ASSESSING COMPRESSIVE STRENGTH AND DIMENSIONAL STABILITY OF DETACHABLE GREEN CONCRETE TILES FOR FLOORING APPLICATIONS

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This report is submitted in accordance with requirement of the University Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Hons.)

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APPROVAL

This report is submitted to the Faculty of Industrial and Manufacturing Technology and Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The member of the supervisory committee is as follow:

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ABSTRAK

Pengurangan agregat semula jadi menjadi isu global walaupun permintaan pembinaan meningkat, sementara pengumpulan sisa plastik juga masalah alam sekitar besar. Mengubah sisa plastik menjadi agregat pembinaan menawarkan penyelesaian terhadap kedua-dua permasalahan. Industri pembinaan semakin menerima bahan mesra alam seperti jubin konkrit daripada agregat semula jadi dan plastik. Namun, struktur kimia plastik yang berbeza boleh menyebabkan perubahan di bawah haba dan tekanan, menjejaskan kekuatan dan ketepatan dimensi jubin. Kajian ini bertujuan untuk memahami kesan polietilena berketumpatan tinggi (rHDPE) kitar semula sebagai agregat halus pada nisbah agregat semula jadi-ke-plastik 100:0, 97:3, 93:7, dan 90:10 untuk campuran konkrit M20. . Kekuatan mampatan dinilai menggunakan mesin UTM mengikut BS EN 12390:3:2000, ketepatan dimensi dengan kaliper (ASTM C157), dan kekasaran permukaan dengan profilometer (ASTM E867). Keputusan menunjukkan kekuatan mampatan menurun dengan peningkatan kandungan rHDPE, dengan campuran 0% rHDPE menunjukkan kekuatan tertinggi 21.73 MPa pada 28 hari. Campuran 10% rHDPE masih memenuhi keperluan minimum 10 MPa untuk aplikasi lantai. Perubahan dimensi mencapai 2.4% untuk campuran 10%. Nilai kekasaran permukaan (Ra) berada dalam julat 6-9 µm untuk semua campuran, memastikan rintangan gelinciran dan estetika yang mencukupi. Analisis morfologi menunjukkan struktur mikro padat untuk sampel agregat semula jadi, manakala campuran rHDPE menunjukkan peningkatan porositi dan mikro-retak. Imej SEM mengesahkan zon peralihan antara muka lemah antara rHDPE dan matriks simen, menyumbang kepada pengurangan kekuatan mampatan. Kesimpulannya, jubin konkrit hijau dengan nisbah agregat semula jadi kepada plastik 93:7 menunjukkan keseimbangan antara menggabungkan plastik kitar semula dan mengekalkan integriti struktur, sesuai untuk aplikasi lantai mesra alam. Campuran nisbah 90:10, walaupun memenuhi keperluan kekuatan minimum, menunjukkan perubahan dimensi lebih besar dan kekuatan mampatan berkurang, tetapi ketumpatan lebih rendah menjadikannya ideal untuk aplikasi ringan dan lestari.

ABSTRACT

Natural aggregate depletion has become a global issue despite increasing structural construction demands. Concurrently, the accumulation of plastic waste has emerged as a significant environmental problem. Converting waste plastics into construction aggregates offers a promising solution to both issues. The construction industry is increasingly adopting eco-friendly materials, such as concrete tiles made from hybrid natural and plastic aggregates. However, the differing chemical structures of plastics and other concrete components may cause structural changes under heat and stress, affecting the strength and dimensional accuracy of the tiles. This study aimed to understand the effect of recycled high-density polyethylene (rHDPE) as fine aggregates at natural-to-plastic aggregate ratios of 100:0, 97:3, 93:7, and 90:10 for M20 concrete mixture. Compressive strength was evaluated using a UTM machine per BS EN 12390:3:2000, while dimensional accuracy was measured within ±3mm tolerance with callipers (ASTM C157) and surface roughness with a profilometer (ASTM E867). Results showed that compressive strength decreased with increasing rHDPE content, with the 0% rHDPE mix exhibiting the highest strength of 21.73 MPa at 28 days. Yet, all tiles met the minimum requirement of 10 MPa for flooring applications. Dimensional changes increased with higher rHDPE content, reaching up to 2.4% for the 10% mix. Surface roughness (Ra) values fell within the optimal range of 6-9 µm for all mixes, ensuring adequate slip resistance and aesthetics. Morphological analysis revealed a dense and uniform microstructure for the natural aggregate sample, while rHDPE mixes showed increasing porosity and micro-cracks with higher plastic content. SEM images confirmed a weaker interfacial transition zone between rHDPE and the cement matrix, reducing compressive strength. In conclusion, green concrete tiles with a 93:7 natural-to-plastic aggregate ratio exhibited a balance between incorporating recycled plastic and maintaining structural integrity, making them suitable for eco-friendly flooring applications. The 90:10 ratio mix, while meeting the minimum strength requirement, showed greater dimensional changes and reduced compressive strength, but its lower density makes it ideal for applications prioritizing lightweight and sustainability.

DEDICATION

This report is dedicated to my loving parents and family, who provided spiritual and financial support to help me complete it without hiccups. Thank you for always being there for me through bad and good and strengthening me. Also, I want to thank my supervisor, Associate Professor Dr. Noraiham Binti Mohamad, for always teaching me and giving me important advice that has helped me improve throughout this journey. Thank you for your kindness and efforts. This work is for every one of you.

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LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
B.C	-	Before Christ
BS EN	-	British Standards European Norm
CO_2	-	Carbon dioxide
DOE	-	Design of Experiment
FA	-	Fly Ash
FKP	-	Faculty of Manufacturing Engineering
GGBFS	-	Ground Granulated Blast Furnace Slag
HDPE	-	High-Density Polyethylene
LDPE	-	Low-Density Polyethylene
PET	-	Polyethylene Terephthalate
NA	-	Natural Aggregates
PP	-	Polypropylene
PVC	-	Polyvinyl Chloride
UTeM	-	University Teknikal Malaysia Melaka
UTM	-	Universal Testing Machine
Ra	-	Average Roughness
Rz	-	Roughness Depth
RCA	-	Recycled Coarse Aggregate
RHA	-	Rice Husk Ash
rHDPE	-	recycled High-Density Polyethylene
SEM	-	Scanning Electron Microscopy
SCMs	-	Supplementary Cementitious Materials
SF	-	Silica Fume
SSD	-	Saturated Surface Dry
UPV	-	Ultrasonic Pulse Velocity

LIST OF SYMBOLS

%	-	Percentage
°C	-	Degree Celsius
g/cm^3	-	Gram per Centimetre Cube
kg/m^3	-	Kilograms Per Cubic Meter
m	-	Meter
mm	-	Millimeter
MPa	-	Mega Pascal
RPM	-	Revolution Per Minute
µm	-	Mi

CHAPTER 1
INTRODUCTION

1.1 Research Background

Portland cement is one of the most used types of cement in concrete. It was named after the Isle of Portland in England, where similar-looking limestone was quarried by Joseph Aspdin in 1824 (Ryan, 1929). Concrete is a composite material composed of a binder, typically Portland cement, aggregates such as sand or gravel, and water (Damme, 2018). Concrete began to be used outdoors and in harsher environments like offshore platforms, bridges, and roads (AïTcin, 2000). However, concrete production has a crucial environmental effect due to the energy-intensive process and the emission of greenhouse gases (GHGs) caused by the extraction of a huge quantity of raw material (Tanash & Muthusamy, 2022).

Green concrete is an innovative idea in the history of the concrete industry. Dr. WG invented it in Denmark in 1998 (Kumar et al., 2021). The need to reduce greenhouse gas emissions is one of the primary factors in green concrete development. Portland cement production, the main ingredient in concrete, is a significant source of carbon dioxide emissions (Sureshkumar et al., 2019). Green concrete, which uses recycled materials as aggregates, can help reduce these emissions (Marey et al., 2022). The need to protect natural resources is another factor in green concrete development. Sand and gravel used in concrete must be extracted from natural deposits (Bamigboye et al., 2016). Green concrete can help reduce the requirement for natural aggregates using recycled materials as aggregates, such as recycled plastic (Nilimaa, 2023). As a result, green concrete is significant because it can aid in promoting sustainable development.

Eco-friendly concrete products have become more prevalent in recent years to reduce concrete manufacturing's environmental impact. Concrete can contain recycled materials like plastic waste (Tahir et al., 2022). Research shows that plastic waste can partially replace aggregates in concrete, reducing demand for natural aggregates and diverting plastic waste from landfills (Khalil and Khalaf, 2017). Sustainability is possible with green concrete tiles made from hybrid natural and plastic waste. They are a promising new sustainable flooring technology made from natural aggregates and recycled plastic waste. Green concrete tiles with hybrid natural/plastic composite aggregates have received little research. Al-Mansour et al. (2022) found that hybrid natural/plastic composite aggregate concrete tiles had higher flexural strength and wear resistance than natural aggregate tiles. The study also found that hybrid natural/plastic composite aggregate concrete tiles were more impact-resistant (Mustafa et al., 2019).

The current research indicates that green concrete tiles with a combination of natural and plastic composite aggregates can be an environmentally friendly and effective substitute for conventional concrete tiles. Further research is required to develop and enhance these tiles' concrete mix designs and assess their long-term performance under various service conditions. This study aimed to fill the existing research void by creating detachable concrete tiles that are environmentally friendly. These tiles were made using a combination of natural and plastic composite aggregates. The study focused on the effect of formulation on the compressive strength, dimensional accuracy, installation stability, and other properties of these tiles. The results of this study were valuable for the production of practical and sustainable concrete floor tiles. Furthermore, the study contributed to advancing sustainable practices in the field of construction materials.

1.2 Problem Statement

Ceramic tile is a famous flooring material because of its great mechanical strength, strong chemical stability, rich designs, and resistance to stains (Wang et al., 2021). However, it is relatively pricey and complicated to install. Furthermore, ceramic tile is not forgiving of mistakes and can be hard to remove once installed. Concrete tile is less expensive and easier to install than ceramic tile. Concrete tile is also more durable and forgiving of errors than ceramic tile. However, traditional concrete tile is heavy and difficult to transport and handle. According to the study by Tanash and Muthusamy (2022), concrete tile production has a significant environmental impact. Consequently, all those issues may be resolved using hybrid natural/plastic composite aggregates in detachable eco-friendly concrete tiles. Compared to conventional concrete tiles, detachable ones are less likely to chip and crack and are simpler to install and remove. Additionally, using hybrid natural/plastic composite aggregates can reduce the environmental impact of concrete tile production (Castro et al., 2021c).

Next, one major environmental problem is plastic waste. An enormous amount of tons of plastic waste produced annually ends up in landfills or incinerators (Kumar et al., 2021). Reducing the environmental impact of plastic waste can be achieved through recycling. However, not all plastic waste can be recycled, and recycled plastic waste is often used to make lower-quality products (Hou et al., 2012). Thus, recycled plastic waste and natural aggregates are combined to create hybrid natural/plastic composite aggregates. According to Khalaf and Khalid (2017), using recycled plastic waste in producing concrete tiles can help lessen the process's environmental impact by keeping plastic waste out of landfills and incinerators. Hybrid natural/plastic composite aggregates have also been shown to improve the mechanical properties of concrete, such as strength, durability, and toughness (Mustafa et al., 2019). Consequently, the process has a smaller environmental impact because less cement is required to get the desired results.

