra cost for the further action needed before the rubber particles can be used and replaced with the aggregate in rubberized concrete.

2.7 Application of Rubberized Lightweight Foamed Concrete

Based on the advantages mentioned in Subchapter 2.5, the rubberized concrete can be applied as a noise screen; the feasibility of using a high volume of rubber aggregate in rubberized concrete promotes sound insulation (Zhang and Poon, 2018). The replacement done by rubber aggregates will improve thermal insulation for the flooring in buildings (Najim and Hall, 2010). Besides, using rubber particles in concrete promotes energy absorption and significant improvement of impact resistance and toughness, which leads to the application of reinforced concrete jersey barriers (Reda Taha et al., 2008). Due to the reduction of concrete's unity and compressive strength, rubberized concrete can be applied for non-bearing concrete walls to reduce the total loading transfer and cost needed to construct structural members such as beams, columns, and foundations. The high dampness ratio enables the rubberized concrete to be used as a reinforced column for earthquake-resistant structures. The enhancement of impact resistance because of the addition of rubber aggregate can be used as a rubberized concrete beam which consists of high impact loading resistance (Al-Tayeb et al., 2013). Furthermore, rubberized concrete can be applied as lightweight concrete due to reducing density or unit weight.

2.8 Material

2.8.1 Cement

Cement is the general material needed to produce concrete, consisting of different properties based on the chemical composition of cement. Several Portland Cements have been commercialised in the market; different cement will have different specific uses or properties. The Portland Cement can be classified into six general types. The types and features of Portland Cement can be seen in Table 2.3.

Table 2.3: General Types and Features of Portland Cement.

Types	Classification	Characteristics	Applications
I	General Purpose	Higher C_3S content causes high early strength	General construction
II	Moderate Sulphate Resistance	Lower content for C_3A	Structures exposed to soil and water
III	High Early Strength	Ground more finely, high C_3S content	Rapid construction, cold weathering concreting
IV	Low Heat of Hydration	Very low C_3S content	Massive structures
V	High Sulphate Resistance	Very low C_3A content	Structures exposed to sulphate ions
White	White Colour	No C_4AF, low MgO content	Decorative

The colour of Ordinary Portland Cement or Type I cement, the commonly used and widely applied cement, usually is available in white or grey. According to BS EN 197–1, the chemical composition of Ordinary Portland Cement will be made by 93 to 100 per cent of cement clinker and zero to five per cent of minor constituents (Neville and Brooks, 1987). The ratio of calcium oxide or lime (CaO) and silicon dioxide (SiO_2) cannot be less than two will be other criteria to be fulfilled. The chemical compounds found in Type I Cement are C_3S, C_2S, C_3A, C_4AF, MgO, and CaO. The chemical composition of Ordinary Portland Cement based on ASTM C 150–05 and BS 12/1996 will be shown in Table 2.4.

Table 2.4: Chemical Composition of Portland Cement.

Chemical Compositions	BS 12/1996	ASTM C 150–05
Loss of Ignition (LOI) %	Max 4.00	Max 3.00
Loss of Ignition (LOI) %	Max 1.5	Max 0.75
Silicon Oxide	-	Min 20.00
Aluminium Oxide	-	Max 6.00
Iron Oxide	-	Max 6.00
Calcium Oxide	-	-
Magnesium Oxide	Max 4.00	Max 6.00
Sulphur Trioxide	Max 3.00	Max 3.00
Lime Saturation Factor (L.S.F) %	Between 0.66 and 1.02	-
Alkali Eq.	-	0.60
C_3S	-	-
C_2S	-	-
C_3A	-	Max 8.00
C_4AF	-	-
Chloride	-	-

2.8.2 Aggregate

Aggregate is one of the inert granular materials and plays the primary role in strengthening concrete. There are several market aggregates: crushed concrete (recycled concrete), sand, gravel, Type 1 MOT, topsoil, and ballast. Cement, water, and aggregate are the main raw materials used to produce concrete. The aggregate consists of bigger proportions in the concrete mixture, around sixty to seventy-five per cent (PCA, 2022). Good quality aggregates must be able to bear compressive and tensile loading acts, provide sufficient toughness, and be free of any impurities. The aggregates can be classified based on the source, unit weight, and size. Based on sources, the aggregate can be classified into natural, crushed rock, artificial and recycled aggregates. From the unit weight, it can be classified into ultralightweight, lightweight, normal weight, and heavyweight. The sizes can be classified into coarse and fine aggregates, a term commonly used to classify the aggregate. The coarse aggregate will be the aggregate that cannot pass through or retain on a 4.75 mm sieve. The coarse aggregate can be classified into fine gravel, medium gravel, coarse gravel, cobbles, and boulders (Anupoju, 2022). Typically, the aggregate with an average of 40 mm size will be used for normal strength, while aggregate with 19 mm size will be used for high-strength concrete due to the lower concentration of stresses around the particles. Besides, the fine aggregate can retain in a 0.075 mm sieve and pass through a 4.75 mm sieve. It fills the gaps and voids between cement particles and coarse aggregates. Fine aggregate can be classified into coarse sand, medium sand, fine sand, silt, and clay, with a size of less than 0.002 mm.

2.8.3 Rubber Particles

Several rubber particles can be used for partial replacement for the coarse or fine aggregate. The aggregate will be classified and separated based on particle size. During the pre-treatment process, the rubber particles treated with a rough surface might further increase the strength of concrete due to the bonding between the cement and rubber particles. The first type of rubber particles will be shredded or chipped rubber with a size of around 14 mm to 75 mm after three shredding stages. Due to the larger particle size, the shredded rubber particles can replace coarse aggregate. Ground rubber can replace the crushed limestone and gravel used in concrete (Ganjian, Khorami and Maghsoudi, 2009).

The second type of rubber particle is crumb rubber, which is between 0.43 mm to 4.65 mm. This rubber particle, which can replace the fine aggregate, is manufactured in a unique mill where the big rubber converts into smaller particles. Throughout this process, particles of different sizes will be produced based on the mill used and the temperature during manufacturing. This study will use this rubber particle to produce the rubberized lightweight foamed concrete for the wall panel.

The third type of rubber particle will be ground rubber with a smaller particle size of 0.08 mm to 0.465 mm. This rubber particle can replace cement, but the equipment governs it for size reduction. Ground rubber will be produced in two stages: magnetic separation and screening of used tyres.

2.8.4 Air Entraining Agent

The entraining air or pre-foaming agent entrains the microscopic air bubbles in the concrete mixture, producing air void content in hardened concrete. The air void produced in hardened concrete can elongate the concrete service life, exposing it to the freezing and thawing surrounding that leads to concrete expansion and cracking if it exceeds the tensile limit (Niaounakis, 2015). The air-entraining agent acts as a lubricant that can improve the workability of the fresh mix. It can also reduce the chances for segregation and bleeding to occur, affecting the expected strength of concrete. The air-entraining agent develops air bubbles by lowering the surface tension of the water. A sturdy shell will be formed, separating the water particles and enhancing the bonding between particles in concrete. The air-entraining agent can be classified into two types: wood resins and synthetic resins (FHWA, 2022). The wood resins can create well-bubble structures and work with cementitious material with low water content, but the air will disappear with time. Synthetic resins function to produce bubbles with smaller gaps and provide a great freezing and thawing resistance.

2.9 Sandwiched Wall Panel

The sandwiched wall panels have been widely used for their advantages which offer low cost, more excellent strength-to-weight ratio, convenient usage, and thermal insulation properties. The sandwiched wall panel comprises the low-density inner concrete core and is covered by a skin layer, the insulating material. Several studies related to sandwiched wall panels have been done in recent decades. The non-load-bearing sandwiched wall panel is fourteen times lighter than the conventional reinforced concrete wall panel and has the same strength and stiffness (Shawkat, Honickman and Fam, 2008). The lightweight concrete cladding wall panel has been proposed to be used and applied for high-rise buildings due to their low unit weight and thermal performance (Yu, Spiesz and Brouwers, 2015). The lower unit weight results in lower weight and load transfer to the structural member. The cladding wall panel can be applied to the building envelope, such as walls, roofs, and windows, and proper heat transfer control will be provided. In order to maintain comfortable indoor temperature surroundings, a proper insulation building material will be provided; hence, the precast cladding wall panel will be used to reduce the energy consumption of the building structure (Mohamad, Omar and Abdullah, 2011). Cladding wall panels have been applied in the construction industry because their thermal performance is better than masonry walls and solid concrete wall panels, commonly used a few decades ago (Bai and Davidson, 2015). The cladding wall panel has only been applied in non-load-bearing walls rather than load-bearing walls due to concerns such as the lower strength properties, stiffness, and interface delamination (Wang et al., 2018). Furthermore, the sandwiched wall panel with a gypsum layer has been proposed to reduce the energy required by the air conditioning system. The study found that the interior surface sandwiched wall panel is 1.1 °C lower than the conventional reinforced concrete walls (Zhou, Wong and Lau, 2014).

2.10 Past Researches

A recent study shows the improvement of thermal and sound insulation properties and compressive and flexural strength reduction by using rubber particles to replace 50 % of fine aggregate in lightweight concrete (Pongsopha et al., 2022). Besides, based on the research done by Mokrenko and Kozlovská (2020), there are six building boards with a material base of magnesium, cement-bonded particle, gypsum, wood veneer, and wood fibre will be studied. The magnesium oxide building board shows a good performance in strength properties, thermal, acoustic, and fire resistance at a lower cost compared with another advanced building board, cetris. Hence, the strength properties, thermal performance, and fire resistance through a combination of rubberized lightweight foamed concrete (80 % crumb rubber proportions) and magnesium oxide board will be studied in this research.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter will detail the raw material needed for the research, the proposed mixing proportions, the procedure to prepare the testing specimen, and the laboratory testing carried out to investigate the objectives of this study. The whole research was carried out, starting with the general introduction, literature review, methodology, laboratory testing, analysis of the data collected, and conclusion. The overall workflow process has been shown in Figure 3.1.

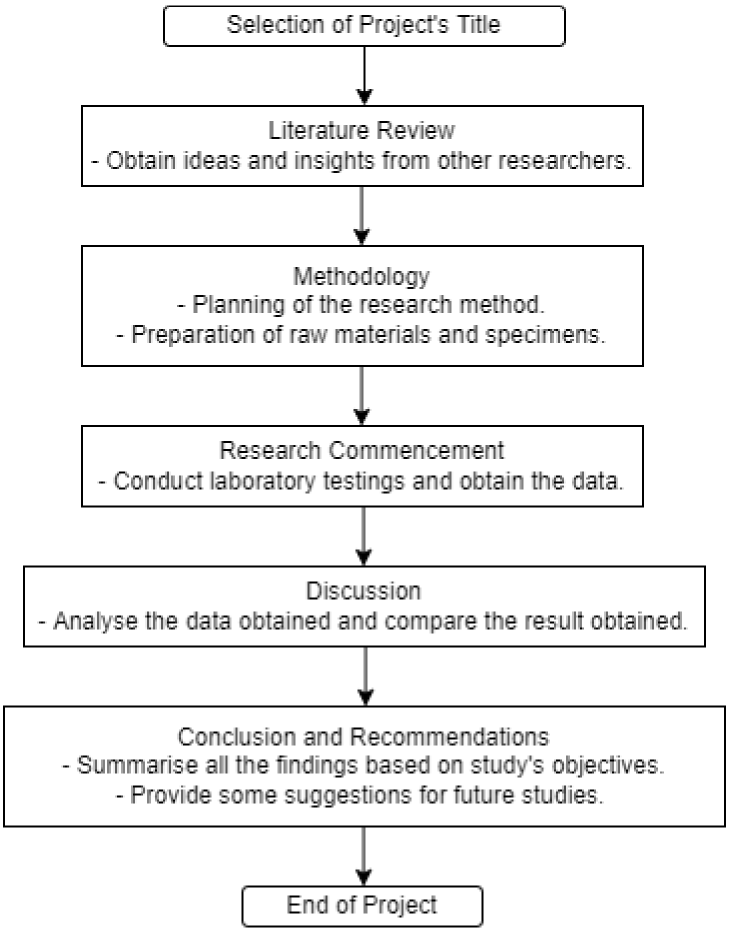


Figure 3.1: Overall Project Workflow.

3.2 Raw Materials

3.2.1 Ordinary Portland Cement

The brand name "Orang Kuat," which is the Ordinary Portland Cement (OPC) manufactured by YTL Cement, shown in Figure 3.2, was used in this study. The certification gained for this product is MS EN 197-1:2014 CEM I 52.5N, a Malaysian Standard related to the composition, specifications, and criteria to be fulfilled by cement. According to ASTM C150, the Ordinary Portland Cement was sieved through a 600 µm sieve, also known as (No. 30), to sieve out the hydrated cement. After the mixing, an airtight container would be used to keep and store the cement to avoid cement exposure to the air, which can cause further hydration that will lead to the premature of the cement particles.

Figure 3.2: "Orang Kuat" Ordinary Portland Cement (OPC) by YTL Cement.

3.2.2 Fine Aggregate

River sand with a density of 1650 kg/m^3, shown in Figure 3.3, one of the fine aggregates, would be selected for this study. The sand was oven-dried at a temperature of 150 °C to remove its moisture content so that no extra water was added to the concrete mixture, which might affect concrete quality. After oven-drying, the fine aggregates were sieved based on the ASTM C136 standard. The fine sand passed through a 475 µm (No. 40) sieve and retained at a 75 µm (No. 200) sieve. The sands were stored in a clean, airtight container.

Figure 3.3: Sieved Sand.

3.2.3 Crumb Rubber

This study will use powder crumb rubber with a maximum size of 40 mesh, shown in Figure 3.4. The rubber particle would partially replace the fine aggregate with a proportion of 80 %. Further, the powdered crumb rubbers were sieved through a No. 40 sieve of 0.425 mm.

Figure 3.4: Powdered Crumb Rubber.