In conclusion, detachable green concrete tiles with hybrid natural/plastic composite aggregates offer many advantages over traditional concrete and ceramic tiles. They are more sustainable, durable, and easier to install and remove. Detachable green concrete tiles can also be reused, reducing their environmental impact. This study assessed the compressive strength, dimensional accuracy and installation stability of detachable green concrete tiles with hybrid natural and plastic composite aggregates for flooring. The study was important because it provided valuable insights into these materials' performance and potential applications.

1.3 Objectives

The objectives are as follows:

(a) To fabricate detachable green concrete tiles using Portland cement reinforced with hybrid natural and plastic waste aggregates using a manual process.

(b) To investigate the effect of the formulation ratio of the hybrid aggregates and types of recycled plastics on the workability and compressive strength of the green concrete tiles.

(c) To evaluate the dimensional accuracy of green concrete tiles using dimensional progressive measurement and roughness test.

1.4 Scopes of the Research

The scopes of research are as follows:

(a) The green concrete tiles were fabricated using Grey Portland cement and hybrid natural/plastic aggregates, specifically HDPE plastics, as the primary raw materials at suitable process parameters. The tiles were manually mixed and molded, ensuring control over the mixture and consistency of the materials used. The formulation scope involved the ratio of natural to plastic aggregates. The specific ratios used were 100:0, 97:3, 93:7, and 90:10, based on the weight percentage of the aggregates. The plastic aggregates were derived from recycled waste recycled high-density polyethylene (rHDPE).

(b) A compressive test was conducted using a UTM machine (B.S. EN 2390-3:2019) to determine the workability and compressive strength of the formulations with a target strength of at least 10 MPa (M10 Concrete). The dimensional accuracy test was assessed through a dimensional progressive measurement using the calliper method (ASTM C157), and the roughness test (ASTM E867) was performed, with roughness values expected to be between 6-9 µm.

(c) The morphological characteristics of the tiles were analyzed using Scanning Electron Microscopy (SEM), which provided high-resolution images to assess microstructural details. Optical microscopy was employed to examine the physical features of the tiles, ensuring that the surface quality met the necessary criteria for flooring applications.

1.5 Rational of Research

The rationale of the research is as follows:

(a) Eco-friendly construction materials are critical for sustainable development, but their functionality must match conventional materials. This research develops green concrete tiles using plastic waste aggregates to achieve suitable compressive strength, dimensional stability and installation reliability for flooring applications. Plastic waste accumulation is an environmental threat; incorporating them into concrete tiles creates a value-added application while resolving waste issues. The study explores suitable natural-to-plastic aggregate ratios to balance sustainability and performance.

(b) Dimensional accuracy during service are vital tile properties. This research thoroughly evaluates these parameters using established test methods to ensure the tiles meet flooring standards before implementation.

(c) The manual production process enables control over mixture consistency and material quality. Comprehensive data is obtained to judge eco-tile suitability for industry adoption coupled with advanced microstructural and morphological analysis. The methodology ensures both green credentials and functional performance are satisfied.

CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

This chapter provides a comprehensive review of the literature related to green concrete tiles. Green concrete tiles are a sustainable and eco-friendly alternative to traditional concrete tiles, offering numerous environmental, technical, and economic benefits. This chapter aims to establish the significance of green concrete tiles, discuss the existing work in the field, and identify any controversies or recent research that has raised questions about earlier assumptions.

2.1 Green Concrete Tiles

In the context of global environmental concerns, the term "green" encompasses the entire environment, highlighting its crucial significance. Similarly, green concrete refers to concrete that incorporates at least one component derived from waste materials, employs an environmentally friendly manufacturing process, or exhibits exceptional performance and life cycle sustainability (Hashmi, 2022). It's important to note that green concrete has nothing to do with its color; rather, it's a concept that emphasizes the use of eco-friendly materials in concrete to enhance the sustainability of the construction industry (Kumar et al., 2021).

Green concrete tiles are a sustainable and eco-friendly alternative to traditional concrete tiles. Green concrete is a type of concrete that is made with sustainable materials and is designed to reduce the environmental impact of construction projects (Liew et al., 2017). It is formed when a percentage of Portland cement is substituted by eco-friendly cementitious materials in a concrete mix, such as recycled glass, fly ash, blast furnace slag, or alternative cements made from agricultural waste products. The use of green concrete aligns with the global shift towards sustainable and environmentally conscious construction practices.

2.1.1 Composition of Green Concrete Tiles

Green concrete tiles are an eco-friendly alternative to traditional concrete tiles, with their composition varying based on the specific formulation and type of waste materials used. According to (Al-Hamrani et al., 2021), the primary binder in green concrete is cement, but a portion of it can be replaced with supplementary cementitious materials (SCMs) such as ground granulated blast furnace slag (GGBFS), fly ash (FA), and silica fume (SF) to reduce environmental impact. Futhermore, aggregates, typically the largest component of concrete, can be partially replaced with recycled coarse aggregate (RCA) or waste materials in green concrete tiles. For instance, waste ceramic tiles can be used as coarse aggregates in concrete at replacement levels of 0, 10, 20, 30, 50, and 100% by weight of natural coarse aggregate (Al-Hamrani et al., 2021).

Other than that, water is another essential component for the hydration of the cement and providing workability to the concrete mix. Admixtures are added to modify the properties of the concrete. For example, superplasticizers can be used to improve the workability of concrete without increasing its water content. Next, recycled aggregates, repurposed from previous construction and demolition waste, can replace natural aggregates in producing green concrete tiles (Saadoon et al., 2019). Table 2.1 shows the composition of green concrete tiles, detailing the various components used, their descriptions, and examples of replacement materials that can be used in their place.

Table 2.1: Composition of green concrete tiles

Component	Description	Example Replacement Materials	References
Cement	Primary binder in concrete	Ground granulated blast furnace slag (GGBFS), fly ash (FA), silica fume (SF), metakaolin, micro silica	(Saadoon et al., 2019)
Aggregates	Largest component of concrete	Recycled coarse aggregate (RCA), waste ceramic tiles, rice husk ash (RHA)	(Saadoon et al., 2019)
Water	Necessary for hydration	-	(Saadoon et al., 2019)
Admixtures	Modify properties of concrete	Superplasticizers	(Saadoon et al., 2019)
Recycled Aggregates	Replacement for natural aggregates	Recycled plastic waste, recycled mosaic tiles, steel slag	(Saadoon et al., 2019)

2.1.2 Advantages of green concrete tiles

Green concrete tiles provide many environmental, technical, and economic advantages, positioning them as a promising and sustainable substitute for conventional concrete tiles. Green concrete tiles offer a notable benefit in their exceptional strength and enhanced durability, rendering them a dependable and enduring building material (Liew et al., 2017). Moreover, using green concrete reduces CO_2 emissions, energy usage, and waste production, thereby conforming to sustainable and eco-friendly construction methods (Imbabi et al., 2012).

According to Agarwal and Garg (2023), green concrete tiles can prolong the lifespan of concrete elements/structures, improve compressive strength, and decrease the carbon footprint compared to traditional concrete. Green concrete tiles exhibit a lower weight than conventional concrete tiles, facilitating their installation in diverse construction contexts. Additionally, they offer exceptional insulation properties, resulting in decreased expenses for heating and cooling (Liew et al., 2017).

In addition, green concrete tiles use industrial waste materials, such as recycled glass, fly ash, and blast furnace slag, thereby decreasing the environmental impact of waste disposal and encouraging the efficient use of resources. Furthermore, green concrete exhibits accelerated strength development and experiences a diminished shrinkage rate compared to conventional concrete, resulting in extended structural durability and decreased maintenance needs. The exceptional thermal insulation properties of green concrete tiles can reduce energy consumption in buildings, thereby encouraging the adoption of sustainable construction methods.

Using local and recycled materials in green concrete tiles ultimately encourages sustainable sourcing and diminishes the environmental consequences of transportation and material extraction (Agarwal & Garg, 2018). Nevertheless, green concrete tiles do possess certain drawbacks that necessitate careful consideration. Hassani et al. (2023) found that green concrete exhibits lower split tensile strength than ordinary concrete, potentially impacting its suitability for specific applications. Green concrete tiles may demonstrate increased water absorption compared to traditional concrete, potentially affecting their durability and resilience against environmental influences (Almohana et al., 2022).

Structures constructed with green concrete may have a shorter lifespan than conventional concrete ones, which could impact their long-term durability and maintenance needs. Reduced Tensile Strength: Green concrete exhibits a diminished tensile strength compared to traditional concrete, potentially impacting its appropriateness for particular structural purposes (Adel & Ayad, 2020).

Ultimately, the manufacturing process of green concrete may necessitate an increased workforce and a longer duration for the mixing process, posing a potential difficulty, especially in the context of extensive construction endeavours (Agarwal & Garg, 2018). Table 2.2 presents a comprehensive evaluation of the different characteristics of green concrete tiles, emphasising their benefits and drawbacks.

Table 2.2: Comparison of advantages and disadvantages of green concrete tiles

Aspect	Advantages	Disadvantages
Strength and Durability	- Greater strength and durability than normal concrete (Liew et al., 2017) - Reduced CO2 emissions related to concrete production (Imbabi et al., 2012) - Utilizes eco-friendly materials with zero environmental impact (Agarwal & Garg, 2018) - Durable material with long lifespan (Liew et al., 2017)	- Less split tensile strength than ordinary concrete (Hassani et al., 2023) - Higher water absorption (Almohana et al., 2022) - Shorter lifespan compared to conventional concrete (Hassani et al., 2023) - Lower tensile strength (Adel & Ayad, 2020)
Environmental Impact	- Reduces CO2 emissions and environmental pollution (Imbabi et al., 2012) - Uses local and recycled materials, reducing overall cement consumption (Agarwal & Garg, 2018) - Economical and thermal/acid resistant (Liew et al., 2017)	- Higher water absorption (Almohana et al., 2022) - Shorter lifespan (Hassani et al., 2023) - Less tension and flexural strength compared to conventional concrete (Imbabi et al., 2012)
Cost and Workability	- Economical compared to ordinary concrete (Agarwal & Garg, 2018) - Better workability than conventional concrete (Liew et al., 2017)	- Increased labor and time requirements for mixing (Agarwal & Garg, 2018)
Application and Construction Ease	- Versatile applications in mass construction projects, building construction, and road construction (Agarwal & Garg, 2018)	- Not much difference in preparation compared to conventional concrete (Imbabi et al., 2012) - Increased cost of reinforcement (Agarwal & Garg, 2018)

2.2 Materials in Flooring Application

Flooring application refers to installing a floor covering or finish material over a floor structure to provide a walking surface. Different materials can be used in flooring applications, each with unique properties and applications. The choice of material can significantly impact the aesthetics, comfort, safety, and durability of the floor ((Atmadi & Purnama, 2021); (Labuan & Waty, 2020)). Flooring materials can be broadly categorized into hard and soft coverings. Hard coverings include materials like wood, concrete, ceramic tile, and stone, while soft coverings typically refer to carpets and area rugs (Labuan & Waty, 2020).