3.2.4 Water

Based on ASTM C1602, an approved source needs to be taken; hence, tap water was used in this study to mix the rubberized lightweight foamed concrete and generate a consistent result. Water was required for the cement hydration process to generate the calcium silicate hydrate (CSH) gel. The water-to-cement ratio of 0.55 would be used to produce every rubberized lightweight foamed concrete specimen for the wall panel's inner core. The tap water, which is safe to use, will reduce the negative impact found in this study because it is free from any impurities, and its pH is normal.

3.2.5 Foaming Agent

The Sika® Aer 50/50 shown in Figure 3.5 would be chosen as the foaming agent in this study due to the high and stable air content that can be produced. The target foam density needed to add to the concrete mixture will be 45 kg/m^3. The first step to produce the foam will be the foaming agent was added through the inlet valve of the foam generator with a foaming agent to water ratio of 1:20. Further, the compressed air in the foam generator was around 0.5 MPa or 5 bar. The foam was then dispensed through the nozzle by opening the water and compressed air valve simultaneously when a stable pressure was observed.

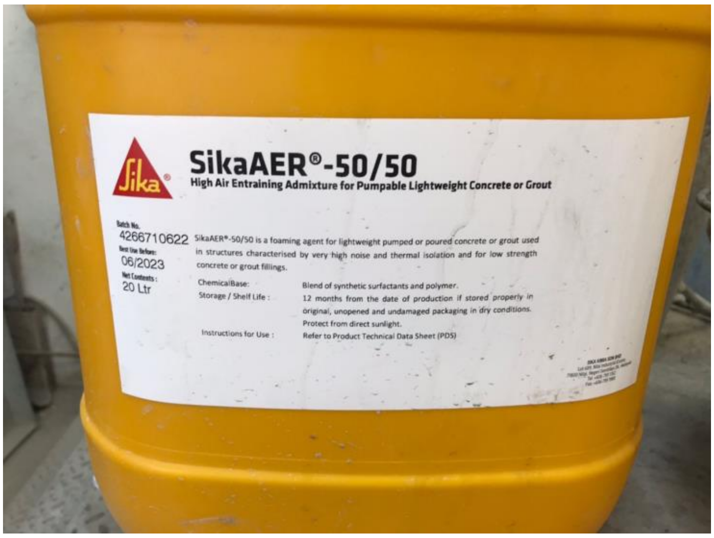


Figure 3.5: Sika® Aer 50/50.

3.2.6 Magnesium Oxide Board

The 6 mm, 9 mm, and 12 mm magnesium oxide board would be selected for 87 mm, 81 mm, and 75 mm of the rubberized lightweight foamed concrete inner core. The magnesium oxide board shown in Figure 3.6 will be chosen as the skin layer, promoting fire resistance, impact resistance, and thermal and sound insulation of the rubberized lightweight foamed concrete inner core. Before the magnesium oxide board was installed using the adhesive agent, the measurement must be done and cut into 300 mm × 300 mm sizing using the handheld circular saw shown in Figure 3.7.

Figure 3.6: Magnesium Oxide Board.

Figure 3.7: Handheld Circular Saw.

3.3 Mix Proportion

The rubberized lightweight foamed concrete mixture was produced in this study using the perfect mix proportions provided by the project supervisor. Twelve sets of rubberized lightweight foamed concrete (RLFC) with three different thicknesses of 87 mm, 81 mm, and 75 mm would be produced. The crumb rubber proportions were 80 %, and the water-to-cement ratio was 0.55, as shown in Table 3.1. The dosages required for three different thicknesses are shown in Table 3.2, 3.3, and 3.4.

Table 3.1: Mix Proportions of 87 mm, 81 mm, and 75 mm Thickness Rubberized Lightweight Foamed Concrete.

Mix Proportions	
Water to cement ratio	0.55
Crumb rubber proportions (%)	80

Table 3.2: Dosage Required for 87 mm Thickness Rubberized Lightweight Foamed Concrete.

0.55CR87 (300 mm x 300 mm x 87 mm) x 4 nos			
Materials	**Weight per Unit Volume (kg/m^3)**	**Dosage of Each Sample (20 % wastage) (kg)**	**Total Dosage Required (kg)**
Cement	545.39	5.12	20.50
Sand	109.08	1.02	4.10
Water	299.97	2.82	11.27
Crumb Rubber	181.11	1.70	6.81
Foam	14.45	0.14	0.54

Table 3.3: Dosage Required for 81 mm Thickness Rubberized Lightweight Foamed Concrete.

0.55CR80 (300 mm x 300 mm x 81 mm) x 4 nos			
Materials	**Weight per Unit Volume (kg/m^3)**	**Dosage of Each Sample (20 % wastage) (kg)**	**Total Dosage Required (kg)**
Cement	545.39	4.77	19.08
Sand	109.08	0.95	3.82
Water	299.97	2.62	10.50
Crumb Rubber	181.11	1.58	6.34
Foam	14.45	0.13	0.51

Table 3.4: Dosage Required For 75 mm Thickness Rubberized Lightweight Foamed Concrete.

0.55CR80 (300 mm x 300 mm x 75 mm) x 4 nos			
Materials	**Weight per Unit Volume (kg/m^3)**	**Dosage of Each Sample (20 % wastage) (kg)**	**Total Dosage Required (kg)**
Cement	545.39	4.42	17.67
Sand	109.08	0.88	3.53
Water	299.97	2.43	9.72
Crumb Rubber	181.11	1.47	5.87
Foam	14.45	0.12	0.47

3.3.1 Preparation of Specimen

While preparing twelve specimens, the electric scale was used to weigh the raw materials to ensure the mixture followed the mixing proportions given. To begin the casting, cement, aggregates, and crumb rubber in dry mix conditions were required in this study to achieve a uniform mixture. After that, the Ordinary Portland Cement was added and mixed thoroughly with sand and powdered crumb rubber until all the ingredients were spread evenly, as shown in Figure 3.9. All the mixings were done using the concrete mini mixer shown in Figure

3.8. The water was added once the evenly spread raw materials had been achieved.

Figure 3.8: Concrete Mini Mixer.

Figure 3.9: Dry Mix of Raw Materials.

Before the dry mixing of raw materials, the foaming agent and tap water were added to the foam generator shown in Figure 3.10. The foaming agent to water ratio will be 1:20. Once a constant pressure had been shown at the pressure gauge of the foam generator, the foam was dispensed out through the nozzle by opening the water and compressed air valve simultaneously.

Figure 3.10: Foam Generator.

In Figure 3.11 and Figure 3.13, the right amount of foam was added to the mixture until it was well mixed and had the proper density. The non-thorough mix of foam and concrete shown in Figure 3.12 is prohibited.

Figure 3.11: Foam Added into Mixture.

Figure 3.12: Non-Thorough Mix of Foam and Concrete.

Figure 3.13: Thorough Mix of Foam and Concrete.

In Figure 3.14 and Figure 3.15, the density of the concrete was measured by pouring the fresh mix into a container.

Figure 3.14: Pour Fresh Mix into The Measurement Container.

Figure 3.15: Measure the Density of Fresh Mix on Weighing Scale.

Once the measured density reached the target density, the concrete was prepared to be cast into the mould. All the concrete was mixed by following the proportions and dosage required, as stated in Table 3.2, 3.3, and 3.4.