2.2.1 Types of Flooring Materials

Flooring application refers to installing a floor covering or finish material over a floor structure to provide a walking surface. It can either be required to 1) withstand high loads as the primary flooring structure, such as concrete slabs, or 2) secondary flooring, not need components to sustain too much load, such as carpet or laminate floors. This process involves using various materials, each with unique properties and applications.

(a) Wood: Wood is commonly used in flooring due to its aesthetic appeal and durability. It can be used in various forms, such as solid wood, engineered wood, or laminate. A study on wooden floors in workspace interiors revealed their advantages in terms of aesthetics, comfort, and safety (Atmadi & Purnama, 2021). Another study proposed a methodology for predicting the service life of wood flooring systems, considering the impact of different factors (Coelho et al., 2021).

(b) Concrete: Concrete tile is often used in large-area flooring applications, especially in garages. It is known for its durability and strength. However, it requires proper surface preparation before application, such as mechanical abrasion or acid-etching (El-Sherbiny, 2011).

(c) Carpet: A carpet is a soft floor covering made of bound or stapled fibers. It provides comfort and noise insulation. However, it requires more cleaning effort than other materials (Labuan & Waty, 2020).

(d) Stone: Stone is another hard flooring material known for its durability and aesthetic appeal. It is often used in high-end residential and commercial applications (Labuan & Waty, 2020).

(e) Ceramic Tile: Ceramic tiles are commonly used in flooring applications. They are durable, easy to clean, and have various designs and colors (Labuan & Waty, 2020).

(f) Laminate: Laminate flooring is a multi-layer synthetic flooring product fused together with a lamination process. It can simulate almost any kind of wood, stone, or ceramic tile with a photographic applique layer under a clear protective layer (Labuan & Waty, 2020).

These are some of the flooring materials and their applications in building construction. Each type has its advantages and disadvantages that should be considered before choosing the best option for a specific project. The next section discussed the potential use of plastic waste as a construction material for flooring applications. In this work, the detachable concrete tiles are targeted for secondary or co-flooring, which is not necessarily required to withstand high loads.

2.3 Utilization of Plastic Waste in Flooring Application

Plastic waste is a significant environmental problem due to its hazardous effects and difficulty in disposal. With the increasing production of plastics and global population growth, plastic waste management has become a pressing issue for developed and developing countries (Ilyas et al., 2018). The utilization of plastic waste in flooring materials offers a sustainable approach to address this problem while promoting eco-conscious construction

Several studies have been conducted on using plastic waste in flooring materials. For instance, Patil et al. (2020) investigated waste plastic as a binding material instead of cement in manufacturing floor tiles. Their study aimed to evaluate the tiles' different physical and mechanical properties, such as water absorption, transverse resistance, resistance to impact, and abrasion resistance. The results showed that plastic waste can be used as a binding material in manufacturing floor tiles, and the tiles exhibited good physical and mechanical properties.

Another study by Raguraman et al. (2022) explored the use of plastic waste in making floor tiles. The study investigated the effect of different proportions of plastic waste and ash on the properties of the tiles, such as compressive strength, water absorption, and abrasion resistance. The results showed that adding plastic waste and ash improved the properties of the tiles, making them suitable for flooring applications.

Using plastic waste in flooring offers several advantages, including sustainability, resource conservation, cost-effectiveness, and design flexibility. However, there are also challenges associated with this approach, such as quality control, contamination, and aesthetics (Ilyas et al., 2018). Therefore, further research is needed to explore the optimum solutions for managing plastic waste in flooring materials.

2.3.1 Types of Plastic Waste Used in Flooring

Various types of plastic waste are used in producing flooring materials. The choice of plastic type depends on the desired properties of the flooring, such as durability, flexibility, and resistance to heat and chemicals. Table 2.3 provides a comprehensive comparison of different types of plastic waste used in flooring, such as:

(a) Low-Density Polyethylene (LDPE): LDPE is used to manufacture plastic-sand composite materials like floor tiles. It acts as a binding material to replace cement and incorporate natural sand (Soni et al., 2022).

(b) High-Density Polyethylene (HDPE): HDPE is used as shredded and recycled plastic waste in making floor tiles. It is also used in the production of foam floors due to its different densities ((Raguraman et al., 2022); (Soni et al., 2022)).

(c) Polyethylene Terephthalate (PET): PET is used to produce flooring materials. It is known to be used in recycled form to develop specific polyester flooring products. PET can sometimes absorb odor and flavor from foods and drinks that are stored in them. Items made from this plastic are commonly recycled (Modhe et al., 2022; Lamba et al., 2021).

(d) Polypropylene (PP): PP is often used for garage floor tiles due to its durability, load rating properties, and chemical resistance. It is a lightweight, strong, and flexible plastic that is resistant to high heat of up to 200 degrees Celsius (Lamba et al., 2021)

(e) Polyvinyl Chloride (PVC): PVC is commonly used in flooring. It can be rigid or flexible, and with the addition of phthalates, it becomes softer and more flexible, making it useful in flooring. PVC flooring is inexpensive and versatile, and chlorinated PVC is resistant to fire, oils, and many chemicals.

Plastic waste is a potential alternative to conventional materials for flooring applications, as it can offer various advantages such as cost-effectiveness, environmental sustainability, and versatility. However, different types of plastic waste have different properties that affect their suitability and performance as flooring materials. Table 2.3 compares the properties of five common types of plastic waste used in flooring: low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), and polyvinyl chloride (PVC).

Table 2.3: Comparison of properties of different types of plastic waste in flooring

Type of Plastic Waste	Properties	References
Polyvinyl Chloride (PVC)	High durability, chemical resistance, dimensional stability, and fire resistance.	(Patil et al., 2008)
Polyethylene Terephthalate (PET)	Good compressive strength, flammability resistance, and water absorption	(Soni et al., 2022)
High-Density Polyethylene (HDPE)	Good compressive strength, flammability resistance, and water absorption	(Soni et al., 2022)
Low-Density Polyethylene (LDPE)	Good compressive strength, flammability resistance, and water absorption	(Soni et al., 2022)
Polypropylene (PP)	Strong, flexible, and resistant to chemicals	(Patil et al., 2008)

2.3.2 Applications of Plastic Waste Used in Flooring

The application of plastic waste in flooring, particularly in concrete, has been gaining traction due to its environmental and functional benefits. One of the primary applications of plastic waste in concrete flooring is as a replacement for traditional aggregates. Plastic aggregates are created by grinding plastic waste into small particles. These aggregates can then be mixed with cement to produce lightweight concrete or replace traditional aggregates. This technique significantly reduces the carbon footprint associated with concrete production and helps manage plastic waste (Da Silva et al., 2021).

Plastic waste can also be used as fiber in cement composites, which does not adversely affect the compressive strength of the concrete. In fact, research has shown that using recycled plastic as fibers in cement composites can control plastic shrinkage cracking and improve the thermal properties of cement-based materials. This application is particularly beneficial in subfloor and sub-pavement construction, where it can enhance the stiffness and load-bearing capacity of the pavement (Da Silva et al., 2021). Another application of plastic waste in concrete flooring is as a partial replacement for sand. For instance, Polyethylene Terephthalate (PET), a common type of plastic waste, has been used as a replacement for sand in concrete due to its low apparent density, low density, and very low water absorption (Almeshal et al., 2020). This application can reduce the quantity of cement and sand by their weight, hence decreasing the overall cost of construction (Jalaluddin, 2017).

Plastic waste can also be incorporated into decorative concrete floors to create unique and sustainable designs. For example, bits of recycled plastic can be included in stained concrete floors, offering a customizable, durable, and eco-friendly flooring option (Jalaluddin, 2017). In conclusion, plastic waste has found various applications in concrete flooring, from replacing traditional aggregates and sand to being used as fiber in cement composites and as a decorative element. These applications contribute to environmental sustainability and enhance the properties of concrete, making it a viable option for flooring applications. Table 2.4 presents a comprehensive overview of the applications of plastic wastes in concrete, as investigated by various researchers.

Table 2.4: Applications of plastic wastes in concrete

Researcher	Type of recycled plastic used	Application in Concrete
Dachowski, 2016	High impact polystyrene and Foamed glass	Different amount of additives (from 5% to 25% by weight relative to cement).
Baskar and Senthil, 2015	High-impact polystyrene with a maximum size of 12.5 mm, the fineness modulus and specific gravity for HIPS were 7.69 and 1.29, respectively. The density of Eplastic was 595.30 kg/m^3.	Coarse aggregate replacement by volume with HIPS% of (0, 10, 20, 30, 40, 50).
Araghi et al., 2015	Ground PET particles of 7 mm were used with a unit weight of 464 kg/m^3, and the specific gravity was 1.11 g/cm^3	Replaced Natural aggregate with PET particles by 5%, 10%, and 15%.
Saikia and Brito, 2012	Three different types of plastic particles were used: • Shredded fine flaky plastic particles (PF), shredded coarse, flaky plastic particles (PC), heat-treated pellet-shaped spherical/cylindrical (PP).	Replaced natural aggregate with 5%, 10% and 15% each type (PF, PF, PC) of plastic particles.

Researcher	Type of recycled plastic used	Application in Concrete
Bhogayata et al., 2013	Metalized polyethene waste bags with sizes ranging from 1 mm to 2 mm.	0.5, 1.0 and 1.5% of plastic fibers were used in concrete by volume.
Rai et al., 2012	Plastic flakes replaced fine aggregate	0, 5, 10, and 15 percent of plastic flakes replaced sand.
Ismail and Al-Hashmi, 2010	Plastic waste granules	Fine aggregate was replaced with 5% and 10% granulated plastics. 0-50% iron was an admixture.

2.3.3 Advantages of Using Plastic Waste in Flooring

Using plastic waste in flooring materials offers several advantages, including sustainability, resource conservation, cost-effectiveness, and design flexibility. Studies have shown that using plastic waste in flooring materials can lead to reduced costs, waste reduction, and innovative recycling practices. Plastic waste can be easily recycled and reused in producing floor tiles, contributing to a sustainable approach for cleaner production (Soni et al., 2022). Additionally, incorporating plastic waste in flooring materials can lead to cost efficiency, resource efficiency, and waste reduction, making it an environmentally friendly and economically viable solution (Patil et al., 2008).

Furthermore, using plastic waste in flooring materials can create value-added products by recycling waste plastics, contributing to the development of sustainable building materials. Using waste plastics in construction industries reduces the requirement for fresh raw materials, lowering construction costs and improving environmental conditions. Additionally, incorporating plastic waste in floor tiles provides a new approach to plastic waste management, offering a viable solution for the recycling and utilization of waste plastics (Soni et al., 2022).

2.3.4 Challenges of Using Plastic Waste in Flooring

There are several difficulties when using plastic waste for flooring. An important concern is the photodegradation of plastic caused by direct sunlight, resulting in decreased durability and lifespan of the flooring tiles. Moreover, plastic waste exhibits low electrical conductivity, which can be a drawback in specific contexts (Patil et al., 2020). Another obstacle lies in the segregation of plastic waste from other categories of waste. According to Modhe et al. (2022), to facilitate the tile-making process, it is necessary to categorise plastic waste into various types, which can be a time-consuming and labor-intensive task.