3.3.2 Skin Layer for Rubberized Lightweight Foamed Concrete

The 6 mm, 9 mm, and 12 mm magnesium oxide boards were selected for 87 mm, 81 mm, and 75 mm of the rubberized lightweight foamed concrete inner core. The magnesium oxide board shown in Figure 3.16 was chosen as the skin layer, promoting fire resistance, impact resistance, and thermal and acoustic insulation of the rubberized lightweight foamed concrete inner core. Based on the catalogue provided by the Board Ply (2022), the combustibility had been classified as non-combustible by referring to BS 476: Part 4. According to GB8624-2012: Classification for burning behaviour of building products (Chinese Standard), the magnesium sulphate board, also known as MGO board, had been classified as A1 level, which is non-combustible.

Figure 3.16: Magnesium Oxide Board.

3.3.3 Casting and Curing Details

After the raw materials were mixed thoroughly, the concrete mixture was poured into the fabricated steel mould. The thickness of the concrete would be controlled by putting plywood on the steel mould shown in Figure 3.17. There will only be one steel mould made. The size of the steel mould was 300 mm × 300 mm × 90 mm. There will be twelve specimens made, each measuring 300 mm by 300 mm. The thickness of the specimens was split into 87 mm, 81 mm, and 75 mm.

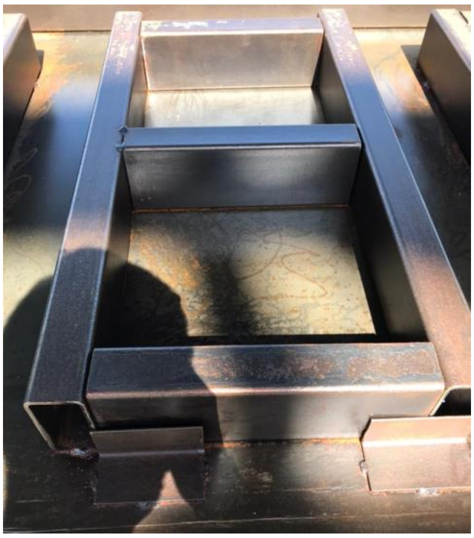


Figure 3.17: Fabricated Steel Mould.

Figure 3.19 shows the mould oil applied to the steel mould and the plywood after the steel moulds had been cleaned using the high-pressure air blower. The VT201C-Clear V-Tech Acetic Sealant, shown in Figure 3.18, was applied at the side or connection area of the steel mould to prevent the bleeding of cement water from the mould.

Figure 3.18: VT201C-Clear V-Tech Acetic Sealant.

Figure 3.19: Oiled Steel Mould.

The concrete was poured into the oiled steel mould, shown in Figure 3.20. During concrete pouring, all the edges and corners of the steel mould were filled with concrete to produce a perfect shape without any defects.

Figure 3.20: Pouring Concrete Mixture to Mould.

After the casting, the concrete was demoulded after one day and cured for 28 days, which is shown in Figure 3.21 and Figure 3.22.

Figure 3.21: Demould of Concrete.

Figure 3.22: Curing of Concrete.

3.3.4 Adhesion between Sheathing Material and Inner Core

The TPS Thin Bed Adhesive Premium 668, shown in Figure 3.23, was selected as the bonding material for the rubberized lightweight foamed concrete inner core and magnesium oxide board. The TPS Thin Bed Adhesive 668 was chosen because of its high-quality, robust cementitious adhesive properties with optimum strength and fire-rating performance. One layer of adhesive-coated rubberized lightweight foamed concrete was applied, and its functions improved bonding and adhesiveness between the concrete and magnesium oxide board. The coating done was shown in Figure 3.24 and Figure 3.25. Another coating was applied on the magnesium board, and the first coating after it was dried, shown in Figure 3.26. Figure 3.27 shows the connection between the inner core and the skin layer after applying the coating.

Figure 3.23: TPS Thin Bed Adhesive Premium 668.

Figure 3.24: Coating on Concrete (Plan View).

Figure 3.25: Coating on Concrete (Side View).

Figure 3.26: Adhesive Applied on Concrete.

Figure 3.27: Bonding Layer between Magnesium Oxide Board and Concrete.

3.3.5 Production of The Specimen

These sandwiched wall panels were made of rubberized lightweight foamed concrete (RLFC) as the inner core and the magnesium oxide board as its skin layer. The two skin layers were bound by the TPS Thin Bed Adhesive Premium 668 to produce the sandwiched wall panel. Those specimens' dimensions were 300 mm × 300 mm × 105 mm, as shown in Figure 3.28, which were tested to determine the structural performance, thermal insulating properties, and fire-resisting abilities.

Figure 3.28: Rubberized Lightweight Foamed Concrete Sandwiched Wall Panel.

3.4 Laboratory Testing

There were twelve sandwiched wall panels with a magnesium oxide board as their skin layer to be tested. The flexural strength and load-bearing tests were conducted to investigate the structural performance of wall panels. The thermal conductivity test was carried out to test the thermal insulating performance of the wall panel. In contrast, the flame exposure test was carried out to test the fire-resisting abilities of the wall panel. There were three different thicknesses of the inner concrete core, 87 mm, 81 mm, and 75 mm, with a skin layer of 6 mm, 9 mm, and 12 mm, respectively, that will be tested for each test.

3.4.1 Flexural Strength Test

The flexural strength test was based on the standard ASTM C 78. The centre point loading would be applied to the specimen to determine its flexural strength. In Figure 3.29., the setup of the flexural strength test is shown. The specimen would be placed on the roller at a distance of 25 mm from each end of the specimen, which has been shown in Figure 3.30. Before the test began, the centre loading was ensured to be in the centre of the specimen. The loading was applied to and acted on the specimen. With the help of the linear variable differential transducer (LVDT) and data logger, which have been shown in Figure 3.31 and Figure 3.32, the displacements were recorded every 2 kN. The modulus of rupture, *R*, can be determined using Equation 3.1.

$$R = \frac{3PL}{2BD^2} \tag{3.1}$$

where

R = modulus of Rupture, MPa

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

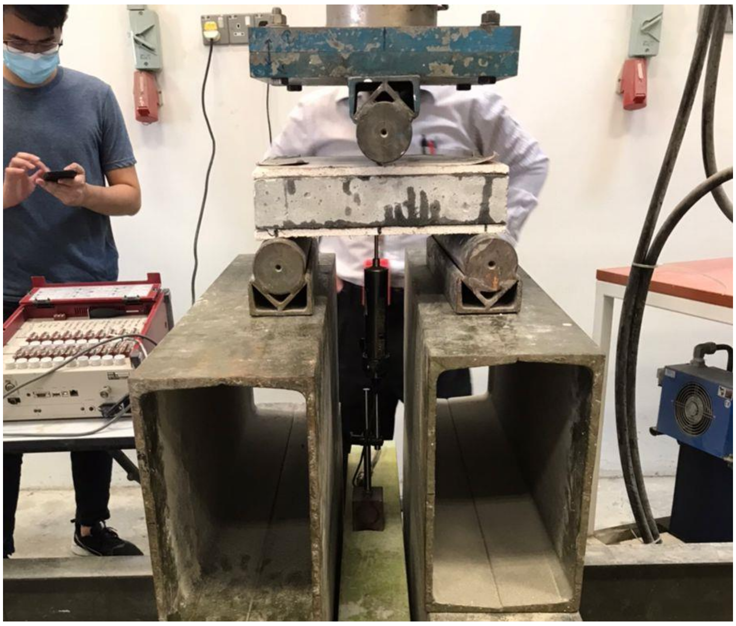


Figure 3.29: Flexural Strength Set Up.

Figure 3.30: 25 mm from Each End of the Specimen at the Centre of the Roller.

Figure 3.31: Linear Variable Differential Transducer (LVDT).

Figure 3.32: Data Logger.

3.4.2 Load Bearing Test

In the load-bearing test, the wall panel specimen was set up vertically and tested with the concrete compression machine shown in Figure 3.33. A flat surface was needed for the specimen's top and bottom. After the setup of the specimen, the linear variable differential transducers (LVDTs) were placed at both sides of the specimen, and the tips were pointed to the centre of both sides of the specimen to determine the lateral deflection. The setup is shown in Figure 3.34. A constant rate of compression load was applied to the specimen; the lateral deflection data were recorded using the data logger. The load-bearing test stopped automatically once the compression machines detected the failure. The ultimate load capacity of the specimens was obtained throughout this test.

Figure 3.33: Concrete Compression Test Apparatus.

Figure 3.34: Setup of Linear Variable Differential Transducer (LVDT).

3.4.3 Thermal Conductivity Test

The thermal conductivity test was carried out based on ASTM C177 to determine the thermal insulation performance of wall panels. The apparatus used to test the thermal conductivity of the specimen is shown in Figure 3.35. In Figure 3.36, the wall panel was placed on top of the thermal conductivity test apparatus's hot panel and covered by a cold plate on top of the wall panel.

Figure 3.35: Thermal Conductivity Test Apparatus.

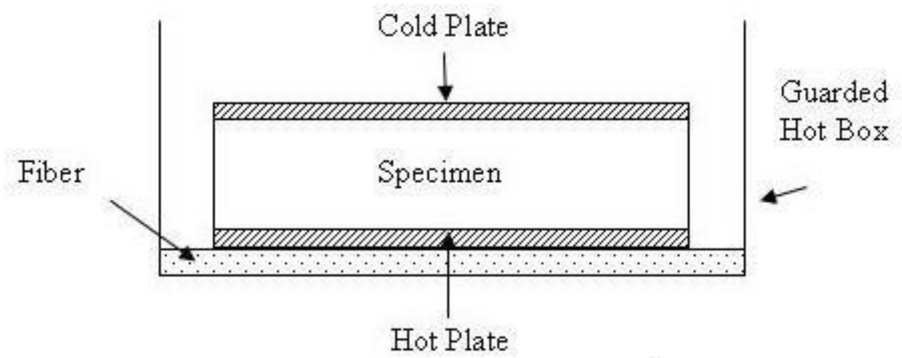


Figure 3.36: The Schematic View of Specimen Inside the Apparatus.

3.4.4 Flame Exposure Test

The wall panel's fire-resisting abilities were tested using a flame exposure test. One of the skin layer surfaces of sandwiched wall panel was heated continuously for 60 minutes at an extreme temperature of 600 °C. Based on ISO 834-1, the standard highlighted that this test's weakest point was the specimen's centre point. The thermocouple was installed in the setup for this test, shown in Figure 3.37. The function of the thermocouple was to record the temperature at the centre of the magnesium oxide board that was not directly exposed to the direct flame. After one hour of continuous heating, the structural strength and cracking were observed.

Figure 3.37: Setup of Flame Exposure Test.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The outcome of this study will be discussed in this chapter to justify the objectives of this study. The structural performance, thermal insulation performance, and fire-resisting properties of rubberized lightweight foamed concrete (RLFC) sandwiched wall panels would be evaluated through a flexural strength test, load bearing test, thermal conductivity test, and flame exposure test. The practicality of magnesium oxide board as the skin layer of this wall panel was justified throughout the test. This chapter will also discuss the analysis and interpretation of the result obtained. The thicknesses of testing specimens have been determined in Table 4.1.

Table 4.1: Thicknesses of Specimens' Inner Core and Skin Layer.

Specimen	Thickness of Core (mm)	Thickness of Skin Layer (mm)
6MGO	87	6
9MGO	81	9
12MGO	75	12

4.2 Flexural Strength Test

The flexural strength test, also known as the modulus of rupture test, is used to determine the strength of the specimen when subjected to bending or flexural forces. The ultimate flexural strength, modulus of rupture, and vertical deflection of specimens were identified throughout the test. The specimens would be placed horizontally and supported at two points; a constant load of 0.5 kN/s was applied until failure was found in the specimens. The results are tabulated in Table 4.2, 4.3, and 4.4 and summarised in Figure 4.1.

Table 4.2: The Flexural Strength Test Result on 6MGO Specimen.

Specimen	Specimen Condition at Ultimate Failure	Load (kN)	Deflection (mm)
6MGO		0	0.0000
Nominal		5	0.4250
Thickness:		9	0.5550
105 mm		10	0.6150
		11	0.6500
Ultimate		12	0.7000
Flexural		13	0.7450
Strength:		14	0.7900
18.13 kN		15	0.8350
		16	0.8800
Modulus of		17	0.9250
Rupture:		18	0.9700
2.0556 MPa		18.13	0.9750

Table 4.3: The Flexural Strength Result Test on 9MGO Specimen.

Specimen	Specimen Condition at Ultimate Failure	Load (kN)	Deflection (mm)
9MGO Nominal Thickness: 105 mm Ultimate Flexural Strength: 19.12 kN Modulus of Rupture: 2.1678 MPa		0	0.0050
		5	1.4750
		8	1.8000
		9	1.9100
		10	2.0000
		11	2.0950
		12	2.1800
		13	2.2650
		14	2.3350
		15	2.4100
		16	2.4850
		17	2.5600
		18	2.6350
		19	2.7050
		19.12	2.7600

Table 4.4: The Flexural Strength Test Result on 12MGO Specimen.