Soni et al. (2022) stated the hazardous effects and challenging disposal of plastic waste present substantial environmental concerns. Plastic requires thousands of years to undergo decomposition, and the improper disposal of plastic waste is a significant issue (Raguraman et al., 2022). Furthermore, the process of converting plastic waste into tiles poses both difficulties and potential advantages. Although the process can result in tiles that are less likely to catch fire and have increased resistance to stretching, plastic solid waste (PSW) continues to pose difficulties for societies, regardless of their technological progress and awareness of sustainability (Dhawan et al., 2019).

Finally, manufacturing tiles from plastic waste may encounter technical obstacles. Obtaining the optimal combination of plastic and other substances, such as sand or cement, to guarantee the tiles' robustness and longevity can pose a challenge (Parangi et al., 2020). These challenges underscore the necessity for additional investigation and advancement in utilising plastic waste for flooring purposes. Notwithstanding these obstacles, the prospective ecological advantages of repurposing plastic waste into flooring materials render it a promising domain for future investigation. Figure 2.1 illustrates the main challenges of using plastic waste in flooring, which include the environmental, social, and economic impacts of plastic production, consumption, and disposal.

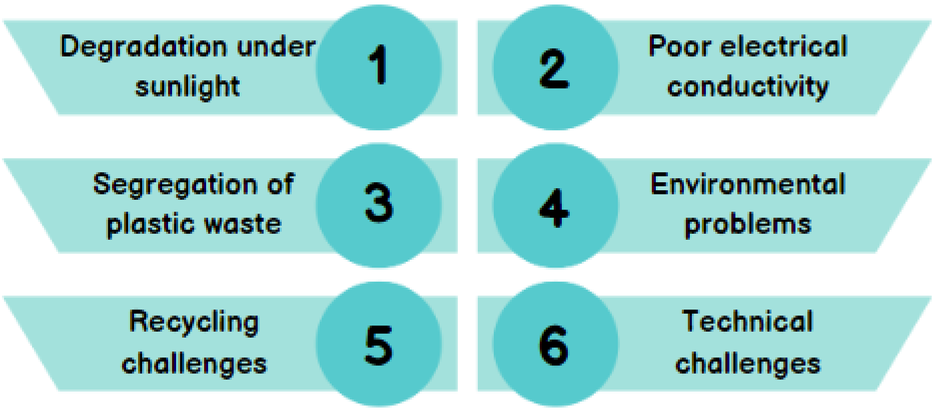

Figure 2.1: Challenges of using plastic waste in flooring

The previous section discussed the utilization of plastic waste in flooring applications, which can offer various advantages such as cost-effectiveness, environmental sustainability, and versatility. The next section focused on processing green concrete tiles incorporating plastic waste. The section described the methods and techniques used to produce concrete tiles that contain plastic waste as a partial or full replacement of natural aggregates.

2.4 Processing of Green Concrete Tiles Incorporating Plastic Waste

The production of environmentally-friendly concrete tiles utilizing plastic waste as coarse aggregates encompasses various stages, such as material preparation, mixing, molding, and curing, as illustrated in Figure 2.2. Initially, it is imperative to gather and organize the necessary materials. It entails gathering plastic waste and transforming it into a state suitable for utilization as coarse aggregates. The plastic waste can be processed through the method of shredding or grinding, producing small fragments comparable in size to the conventional coarse aggregates commonly employed in concrete (Almohana et al., 2022; Kumar & Kumar, 2023).

Figure 2.2: Plastic aggregate manufacturing process (Almohana et al., 2022).

After the plastic waste has been processed, it can be blended with other constituents of the concrete. The concrete mixture commonly comprises cement, water, and aggregates. In this scenario, the plastic waste substituted a fraction of the conventional coarse aggregates. The optimal results were obtained when using a ratio of 30:70 of low-density polyethylene (LDPE) plastic waste to sand, as determined by a study conducted by Iftikhar et al. in 2023.

Once the components are completely blended, the concrete can be poured into molds to shape the tiles. The molds can vary in shape and size, contingent upon the intended end product. As stated by Risson et al. (2021), to ensure the complete filling of all corners and the elimination of any air pockets, it is necessary to compact the concrete within the mold.

The last stage involves curing, which refers to the process of preserving the appropriate moisture content and temperature conditions of concrete to facilitate hydration, the chemical reaction between cement and water. This process facilitates the solidification and enhancement of the concrete. Curing can be achieved through various methods, such as creating a high-humidity environment, applying water through spraying, or utilizing curing compounds. The duration of the curing process may differ, but it generally lasts for a minimum of 28 days (Alhazmi et al., 2021).

2.4.1 Preparation of Materials

Preparing materials for green concrete tiles incorporating plastic waste involves several steps. The first step is the collection and preparation of plastic waste. The process involves gathering plastic waste, cleaning it, and crushing it into the desired aggregate size. Plastic waste can include various types, such as polyvinyl chloride (PVC), polypropylene, and polyethylene (Lamba et al., 2021). The plastic waste is then used as a replacement for natural aggregates in the concrete mix.

According to Sau et al. (2023), using plastic waste as a replacement for natural aggregates can help reduce environmental hazards, social issues, and health risks associated with the extraction of natural aggregates. Furthermore, the type of plastic waste used can affect the properties of the concrete. For example, different types of plastic waste, such as polyethylene (PE) and polypropylene (PP), can have different effects on the properties of the concrete, including its strength and durability. Figure 2.3 shows the appearance of HDPE waste aggregates.

Figure 2.3: HDPE waste aggregates

2.4.2 Mixing of Green Concrete Tiles

Blending green concrete tiles that integrate plastic waste encompasses multiple stages. The initial stage involves preparing the plastic waste to be used as coarse aggregates. The process entails gathering plastic waste, its subsequent purification, and finally, its fragmentation into the intended aggregate dimensions (Almohana et al., 2022; Lamba et al., 2021).

Subsequently, it is necessary to combine the materials. The concrete mixture typically comprises cement, water, fine aggregate (typically sand), and coarse aggregate (in this instance, processed plastic waste). The precise ratios of these constituents may vary based on the desired characteristics of the end product, but a typical blend could consist of one part cement, two parts sand, and four parts coarse aggregate (Baciu et al., 2022).

The materials are thoroughly blended until a homogeneous mixture is attained. An uncomplicated method to incorporate plastic as an aggregate in the mixture is directly adding plastic to the concrete during the mixing process. This straightforward technique enables the production of batches (Almohana et al., 2022). It is crucial to acknowledge that the choice of plastic material can impact the concrete's characteristics.

2.4.3 Molding of Green Concrete Tiles

The production process of green concrete tiles, which utilize plastic waste as coarse aggregates, comprises multiple stages. Once the components are fully blended, the concrete mixture is discharged into molds, which can vary in shape and size depending on the intended result (Sau et al., 2023). Compacting the concrete in the mould is necessary to ensure the complete filling of all corners and eliminating any air pockets. Ensuring the concrete mix fills the mold is essential for the strength and durability of the final product, as it eliminates voids (Lamba et al., 2021). Utilizing plastic waste as a substitute for natural aggregates has the potential to impact the process of molding. Plastic waste can impact the workability of the concrete mixture, thereby affecting the ease of pouring and compacting the mixture (Alqahtani & Zafar, 2023).

Furthermore, the specific type of plastic waste utilized can also impact the end product's characteristics. Various forms of plastic waste, such as polyethylene (PE) and polypropylene (PP), can exert distinct influences on the characteristics of concrete, including its strength and durability (Sau et al., 2023; Alqahtani & Zafar, 2023; Gour et al., 2022). Once the concrete mix has been poured into the moulds, it must be allowed to cure. The duration for the solidification process may differ based on the particular composition employed and the prevailing environmental circumstances. Once the concrete tiles have been set, they are extracted from the moulds and allowed to undergo the curing process (Almohana et al., 2022).

2.4.4 Curing of Green Concrete Tiles

Effective curing is essential for regulating the rate of moisture loss and temperature in concrete during the cement hydration and evaporation process (Hamzah et al., 2020). The inclusion of plastic waste in concrete has been demonstrated to impact both the curing process and the ultimate characteristics of the concrete. An effective method for achieving a cure is through the utilization of self-curing agents. Green synthetic aggregates can serve as self-curing agents in concrete, reducing water evaporation and enhancing water retention capacity in the material. The continuous hydration process results in the formation of denser concrete (Hamzah et al., 2020).

The curing process can also be influenced by the specific type of plastic waste utilised. Concrete containing waste-polyethylene (PE) and waste-polyethylene-terephthalate (PET)-based aggregate showed an increase in compressive strength as it aged, with better results seen at 28 days compared to 7 days (Sau et al., 2023). Alqahtani and Zafar (2023) discovered that the compressive and flexural strength of concrete containing synthetic plastic aggregate increased as the curing period extended from 28 to 90 days.

Introducing plastic waste into concrete can assist in reducing heat-induced concrete spalling by relieving internal pressure by melting polymers (Röhden et al., 2020). This can be especially advantageous during curing, which frequently entails heat treatment. Nevertheless, it is crucial to acknowledge that the compressive strength of PET aggregate diminishes with the escalation of plastic aggregate substitution, irrespective of the duration of curing (Ahmad et al., 2022).

Table 2.5 compares different types of plastic waste used in flooring applications. The table provides an overview of the types of plastic waste and the effects they have on the curing process when used to produce green concrete tiles. This information is crucial in understanding how different types of plastic waste can influence the properties and performance of green concrete tiles.

Table 2.5: Type of plastic waste used and effect on curing process

Type of Plastic Waste	Effect on Curing Process	References
Polyethylene (PE)	Compressive strength of concrete incorporating waste-PE improves with curing age	(Sau et al., 2023)
Polyethylene Terephthalate (PET)	Compressive strength of PET aggregate reduces as the replacement of plastic aggregate increases, regardless of the curing time	(Jibrael & Peter, 2016)
High-Density Polyethylene (HDPE)	Compressive and flexural strength of concrete incorporating fabricated plastic aggregate increases with an increase in the curing period from 28 to 90 days	(Sau et al., 2023)
Polypropylene (PP)	PP can decrease the workability of the concrete and the compressive strength, but it can increase the resistance to abrasion and the impact energy of the concrete	((Reda et al., 2023); (Tanlı et al., 2022))

2.4.5 Testing Methods

There are multiple steps involved in the testing procedures to evaluate the dimensional accuracy and installation stability of green concrete tiles made from plastic waste. Initially, the tiles are manufactured using varying proportions of natural and plastic waste aggregate. After manufacturing, the tiles undergo a series of tests to assess their dimensional precision and stability during installation.

The assessment of dimensional accuracy can be conducted by employing tools such as callipers and micrometers to measure the tiles' length, width, and thickness precisely. The measurements are subsequently compared to the intended dimensions to ascertain their accuracy. This procedure resembles the assessment of production process capability employed in 3D printing (Zaneldin et al., 2021).

The stability of the installation can be assessed by conducting load-bearing tests, in which the tiles are exposed to different loads to determine their capacity to retain their form and structural integrity. These tests may encompass compression, flexural, and tensile strength tests. An investigation conducted by Ivan et al. (2023) employed flexural strength and compressive strength tests to assess the mechanical properties of tiles produced from Polyethylene Terephthalate (PET) plastic waste and alluvial sand.