Specimen	Specimen Condition at Ultimate Failure	Load (kN)	Deflection (mm)
		0	0.0000
		5	0.5850
		7	0.6700
12MGO		8	0.7300
Nominal		9	0.7800
Thickness:		10	0.8300
105 mm		11	0.8750
		12	0.9200
Ultimate		13	0.9700
Flexural		14	1.0100
Strength:		15	1.0550
22.49 kN		16	1.1000
		17	1.1500
Modulus of		18	1.1950
Rupture:		19	1.2400
2.5499 MPa		20	1.2800
		21	1.3200
		22	1.3650
		22.49	1.3870

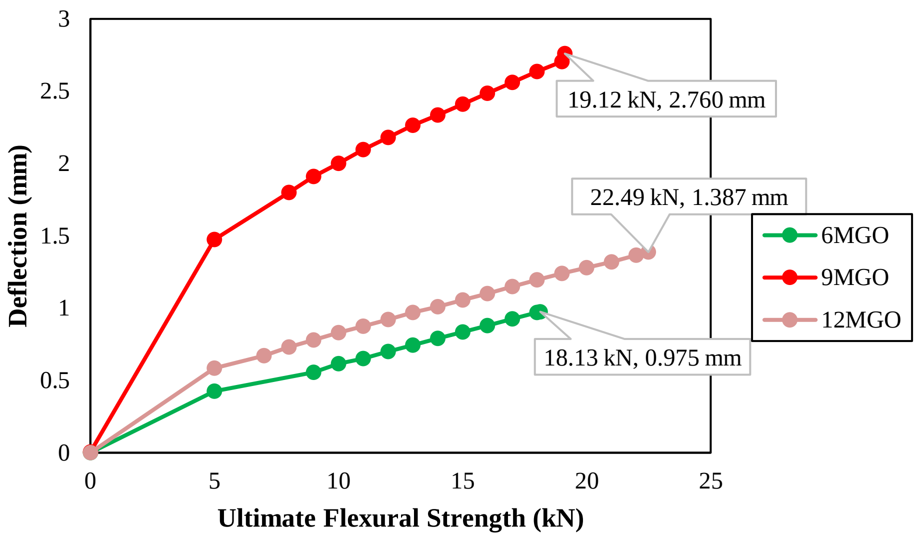


Figure 4.1: Relationship between Ultimate Flexural Strength and Deflection of Specimens.

Based on Figure 4.1, the result presents the flexural strength of the RLFC sandwiched wall panel varied with the different thicknesses of the magnesium oxide board. The thicker the magnesium oxide board, the thinner the RLFC inner core, and the greater the ultimate flexural strength of the specimen. Throughout the flexural strength test, the 12MGO specimen experienced shear failure on the highest ultimate flexural strength, 22.49 kN; while the 6MGO specimen experienced shear failure on the lowest ultimate flexural strength, 18.13 kN. The flexural strength of 9MGO and 12MGO increased by 5.46 % and 24.05 % compared to 6MGO, which was 18.13 kN. The same trend was reported in the study by Ting (2023), which utilised cement board as the skin layer for the RLFC sandwiched wall panel. Table 4.5 shows the same trend between the RLFC wall panel utilizing the magnesium oxide board and the cement board as the skin layer. According to ASTM C78, the modulus of rupture was calculated based on the ultimate flexural strength obtained using Equation 3.1. Likewise, the 12MGO specimen obtained the highest modulus of rupture, 2.5499 MPa, while the 6MGO specimen obtained the lowest modulus of rupture, 2.0556 MPa.

Table 4.5: Comparison of Ultimate Flexural Strength Results for Each Sized Down Wall Panel with Different Skin Layers.

Specimen	Ultimate Flexural Strength (kN)	Specimen	Ultimate Flexural Strength (kN)
6MGO	18.13	**6CS**	22.00
9MGO	19.12	**9CS**	30.68
12MGO	22.49	**12CS**	41.00

Besides, the loading applied leads to the deflection at the mid-span of the specimen. The 9MGO specimen experience the highest deflection, 2.7600 mm, while the 6MGO specimen experience the lowest deflection, 0.9750 mm. The relationship between the deflection and the thickness of the RLFC core or skin layer is dissimilar to the relationship between the ultimate flexural strength and the thickness of the RLFC core or skin layer. Based on the result shown above, the factor which affects the ultimate flexural strength and mid-span deflection will be the thickness of the magnesium oxide board. This can be adequately explained by the thicker magnesium oxide board having a greater cross-sectional area which can resist higher bending forces and become less susceptible to cracking and breaking than a thinner board. A low ultimate flexural strength will lead to a low toughness specimen and low deflection value because the specimen will fail before it achieves a higher deflection.

4.3 Load Bearing Test

The load-bearing test is a compression test used to test and measure the maximum load of the specimens before it fails. The specimen's load-bearing capacity and lateral deflection were identified throughout the test. The specimens were placed between two plates of a testing machine, and an increasing steading load of 0.5 kN/s was applied to the specimen before the failure was found. The results obtained have been tabulated in Tables 4.6, 4.7, and 4.8 and summarised in Figure 4.2.

Table 4.6: The Load Bearing Test Result on 6MGO Specimen.

Specimen	**Specimen Condition at Ultimate Failure**	**Load (kN)**	**Lateral Deflection, LVDT 1 (mm)**	**Lateral Deflection, LVDT 2 (mm)**
6MGO Nominal Thickness: 105 mm Load Bearing Capacity: 131.6 kN		0	0.0000	0.0000
		5	-0.0200	0.0300
		10	-0.0500	0.0500
		15	-0.0850	0.0900
		20	-0.0950	0.1000
		25	-0.0950	0.1100
		30	-0.1000	0.1200
		35	-0.0950	0.1200
		40	-0.0900	0.1200
		45	-0.0850	0.1150
		50	-0.0850	0.1200
		55	-0.0750	0.1200
		60	-0.0750	0.1200
		65	-0.0550	0.1200
		70	-0.0500	0.1200
		75	-0.0300	0.1100
		80	-0.0150	0.1000
		85	0.0000	0.0900
		90	0.0150	0.0700
		95	0.0400	0.0600
		100	0.1200	0.3350
		105	0.1350	0.5100
		110	0.1550	0.6000
		115	0.1650	0.6650
		120	0.1750	0.7150
		125	0.1850	0.7700
		130	0.1950	0.8250
		131.6	0.6000	0.9650

Table 4.7: The Load Bearing Test Result on 9MGO Specimen.

Specimen	Specimen Condition at Ultimate Failure	Load (kN)	Lateral Deflection, LVDT 1 (mm)	Lateral Deflection, LVDT 2 (mm)
9MGO Nominal Thickness: 105 mm Load Bearing Capacity: 121.3 kN		0	0.0000	0.0000
		5	0.0050	-0.0050
		10	0.0050	0.0000
		15	0.0150	0.0000
		20	0.0300	-0.0100
		25	0.0500	-0.0250
		30	0.0600	-0.0300
		35	0.0650	-0.0350
		40	0.0750	-0.0400
		45	0.0800	-0.0450
		50	0.0900	-0.0500
		55	0.1000	-0.0600
		60	0.1150	-0.0700
		65	0.1350	-0.0850
		70	0.1550	-0.1000
		75	0.1800	-0.1150
		80	0.2050	-0.1300
		85	0.2500	-0.1000
		90	0.2900	-0.0250
		95	0.3500	0.0300
		100	0.4300	0.0850
		105	0.8000	0.1850
		110	0.8900	0.2400
		115	1.2350	0.6450
		120	1.2350	0.8050
		121.3	1.8650	1.7450

Table 4.8: The Load Bearing Test Result on 12MGO Specimen.