Furthermore, the tiles can undergo water absorption tests and porosity tests to evaluate their durability and appropriateness for various environments ((Ivan et al., 2023); (Sau et al., 2023)). The tests adhere to the ISO 62: 2008 standard, which sets a maximum water absorption rate of 6% for roof tiles (Ivan et al., 2023).

The Ultrasonic Pulse Velocity (UPV) test is another significant testing method. This non-destructive test aims to assess the integrity and uniformity of the concrete tiles. The UPV test quantifies the speed of an ultrasonic wave pulse propagating through the concrete. The duration for the pulse to dissipate through the test specimen is recorded, and the ratio of the test specimen's width to the time taken by the wave pulse to dissipate is computed (Yang et al., 2022).

Furthermore, Young's modulus and the testing element's density depend on the ultrasonic wave speed (Yang et al., 2022). This test is valuable for forecasting a substance's sound-insulating properties (Kougnigan et al., 2023) and approximating the comprehensive mechanical performance of recycled aggregate self-compacting concrete (Espinosa et al., 2023). Table 2.6 thoroughly compares different testing methods employed in producing green concrete tiles that utilize plastic waste as aggregates.

Table 2.6: Comparison of testing techniques for processing green concrete tiles

Testing Technique	**Standards**	**Purpose**	**References**
Load-Bearing Test (Compressive Strength Test)	ASTM C39/C39M	To evaluate the load-bearing capacity of green concrete tiles.	(Senthilkumar et al., 2023); Qasim et al., 2021)
Load-Bearing Test (Tensile Strength Test)	ASTM C496/C496M	To assess the tensile durability of the tiles, which affects crack resistance	(Senthilkumar et al., 2023); Qasim et al., 2021)
Load-Bearing Test (Flexural Strength Test)	ASTM C78/C78M	To determine the tiles' bending strength, which is important for handling and installation	(Senthilkumar et al., 2023); Qasim et al., 2021)
Water Absorption Test	ASTM C642	To evaluate the porosity and potential for water damage or mold growth	(Bamigboye et al., 2021; Fahim et al., 2023)
Ultrasonic Pulse Velocity (UPV) Test	ASTM C597	Non-destructive testing to detect internal flaws or inhomogeneities	(Agrawal et al., 2023; Romagnoli, 2007)
Microstructural Analysis (SEM)	-	To examine the microstructure of the concrete	(Paul et al., 2023)
Dimensional Accuracy Test (Vernier Calipers/ Micrometer)	ASTM C490, EN 12504-4	To measure the length, width, and thickness of the tiles and compare them to the intended dimensions	(Xu et al., 2023)

In this study, the load-bearing and dimensional accuracy tests were conducted to determine the compressive strength and dimensional stability of the potential of the detachable concrete tiles from hybrid natural and plastic waste aggregates.

2.4.6 Formulation Effects on Plastic Waste in Concrete Tiles

The formulation significantly influences the properties of green concrete tiles, specifically the ratio of natural to plastic waste aggregate. Studies have demonstrated that substituting a portion of sand with residual high-density plastic can create prefabricated cement tiles (Gaibor et al., 2019). Moreover, various types of waste plastics, such as low-density polyethylene, high-density polyethylene, and polyethylene terephthalate can be binding agents to replace cement in producing floor tile samples (Soni et al., 2022).

The proportion of plastic waste to natural aggregate in the composition can impact the tiles' dimensional stability, mechanical strength, and durability. An investigation discovered that tiles containing over 20% plastic exhibited a water absorption rate below 2.25% and a porosity rate below 4.37%, indicating excellent dimensional stability and durability (Ivan et al., 2023).

The composition of the tiles can also influence their environmental footprint. Utilizing plastic waste in the composition can mitigate the environmental risks associated with concrete waste disposal and foster the generation of eco-friendly concrete. Moreover, incorporating plastic waste into the formulation can effectively decrease the need for new materials, reducing construction expenses and enhancing environmental conditions (Soni et al., 2022).

2.5 Design of Flooring Tiles and Installation

Flooring tile design and installation can be categorized into two main types: conventional design and installation and detachable design and installation.

2.5.1 Conventional Design and Installation

Flooring tiles are available in various standard modular sizes and shapes, such as square, rectangular, and hexagonal, which facilitate efficient installation. Typical dimensions include 300x300 mm and 600x600 mm. The design considerations encompass specifications, area layout, tile format, and necessary stability (Ariffin et al., 2018). The utilization of parametric and modular computer-aided design methodologies aids in the optimization of tiles for particular applications (Wu et al., 2021; Kunkhet & Chudasri, 2022).

Conventional installation methods involve using wet mortar or adhesives to attach tiles to substrates such as concrete or screed securely. Tiles are arranged sequentially, with spacers, to ensure consistent spacing between them for the grout joints. This durable adhesion facilitates the transfer of loads but restricts the ability to replace individual tiles in the future. The procedure depends on the meticulous aptitude for accurate alignment (Ariffin et al., 2018).

ANSI and TCNA, industry standards organizations, establish specifications regarding materials, properties, dimensions, and installation methods to guarantee the quality and safety of tiles (Carothers, 2022). Complying with these standards is of utmost importance. To summarise, traditional tile design necessitates interlocking features or bonding to adjacent tiles or substrates to limit movement. Although the integrated floor surface ensures stability, it impedes the ability to detach and access after installation. Adhering to standards provides guidance for selecting and installing tiles in the most efficient manner.

2.5.2 Detachable Design and Installation

Detachable tile systems allow for the removal and replacement of individual tiles without disturbing adjacent tiles or the substrate. This is enabled by loose-lay installation rather than permanent bonding. Common detachable formats include interlocking, mortise-and-tenon, and magnetic tiles. The installation methodology involves laying tiles with gaps to accommodate connectors and account for expansion. Mechanical locking mechanisms then securely join tiles, as shown in Figure 2.4. Gasketed joints prevent debris intrusion while allowing movement. The modular, floating floor can be disassembled later by disengaging the connections.

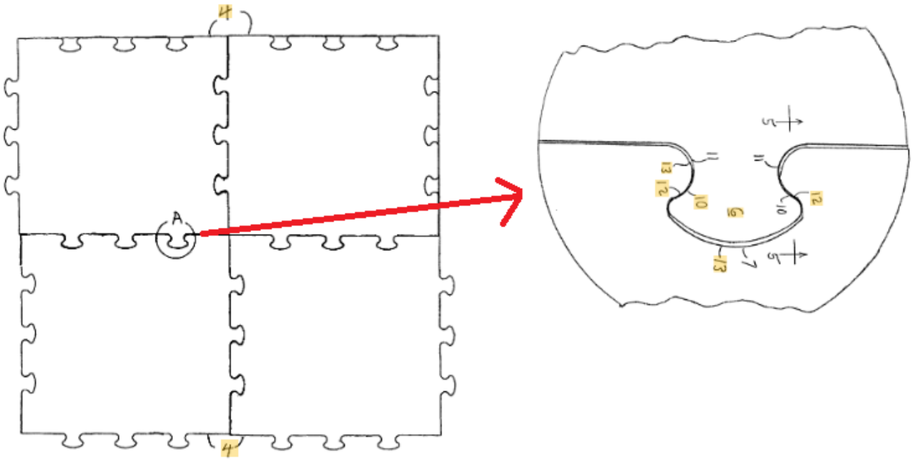

Figure 2.4: Puzzle interlocking mechanism in floor tiles

Detachable systems eliminate adhesive usage and reliance on precise fitting during placement. Accessibility to the subfloor is enabled for maintenance and concealed infrastructure upgrades. However, the loose-lay method is more prone to vibration and vertical displacement unless interfaces are properly designed. Thus, the detachable tile approach focuses on reversible, accessible installation rather than monolithic fusion with the substrate. This facilitates adaptability and tile replacement, though stability may be slightly reduced.

2.6 Performance of Green Concrete Tiles for Flooring

The performance of green concrete tiles for flooring is influenced by several critical factors. These include workability and physical properties, mechanical strength (especially compressive strength), dimensional accuracy, morphological properties (such as particle size distribution and surface texture), and density and porosity. Balancing these factors ensures the development of durable, high-performance tiles suitable for various flooring applications.

2.6.1 Workability and Physical Properties

Green concrete tiles, particularly those incorporating plastic waste as aggregates, exhibit unique physical properties. Plastic waste as aggregates in concrete has been found to reduce the overall density of the concrete, with studies indicating a decrease of about 10% in densities (Shiuly et al., 2022). This reduction in density can be attributed to plastic's lower density than traditional aggregates like sand or gravel. This property can be advantageous in flooring applications where weight considerations are important.

The water absorption values of concrete tiles with plastic waste aggregates can be higher than those of conventional concrete. For instance, a study reported that mortar specimens with 100% PET aggregates had more water absorption values (Sau et al., 2023). This could be due to the porous nature of some plastic materials, which can absorb water when exposed. However, this property might affect the durability of the tiles in wet conditions, and it's important to consider this during the formulation process.

The workability of the concrete also increases with the increased ratio of plastic waste to natural aggregates (Shiuly et al., 2022). One of the most important things about concrete is how easily it can be mixed, moved, cast, and finished without separating. Numerous tests, like the slump, inverted slump cone, and K-test, can be used to determine the workability of concrete. The water-cement ratio (w/c), the plastic shape, and the PWA replenishment level are some factors that influence the droop of PWA concrete. The amount of free water in the concrete is impacted by PWA, which impacts the concrete's mechanical qualities. Numerous outcomes have been produced using these analyses. Increasing the substituted plastic aggregates (SPA) decreased fresh concrete's slump in most experiments (Almeshal et al., 2020). This can be beneficial during installation, making the tiles easier to handle and install. Table 2.7 provides a comprehensive overview of the physical properties of green concrete tiles. These properties include density, compressive strength, water absorption, and thermal conductivity.

Table 2.7: Physical properties of green concrete tiles

Property	**PET**	**PP**	**PE**	**PVC**
Density	Lower by 5-12% (Sau et al., 2023)	Lower by 10-15% (Pavlík et al., 2019; Islam, 2022)	Lower by 5-15% (Belmokaddem et al., 2020); Awoyera et al., 2021)	Lower by 10-12% (Kathe et al., 2015)
Compressive strength	10-35 MPa (Almohana et al., 2022; Lamba et al., 2021))	15-40 MPa (Almeshal et al., 2020; Kathe et al., 2015)	10-50 MPa ((Sau et al., 2023); (Kathe et al., 2015))	20-45 MPa (Kathe et al., 2015)
Tensile/ flexural strength	Comparable or higher (Sau et al., 2023; Lamba et al., 2021)	Comparable or higher (Almeshal et al., 2020)	Comparable or improved (Almeshal et al., 2020; Kathe et al., 2015)	Comparable or higher (Kathe et al., 2015)
Thermal conductivity	0.3-0.8 W/mK (Almohana et al., 2022)	0.23 W/mK (Poonyakan et al., 2018)	0.1-1 W/mK (Almohana et al., 2022)	0.3-0.7 W/mK (Kathe et al., 2015)
Water absorption	Higher (Sau et al., 2023)	Higher (Alrshoudi et al., 2022)	Higher than conventional concrete (Belmokaddem et al., 2020)	Higher (Kathe et al., 2015)

2.6.2 Mechanical Properties and Compressive Strength

The mechanical properties of green concrete tiles utilizing plastic waste as aggregates are crucial for assessing their performance in flooring applications. These properties include compressive strength, tensile strength, flexural strength, and durability. The type of plastic waste used, its form, and the percentage incorporated into the concrete mix can significantly influence these mechanical properties. A study found that the inclusion of plastic waste in concrete can reduce mechanical properties due to the poor bond strength between the cement and plastic aggregate (Jaivignesh & Sofi, 2017). For example, concrete with recycled plastic particles (PP) decreased strength with increasing waste PP content. However, waste PP demonstrated better abrasion resistance than the control mix. Another study indicated that replacing 5% of sand with waste plastic increased the concrete's compressive, flexural, and split tensile strength (Reda et al., 2023).