Specimen	Specimen Condition at Ultimate Failure	Load (kN)	Lateral Deflection, LVDT 1 (mm)	Lateral Deflection, LVDT 2 (mm)
12MGO Nominal Thickness: 105 mm Load Bearing Capacity: 107.7 kN		0	0.0000	0.0000
		5	-0.0900	0.0300
		10	-0.1000	0.0400
		15	-0.1000	0.0450
		20	-0.1000	0.0450
		25	-0.0950	0.0400
		30	-0.0950	0.0400
		35	-0.0950	0.0450
		40	-0.0900	0.0450
		45	-0.0900	0.0400
		50	-0.0950	0.0400
		55	-0.1100	0.0400
		60	-0.1200	0.0600
		65	-0.1000	0.0700
		70	0.1050	0.0850
		75	0.7000	0.1250
		80	0.8950	0.1550
		85	1.2300	0.1750
		90	1.4800	0.1850
		95	1.6600	0.1850
		100	1.9150	0.2400
		105	2.0800	0.3050
		107.7	2.7500	1.5000

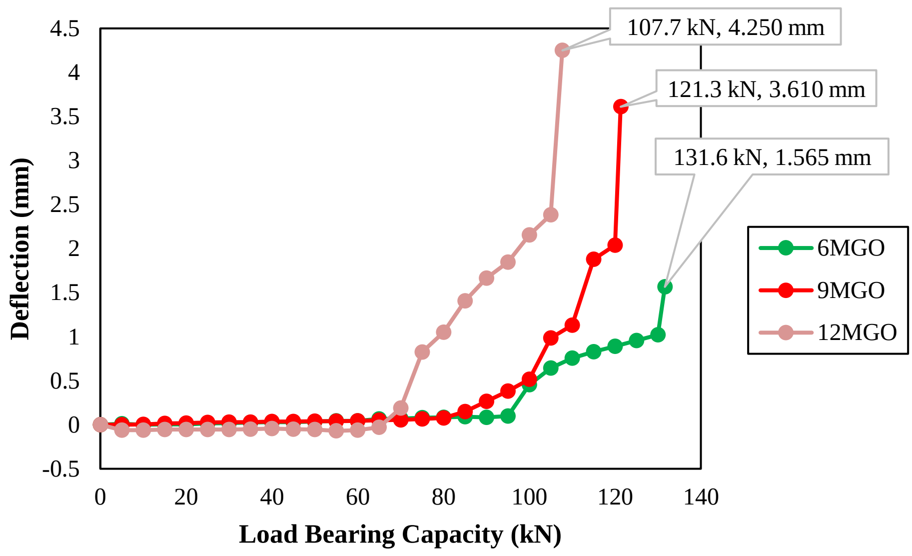


Figure 4.2: Relationship between Load Bearing Capacity and Lateral Deflection.

Based on Figure 4.2, generated from the result shown in Tables 4.6, 4.7, and 4.8, the highest load-bearing capacity, 131.6 kN, was found in the 6MGO specimen. In contrast, the lowest load-bearing capacity, 107.1 kN, was found in the 12MGO specimen. The load-bearing capacity of 9MGO and 12MGO decreased by 7.83 % and 22.19 % compared to 6MGO, which was 131.6 kN. The results above show that the greater the rubberized lightweight foamed concrete (RLFC) core thickness, the thinner the magnesium oxide board, and the higher the load-bearing capacity. Besides, the loading applied also leads to the lateral deflection of the specimen. The 12MGO specimen experience the highest lateral deflection, 4.2500 mm, and the 6MGO specimen experience the lowest lateral deflection, 1.5650 mm.

Throughout this test, the result shows that the thicker the RLFC inner core, the greater the compression loading it can sustain. This can be adequately explained by the thicker RLFC core will provide more material to resist the applied loading than a thinner core, increasing the load-bearing capacity of the sandwiched wall panel. The same relationship also has been found in the study by Yahaghi, Shafigh and Beddu (2016); the increase in lightweight concrete leads to an increase in ultimate energy absorption and crack resistance. The other possible explanation will be that the thicker RLFC core consists of more rubber particles which act as a small shock absorber and help to distribute the applied loading more evenly throughout the concrete. According to Youssf, Hassanli and Mills (2017), the rubber particles added to lightweight concrete can improve energy adsorption performance. Furthermore, the relationship between the lateral deflection and the thickness of the concrete core or skin layer contrasts with the relationship between the load-bearing capacity and the thickness of the RLFC core or skin layer. The deflection will generally increase when the applied loading increases because the specimen will continue to deform before it fails. The lateral deflection is dissimilar to the theory highlighted above throughout the load-bearing test. This can be explained based on the image provided in Tables 4.6, 4.7, and 4.8 shows that crushing the RLFC core leads to detaching the magnesium oxide board from the RLFC core when it fails. This may be argued that the failure pattern of the specimen affects the lateral deflection results obtained.

4.4 Thermal Conductivity Test

The thermal conductivity test determines the quantity of heat transmitted through the specimen. The specimens were placed between two temperature-controlled plates, and the temperature difference was measured to calculate the thermal conductivity. The result obtained has been calculated and tabulated in Table 4.9.

Table 4.9: The Thermal Conductivity Test Results for All Specimens with Different Skin Layer Thickness.

Specimen	**Thermal Conductivity ($Wm^{-1}K^{-1}$)**
6MGO	0.3904
9MGO	0.3651
12MGO	0.3642

According to Table 4.9, the thermal conductivity value was reduced with increased magnesium oxide board thickness and decreased rubberized lightweight foamed concrete (RLFC) core thickness. The 6MGO specimen had the highest thermal conductivity of 0.3904 $Wm^{-1}K^{-1}$, while 12MGO had the lowest thermal conductivity of 0.3642 $Wm^{-1}K^{-1}$ and the best thermal insulation performance among all the specimens. This can be explained by the material and thermal properties of magnesium oxide board. The thermal conductivity will reduce as the board thickness increases because it consists of more insulating material, which slows the heat transfer. The same trend was reported in the study by Loh (2023), the thermal conductivity of RLFC sandwiched wall panels that utilised calcium silicate board as the skin layer. Table 4.10 shows the same trend between the RLFC wall panel utilizing the magnesium oxide board and the calcium silicate board as the skin layer. On the other hand, changing skin layer thickness from 6 mm to 9 mm and 9 mm to 12 mm leads to a 6.48 % and 0.25 % reduction of thermal conductivity, respectively. Based on the result above, the thermal conductivity difference reduces significantly with increased magnesium oxide board thickness and reduced RLFC core thickness. It can be explained by reducing the RLFC core thickness, which reduces the air voids and rubber particle amounts produced and leads to poor thermal insulation performance. Besides, a thicker skin layer has greater mass and higher density, leading to decreased thermal conductivity. This is because the heat needs to pass through a greater volume of material which encounters more resistance to its flow than the thinner skin layer.

Table 4.10: Comparison of Thermal Conductivity Results for the Specimens with Different Types of Skin Layers.

Specimen	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Specimen	Thermal Conductivity ($Wm^{-1}K^{-1}$)
6MGO	0.3904	**6CS**	0.3546
9MGO	0.3651	**9CS**	0.3409
12MGO	0.3642	**12CS**	0.3294

4.5 Flame Exposure Test

The flame exposure test assesses the fire-resisting abilities of the rubberized lightweight foamed concrete (RLFC) sandwiched wall panel consisting of different thicknesses of RLFC inner core and magnesium oxide board. The specimens were exposed to a controlled continuous flame from a gas burner for 60 minutes. After the test, surface condition and structural integrity observations were made. The surface temperatures of the front and rear of the specimens exposed and unexposed to direct flame have been recorded and tabulated in Tables 4.11, 4.12, and 4.13.