The most significant of the several tests performed to assess the performance of concrete is its compressive strength. This one test covers many different concrete properties. Numerous factors are closely related to concrete's compressive strength. The compressive strength of concrete can be used to assess its quality. The water-to-cement ratio, plastic waste shapes and forms, and SPA all affect the compressive strength of plastic concrete. The use of Polyethylene Terephthalate (PET) particles in concrete has been shown to affect the physical and strength-related properties of the material. Adding PET particles can influence compressive strength, tensile strength, modulus of elasticity, flexural strength, and concrete shrinkage (Al-Luhybi & Qader, 2021). Similarly, the use of High-Density Polyethylene (HDPE) and electronic wastes as partial replacements for natural coarse aggregates has been found to positively affect the mechanical properties of the concrete (Nafees et al., 2023).

According to Almeshal et al., (2020), a few important variables may lower the compressive strength of PWA-contained concrete. Water blockages may stop the cement hydration reaction since PWA has a hydrophobic quality. Second, there is not much of a bond between the cement paste and the PWA's surface. Third, the higher air content and porosity of the concrete PWA. Compared to a traditional CA or FA, the PWA has a lower elastic modulus, which brings us to our final point—PWA aggregates exposed to the environment may eventually deteriorate.

However, optimizing the concrete formulation can mitigate the reduction in strength. For instance, adding steel fibers to concrete has been found to improve its mechanical properties (Jaivignesh & Sofi, 2017). The compressive strength of the concrete tiles can also decrease with the inclusion of plastic waste (Sau et al., 2023). This is due to the poor adhesion between the plastic waste-based aggregates and the cement (Sau et al., 2023). However, the compressive strength is still sufficient for most flooring applications, and the reduction in weight due to the inclusion of plastic waste can be a significant advantage in certain applications. In terms of flexural strength, studies have shown varying results. Some studies have reported a decrease in flexural strength with the inclusion of plastic waste (Jaivignesh & Sofi, 2017), while others have reported an increase (Alqahtani & Zafar, 2023). This discrepancy could be due to differences in the type and proportion of plastic waste used and in the formulation of the concrete.

2.6.3 Dimensional Accuracy

Dimensional accuracy is a critical factor in the performance of green concrete tiles for flooring. It refers to the consistency of the tile dimensions, which directly affects the ease of installation and the overall aesthetic of the finished floor. The dimensional accuracy of green concrete tiles can be influenced by several factors, including the formulation of the concrete mix, the molding process, and the curing conditions (Obaid et al., 2021; Saadoon et al., 2019; Al-Azzawi & Al-Azzawi, 2020).

Research has shown that using waste materials, such as ceramic tiles and plastic waste, as aggregates in the concrete mix can affect the dimensional stability of the resulting tiles. For instance, a study found that the optimum content of ceramic tile aggregate in concrete is around 10-20%. Beyond this level, the dimensional accuracy of the tiles may be compromised due to increased water absorption and porosity (Paul et al., 2023).

Plastic waste as a replacement for natural aggregates in concrete has decreased the composite concretes' compressive strength and unit weight (Sau et al., 2023). However, the impact resistance of the concrete is improved with the use of waste plastic aggregate (WPA), which has a significant capacity for absorbing energy and can effectively transmit impact stresses to the components (Sau et al., 2023). The dimensional accuracy of green concrete tiles using plastic waste as aggregates is a critical factor in their performance. The size and shape of the plastic waste-based aggregates do not significantly affect the strength of the tiles, but they can influence the dimensional accuracy (Lamba et al., 2021). A study found that using a 30% plastic waste ratio and 70% glass and sand resulted in high-quality floor tiles (Behera, 2018). This suggests that the ratio of plastic waste to other materials can be optimized to achieve the desired dimensional accuracy. However, it’s important to note that the adhesion between the plastic waste-based aggregates and the cement matrix can be poor, which may affect the dimensional stability of the tiles (Sau et al., 2023).

2.6.4 Morphological Properties

The morphological properties of green concrete tiles, which include particle size distribution, shape and surface texture, pore structure, density, and porosity, are critical factors that influence the performance and durability of the tiles. These properties are interconnected and can significantly affect the workability of the concrete mix, the compressive strength of the tiles, and their overall suitability for flooring applications.

Particle size distribution (PSD) is a key characteristic of the aggregates used in green concrete tiles. It affects the workability of the concrete mix, the density of the tiles, and the inter-particle voids within the concrete matrix. A well-graded aggregate with a continuous PSD can lead to a denser and more workable mix, as seen in the study of ceramic tile dust, which showed a composition of various particle sizes (Chong et al., 2022). The PSD of the aggregates should conform to specific standards to ensure the quality of the concrete tiles.

The shape and surface texture of the aggregates contribute to the mechanical interlock and bonding between the cement paste and the aggregates. Angular and rough-textured particles, such as those found in crushed tiles, can enhance the strength of the concrete due to better interlocking and bonding (Muwafaq et al., 2016). However, they may also increase the water demand of the mix. The surface texture of the tiles themselves is also important for functional and aesthetic purposes, as it can influence water runoff and slip resistance.

The pore structure of green concrete tiles is related to their durability and mechanical properties. The presence of pores and their distribution within the concrete matrix can affect the permeability, strength, and freeze-thaw resistance of the tiles. Factors influencing the pore structure include the type and proportion of aggregates, air void content, and the presence of admixtures ((Xiao et al., 2023); (Mendes et al., 2019)).

Density and porosity are closely related to the overall quality of green concrete tiles. Higher density typically indicates lower porosity, which can lead to improved strength and durability. Density, typically ranging between 2400 and 2900 kg/m^3 for aggregates used in concrete, is inversely related to porosity. Higher density often indicates lower porosity, improving the tiles' strength and durability (Paul et al., 2023).

Porosity, the percentage of void spaces in the concrete matrix, significantly impacts the water absorption and permeability of the tiles. These properties are critical for their performance in flooring applications. For instance, a study on pervious concrete found that the size of aggregates plays a crucial role in the porosity, permeability, and strength of the concrete mixes (Zhang et al., 2023). Table 2.8 concisely summarises the key morphological properties of green concrete tiles and their impact on the tiles' performance.

Table 2.8: Morphological properties of green concrete tiles

Morphological Properties	Description	Impact on Green Concrete Tiles	References
Particle Size Distribution	The spread of sizes of the aggregates used in the tiles	Influences the workability of the concrete mix, the density of the tiles, and the inter-particle voids within the concrete matrix	(Al-Azzawi & Al-Azzawi, 2020; Hassani et al., 2023)
Shape and Surface Texture	The form and angularity of the aggregate particles, the degree of roughness or smoothness of the tiles.	It affects the mechanical interlock and bonding between the cement paste and the aggregates. It influences the aesthetic and functional properties of the tiles, such as water runoff and slip resistance.	(Dang et al., 2022; Faridmehr et al., 2020)

Morphological Properties	Description	Impact on Green Concrete Tiles	References
Pore Structure	The presence and distribution of pores within the concrete matrix.	It impacts the permeability, strength, and freeze-thaw resistance of the tiles.	(Faridmehr et al., 2020; Hassani et al., 2023)
Density	The mass per unit volume of the tiles.	A higher density typically indicates lower porosity, improving strength and durability.	(Awoyera et al., 2016; Maheswaran et al., 2023)
Porosity	The percentage of void spaces in the concrete matrix.	It affects the water absorption and permeability of the tiles, which are critical for their performance in flooring applications.	(Awoyera et al., 2016; Maheswaran et al., 2023)

CHAPTER 3
METHODOLOGY

3.0 Introduction

This chapter outlines the methodology used in the project, which aims to fabricate detachable green concrete tiles using Portland cement reinforced with hybrid natural and plastic waste aggregates. The process also investigates the effect of the formulation ratio of the hybrid aggregates on the mechanical and physical structure of the green concrete tiles. It assesses their compressive strength, dimensional accuracy and installation stability.

3.1 Overview

Figure 3.1 shows the methodology flow chart for this research project. All the activities and important parameters are shown in the flow chart. This chapter covers the methodology of this research, which is divided into several subsections.