Table 4.11: The Flame Exposure Test Result on 6MGO Specimen.

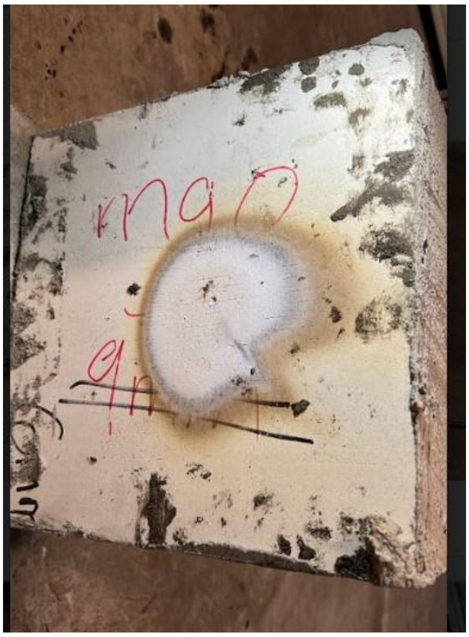
Specimen	**The Condition of Exposed Surface to Flame after Testing**	**Time (min)**	**Temperature (°C)**	
			Front	**Rear**
6MGO		10	970	28.8
		20	969	29.6
		30	970	28.8
		40	970	28.8
		50	961	28.8
		60	963	29.5

Table 4.12: The Flame Exposure Test Result on 9MGO Specimen.

Specimen	**The Condition of Exposed Surface to Flame after Testing**	**Time (min)**	**Temperature (°C)**	
			Front	**Rear**
9MGO		10	961	28.7
		20	949	28.3
		30	947	28.3
		40	941	28.4
		50	940	28.5
		60	937	28.7

Table 4.13: The Flame Exposure Test Result on 12MGO Specimen.

Specimen	**The Condition of Exposed Surface to Flame after Testing**	**Time (min)**	**Temperature (°C)**	
			Front	**Rear**
12MGO		10	948	28.9
		20	955	28.8
		30	947	28.7
		40	947	29.0
		50	937	29.3
		60	945	29.5

The results show that the skin layer surface conditions for every specimen after exposure to the continuous flame of 60 minutes are the same. No cracking or damage is found on the skin layer's exposed surface for each specimen. For both 6MGO, 9MGO, and 12MGO specimens, the unexposed rear surface's temperature was within the range of 28.3 - 29.6 °C, close to the ambient temperature at the testing space. The results obtained from the flame exposure test verified the fire safety properties of the magnesium oxide board. One of the material characteristics of magnesium oxide board is the fire rating of A1, the highest fire resistance rating possible for a building material.

On the other hand, the adhesive agent that acts as a binder maintains its function well after exposure to direct flame. Throughout this test, the condition of all RLFC sandwiched wall panel specimens was good and without any defect. Hence, the sandwiched RLFC wall panel utilizing magnesium oxide board as its skin layer has proven to provide fire resistance when directly exposed to continuous flame for 60 minutes at a peak temperature that is equal to or higher than 600 °C.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Numerous tests were conducted to distinguish and identify the practicality of utilizing magnesium oxide board as the skin layer of rubberized lightweight foamed concrete (RLFC) sandwiched wall panel. As a result, several conclusions have been made regarding the study's objectives.

The first objective of this study is to evaluate the structural performance of RLFC sandwiched wall panels in flexural and load-bearing. The structural performance in flexural and load bearing is dissimilar when the varied thickness of magnesium oxide board has been used. For ultimate flexural strength, it increased exponentially with the increase of skin layer thickness. The 9MGO and 12MGO increased by 5.46 % (19.12 kN) and 24.05 % (22.49 kN) based on the ultimate flexural strength of 6MGO (18.13 kN). This is because thick magnesium oxide boards have a greater cross-sectional area which can resist higher bending forces and become less susceptible to cracking and breaking. The load-bearing capacity decreased exponentially with the increase of skin layer thickness, which contrasts with the flexural strength of sandwiched wall panel. The 9MGO and 12MGO decreased by 7.83 % (121.3 kN) and 22.19 % (107.7 kN) based on load bearing capacity of 6MGO (131.6 kN). The RLFC core can explain this sustained a higher compressive load than the magnesium oxide board. The further increment of skin layer thickness significantly affects the flexural and load-bearing performance of sandwiched wall panel.

The second objective is to identify the thermal insulation performance of RLFC sandwiched wall panels. This objective was achieved by conducting a thermal conductivity test for the specimen and concluded that the 12MGO has better thermal insulation performance than other specimens. The thermal conductivity decreases exponentially with increased magnesium oxide board thickness and reduced RLFC core thickness. The change from 6MGO to 9MGO leads to a 6.48 % reduction of thermal conductivity while changing from 9MGO to 12MGO leads to a 0.25 % reduction of thermal conductivity. This is because the magnesium oxide board with greater thickness has more insulation material to slow the heat transfer. The reduction of thermal conductivity difference has been found when the thickness of the skin layer increase.

The last objective of this study is to investigate the fire-resisting properties of magnesium oxide board as the skin layer of RLFC sandwiched wall panel. This objective is achieved by conducting the flame exposure test, which has provided conclusive evidence that the fire-resisting performance of the RLFC sandwiched wall panel, which utilised magnesium oxide board as the skin layer, is satisfactory. No cracking or damage was found on the skin layer exposed directly to 60 minutes of continuous flame. On the other hand, the connection between the magnesium oxide board and the RLFC core is in good condition and without any defects. Hence, this study verifies that magnesium oxide board has fire-resisting properties and is suitable to be applied as the skin layer for good fire-resisting performance.

5.2 Recommendations

The study of structural performance, thermal conductivity, and fire-resisting properties of RLFC sandwiched wall panels with an 1150 kg/m^3 density inner core and magnesium oxide board as skin layer found that the study in this field is still limited and not specific. There are a few recommendations and suggestions that could be taken into consideration to improve the reliability and accuracy of testing results in the future study:

(i) Various types of sheathing material, such as oriented strand board (OSB), Cement Bonded Particle Board (CBPB), and Medium-Density Fibreboard (MDF), can be proposed and used as the skin layer of RLFC sandwiched wall panel to compare the structural performance, thermal conductivity, and fire-resisting performance.

(ii) The thickness of the inner core or skin layer can be fixed to study how each thickness affects the structural performance, thermal conductivity, and fire-resisting abilities of the RLFC sandwiched wall panel.

(iii) Since the lateral deflection of the load-bearing test is affected by the failure pattern, instead of recording the lateral deflection value, the damage characterisation of each specimen can be captured for further comparison.

(iv) Since the inner core affected the thermal conductivity of the RLFC sandwiched wall panel, different mix proportions can be tried to compare how it affects the thermal conductivity of sandwiched wall panel.

(v) The life cycle assessment of rubberized lightweight foamed concrete and magnesium oxide board needs to be studied further to analyse the life cycle of this sandwiched wall panel and evaluate its environmental impact, including the whole manufacturing process of its raw material and final product.

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