1. Raw materials
2. Formulation Ratio
3. Tile Fabrication
4. Testing and Analysis
5. Data Analysis

3.1.1 Flow Chart

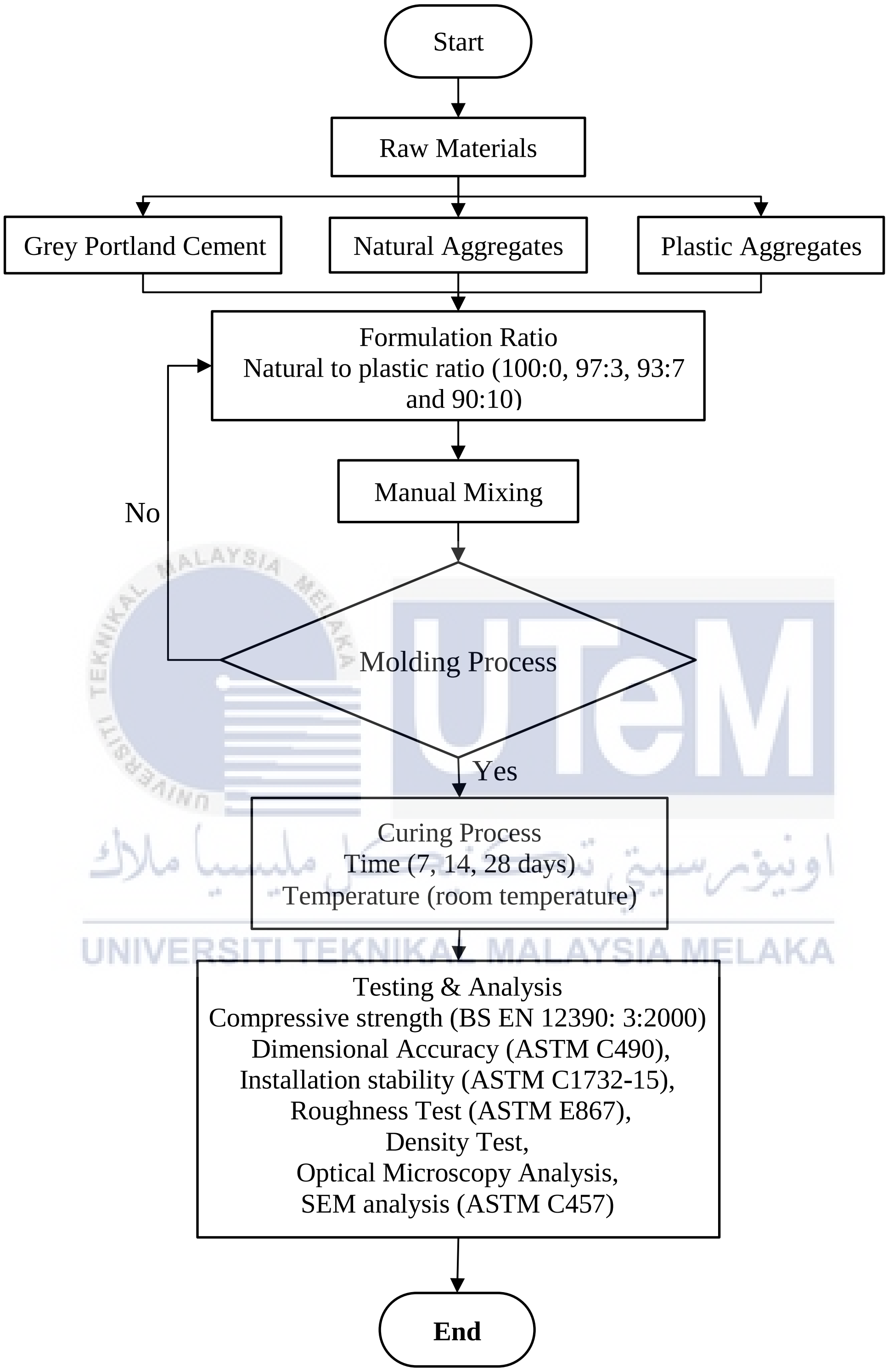

Figure 3.1: Flow chart

3.2 Raw Materials

The first step in the fabrication of green concrete tiles involves the preparation of raw materials. The raw materials required to make concrete tiles are Portland cement, natural aggregates, and plastic aggregates.

3.2.1 Portland Cement

Grey Portland cement was used as the primary binder for the green concrete tiles. The cement bag is shown in Figure 3.2. The cement was sourced from a reliable supplier to ensure consistent quality. Prior to its use, the cement was sieved to remove any lumps and stored in a dry place to prevent moisture absorption. Table 3.1 provides an overview of the basic chemical composition of the Grey Portland cement used in this project.

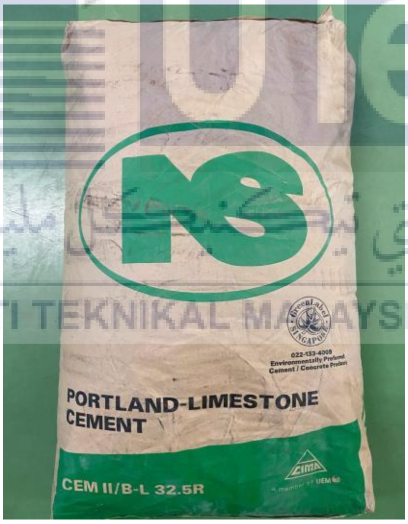

Figure 3.2: Grey portland cement 50kg

Table 3.1: The properties of grey Portland cement

Properties	Description
Composition	Clinker (65-79%), Limestone (21-35%), Other Constituents (0-5%)
Setting Time	60 - 600 minutes
Fineness	3500 - 4000 Blaine

Properties	Description
Strength	20 - 62.5 MPa
Soundness	Maximum 10 mm
Workability	Good

3.2.2 Natural Aggregates

This project's specific type of sand was granule sand with a 2-4 mm particle size, as shown in Figure 3.3. This sand is a naturally occurring granular material composed of finely divided rock and mineral particles. Its strength and durability are common attributes that make it suitable as a concrete component. The properties of the sand, such as its fineness modulus, specific gravity, and absorption, are detailed in Table 3.2.

Figure 3.3: Granule sand

Table 3.2: Properties of granule sand

Properties	Granule Sand
Particle Size	2-4 mm
Fineness Modulus	2.5-3.5
Specific Gravity	2.65-2.75
Absorption	0.5-1.5%

3.2.3 Plastic Waste Aggregates

The plastic aggregates were derived from recycled high-density polyethylene (rHDPE), as depicted in Figure 3.4. The plastic waste was thoroughly cleaned and then shredded into small pieces using a crusher. These shredded pieces were subsequently processed into a granular form, rendering them suitable for use as an aggregate in the green concrete tiles.

Figure 3.4: Crushed recycled high-density polyethylene (rHDPE)

Figure 3.5: Shredded rHDPE process using crusher

Table 3.3 presents the properties of High-Density Polyethylene (HDPE) plastic waste. These properties are crucial in understanding the behavior of these materials when used as aggregates in the production of green concrete tiles.

Table 3.3: Properties of rHDPE plastic waste

Property	**rHDPE (Recycled High-Density Polyethylene)**
Density (g/cm3)	0.94-0.97
Melting Point (°C)	120-180
Tensile Strength (MPa)	20-37
Elongation at Break (%)	100-600
Hardness (Shore D)	60-70

These raw materials were combined in various ratios to form the green concrete mix in the subsequent step. The specific formulation ratios were determined based on the objectives of the research and the desired properties of the green concrete tiles, as further explained in Section 3.3. The preparation process of the raw materials was crucial as it directly impacted the quality of the final product. Therefore, it was carried out with utmost care and precision.

3.3 Formulation Ratio

The formulation ratio refers to the proportion of natural to plastic waste aggregates used to produce green concrete tiles. The specific ratios used were based on the weight percentage of the aggregates. Table 3.4 details the three combinations of natural and plastic waste aggregates that were evaluated, outlining the exact proportions utilized.

Table 3.4: Natural to plastic waste aggregates ratio

Formulation	**Natural Aggregates (Sand ~ 4 mm)**	**HDPE**
Natural to plastic aggregates ratio	97	3
	93	7
	90	10

The plastic aggregates are derived from recycled waste high-density polyethylene (HDPE). The chosen ratios provide a comprehensive understanding of how the proportion of natural to plastic waste aggregates affects the properties of green concrete tiles. The results were intended to guide the selection of the optimal formulation ratio for producing dimensionally accurate and easily installable tiles.

3.4 Tile Fabrication

The fabrication process of green concrete tiles began with the manual mixing process, where a precise mix of concrete was prepared, followed by the molding process, which involved pouring the mix into molds and ensuring uniformity through vibration and smoothing techniques. The steps were concluded with the curing process that detailed the time-dependent hardening phase crucial for achieving the tiles' optimal strength and stability.

3.4.1 Manual Mixing Process

The fabrication of green concrete tiles began with preparing the concrete mix. The main components of the mix were Grey Portland cement, a hybrid aggregate composed of natural and plastic waste materials, and water. The ingredients were mixed in a ratio of 1:2.5:3, respectively, to achieve maximum strength. All ingredients were individually weighed in a container, as shown in Figure 3.6.

Figure 3.6: Concrete mix preparation

The hybrid aggregate was prepared for saturated surface dry (SSD) conditions before mixing. Water was added to the mix, with the least amount used, which would still give a workable mix. The water used was clean and fresh, not salty. The mix was then thoroughly mixed until a uniform consistency was achieved. The fresh concrete tile mixture is shown in Figure 3.7.

Figure 3.7: Uniform of concrete mixture

3.4.2 Molding Process

The mixture was poured into molds to shape the tiles. A plastic mold based on the desired size and pattern for the detachable final product, as depicted in Figure 3.8, was used. The concrete mix, once ready, was poured into the molds, as shown in Figure 3.9 (a), ensuring that it was evenly distributed to avoid any inconsistencies in the tile's surface or thickness. The molds were then manually shaken to remove air pockets and ensure a compact and uniform tile. After shaking, the surface was smoothed to eliminate any imperfections, as illustrated in Figure 3.9 (b). The tiles were then left to set, achieving the form of the final product ready for the curing stage. This meticulous process was critical to ensure the quality and uniformity of the green concrete tiles. The final products from once the molds were removed, as displayed in Figure 3.10. The figure showcases the successful molding of the tiles into the desired shapes and sizes.

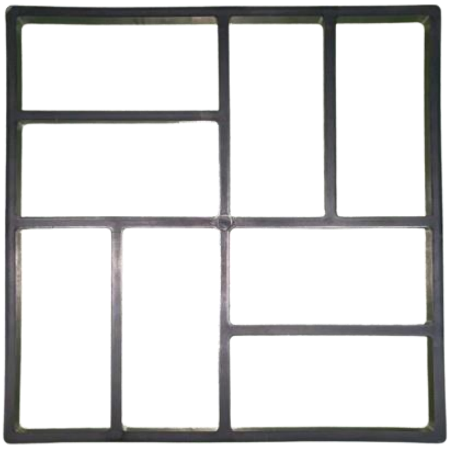

Figure 3.8: Detachable molds for concrete tiles

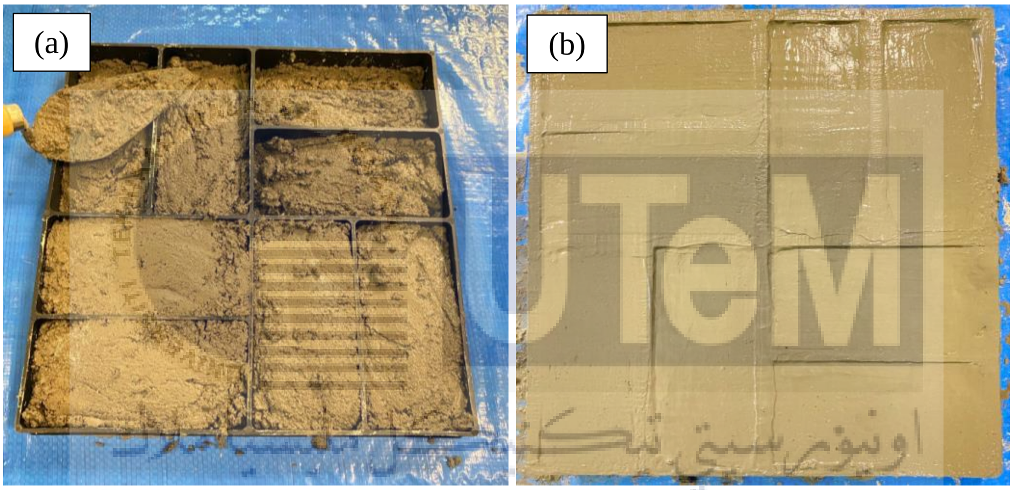

Figure 3.9: Images of (a) pouring mixture into molds process and (b) even distribution of concrete in molds

Figure 3.10: Concrete tiles final product

3.4.3 Curing Process

Once the tiles were molded, they underwent a curing process. The curing process was performed in water, called water curing, to maintain hydration. The tiles were immersed in water, as shown in Figure 3.11. The curing process was observed over three distinct durations: 7 days, 14 days, and 28 days. These timeframes were chosen to provide a comprehensive understanding of the curing process over a short-, medium-, and long-term period. Each duration was analyzed separately to observe the changes and developments in the curing process. The curing process was conducted at room temperature, which was recorded to be within the range of 22°C to 32°C. This range represents typical ambient temperatures, providing a realistic environment for the curing process. However, the impact of these temperatures on the curing process was not analyzed. Table 3.5 illustrates the estimated effect of curing duration on the design strength achieved in producing concrete tiles.

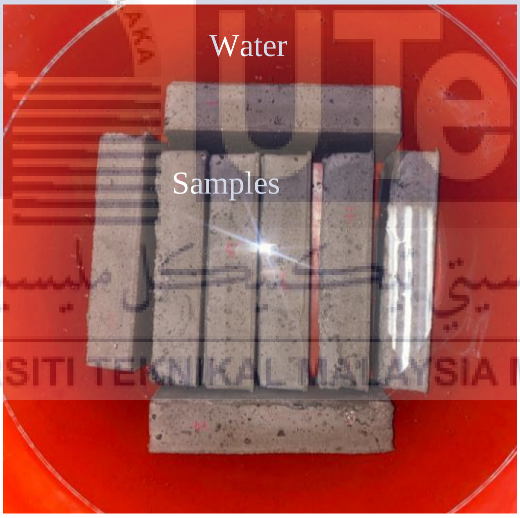

Figure 3.11: Curing process of tiles

Table 3.5: Effect of curing duration on design strength achieved (Abeysinghe et al., 2021).

Curing Duration	Design Strength Achieved
7 days	50%
14 days	75%
28 days	90%

3.5 Testing and Analysis

This section presents a detailed examination of the green concrete tiles through a series of tests and analyses, ranging from compressive strength to microstructural evaluation. The compressive test gauged the tiles' ability to withstand crushing forces, while the dimensional accuracy test confirmed the precision of their measurements. The roughness test assessed the surface texture, and the density test measured mass per unit volume, both crucial for quality assurance. Additionally, optical microscopy provided a macroscopic view of the tiles' surface features, complementing the SEM analysis, which offered an in-depth look at the microstructure. Together, these tests ensured a comprehensive understanding of the tiles' properties, affirming their structural integrity and suitability for flooring applications.

3.5.1 Compressive Test

Cube specimens with each dimension of 100 mm were subjected to compressive strength tests following the B.S. EN 2390-3:2019 standard (Figure 3.12). A compression test is frequently carried out to examine the specimen's behaviour under applied crushing loads. The test identified the concrete's compressive strength at a maximum load of 500 kN or a maximum extension of 10 mm, with the machine stopping if either of these variables was reached first. The maximum testing speed was set at 10 mm/min, and the crosshead speed was also maintained at 10 mm/min. The test determined the concrete's compressive strength. The compression test was performed at room temperature using a Universal Testing Machine Instron 600DX (USA), depicted in Figure 3.13.

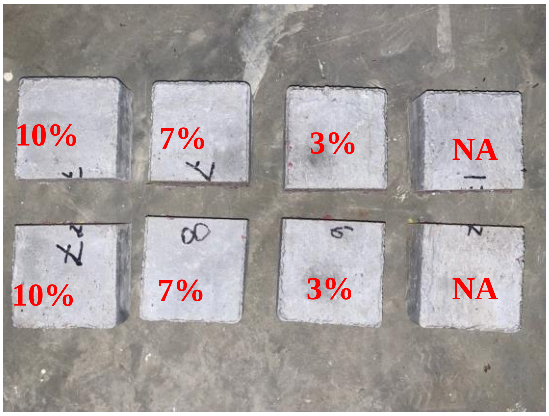

Figure 3.12: Sample of concrete cube specimens for the compressive test.

Figure 3.13: Universal Testing Machine Instron 600DX

3.5.2 Dimensional Accuracy Test via Progressive Dimensional Measurement

The dimensional accuracy test for green concrete tiles was performed through a progressive dimensional measurement using the caliper method referring to ASTM C490. The procedure is shown in Figure 3.14. This test involves measuring the tiles' length, width, and thickness with a Vernier caliper, an accurate tool for measuring. The measurements were performed progressively to collect data from 0-day to 28-day curing. They were collected from several spots on the tiles to ensure consistency and accuracy.

Figure 3.14: Caliper method

3.5.3 Roughness Test

The roughness test for the green concrete tiles was performed using a surface roughness measuring device, the Surface Tester Mitutoyo SJ-301 (Japan), as shown in Figure 3.15, per ASTM E867. The device measured the surface roughness of the tiles, and the roughness values were determined using Ra and Rz parameters. The Ra parameter is the arithmetic average of the roughness profile, while the Rz parameter is the maximum peak-to-valley height of the roughness profile. The formula for Ra is in Equation 3.1:

$$Ra = \frac{1}{L}\Sigma_{i=1}^{n}|z_i - z_{i-1}| \qquad \text{Equation 3.1}$$

where *Ra* is the arithmetic average roughness, *L* is the length of the roughness profile, and *Zi* is the height of the *i*th point on the roughness profile. The formula for Rz is in Equation 3.2:

$$R_z = max(|Z_i - Z_{i-1}|) \qquad \text{Equation 3.2}$$

where Rz is the maximum peak-to-valley height, and Zi is the height of the *i*th point on the roughness profile. The roughness values were expected to be between 6-9 µm. The results were recorded and analyzed to determine the surface quality of the tiles for flooring applications.

Figure 3.15: Surface Tester Mitutoyo SJ-301 (Japan)

3.5.4 Density Test

The density test for the green concrete tiles was performed to determine their mass per unit volume, which is a critical factor in assessing the quality and suitability of the tiles for flooring applications. The test was in accordance with relevant standards and involved measuring the mass and volume of each tile. The mass of the tile was calculated using a Digital Weight Scale Fuji FI05 (Japan) as shown in Figure 3.16, ensuring precise measurements. The volume of the tile was determined by multiplying its length, width, and thickness, with these dimensions obtained from the Dimensional Accuracy test. The formula used to calculate the density is as per Equation 3.3:

$$\text{Density } (\rho) = \text{Mass (m) / Volume (V)} \qquad \text{Equation 3.3}$$

where ρ (rho) is the tile's density, m is the mass of the tile, measured using a precise weighing scale, and V is the volume of the tile, calculated by multiplying its length, width, and thickness. The results from this test were meticulously recorded and analyzed to ensure that the tiles met these standards, thereby confirming their robustness and durability for practical use.

Figure 3.16: Surface Tester Mitutoyo SJ-301 (Japan)

3.5.5 Optical Microscopy Analysis

Figure 3.17 illustrates the microstructural characteristics of the green concrete tiles as observed through Optical Microscopy following ASTM E2015. The Optical Microscopy examination was conducted using Meiji Stereo Microscope EMZ-13TR (Japan) as shown in Figure 3.18 to complement the SEM analysis by providing a broader view of the samples' surface features. The microscope captured high-resolution images at 70x magnification, enabling a detailed observation of the tiles' surface texture and components. These images were scrutinized to assess morphological aspects such as aggregates' distribution and gradation, the cement matrix's homogeneity, and any surface imperfections or inconsistencies. The data obtained from Optical Microscopy were carefully analyzed and interpreted to provide insights into the tiles' macroscopic properties. This analysis aimed to correlate surface features with material performance, particularly regarding fracture mechanisms. Through a comparative analysis of the findings from Optical Microscopy and those from SEM, along with other tests, a comprehensive understanding of the relationship between the tiles' microstructure and their functional properties can be developed. This knowledge significantly contributes to our overall evaluation of their appropriateness for flooring applications.

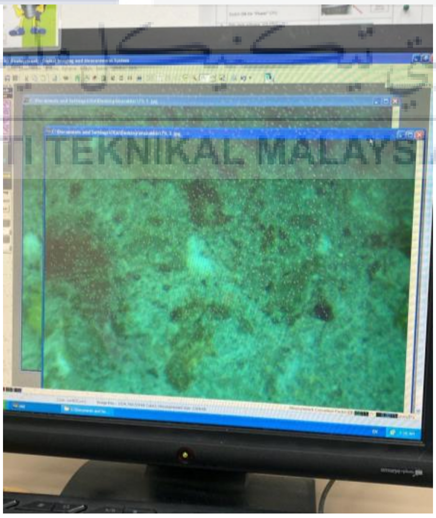

Figure 3.17: Optical microscopy analysis on computer's screen

Figure 3.18: Stereo Microscope Meiji EMZ-13TR (Japan)

3.5.6 SEM Analysis

Figure 3.17 shows the Field Emission Scanning Electron Microscopy (FESEM) apparatus used to examine the morphology of the green concrete tiles per ASTM C457. The analysis was conducted using the FESEM Hitachi SU5000 (Japan) in semi-power mode (variable pressure mode) for the samples. The SEM examination is intended to investigate the microstructure of the samples' fracture surfaces. The SEM recorded images of the materials at 40x and 1000x magnifications, allowing the microstructure to be seen. The SEM images were analyzed to determine the samples' morphological properties, such as aggregate size and shape, binding quality between aggregates and cement matrix, and the existence of any defects. The SEM data were evaluated in the context of the overall project objectives, and the SEM findings were compared to the results of other tests to understand better how the microstructure of the samples influences their performance.

Figure 3.18: FE-SEM Hitachi SU5000 (Japan)

CHAPTER 4
RESULTS AND DISCUSSION

4.0 Introduction

This chapter presents the comprehensive findings of the experimental investigation to evaluate the performance of detachable green concrete tiles for flooring applications. The study's primary focus is on assessing the physical and mechanical properties of the tiles, which include compressive strength, dimensional accuracy, surface roughness, and density. Additionally, detailed morphological analyses using Physical Fracture Criteria, Optical Microscopy, and Scanning Electron Microscopy (SEM) are conducted to understand the microstructural behavior of the tiles. These analyses are crucial for determining the viability of using recycled High-Density Polyethylene (rHDPE) as a partial replacement for natural aggregates in concrete tile production. The results are expected to provide insights into the potential of these eco-friendly materials in contributing to sustainable construction practices.

4.1 Compressive Strength

The graph in Figure 4.1 illustrates the variation in compressive strength of concrete tiles with different percentages of recycled high-density polyethylene (rHDPE) aggregates over a curing period of 7, 14, and 28 days. It is observed that the compressive strength of all formulations increases with the curing time. For the control sample with 0% rHDPE, the compressive strength starts at approximately 20 MPa at 7 days and increases to about 22 MPa at 28 days. Similarly, the samples with 3% and 7% rHDPE show an increase in compressive strength from around 15 MPa and 14 MPa at 7 days to approximately 17 MPa and 16 MPa at 28 days, respectively. The sample with 10% rHDPE exhibits the lowest initial compressive strength of about 12 MPa at 7 days, which increases to around 13 MPa at 28 days.

The observed increase in compressive strength over the curing period is expected due to the continued hydration of cement over time (Uddin et al., 2012). The rate of strength gain is higher at early ages (up to 14 days) and gradually slows down at later ages, which is a typical behavior observed in concrete. The increase in compressive strength with curing time can be attributed to the formation of additional calcium silicate hydrate (C-S-H) gel, which is the primary strength-contributing component in concrete (Jaivignesh & Sofi, 2017). As the curing time increases, more cement particles react with water, forming denser and stronger C-S-H gel, enhancing compressive strength (Jantarachot et al., 2023).

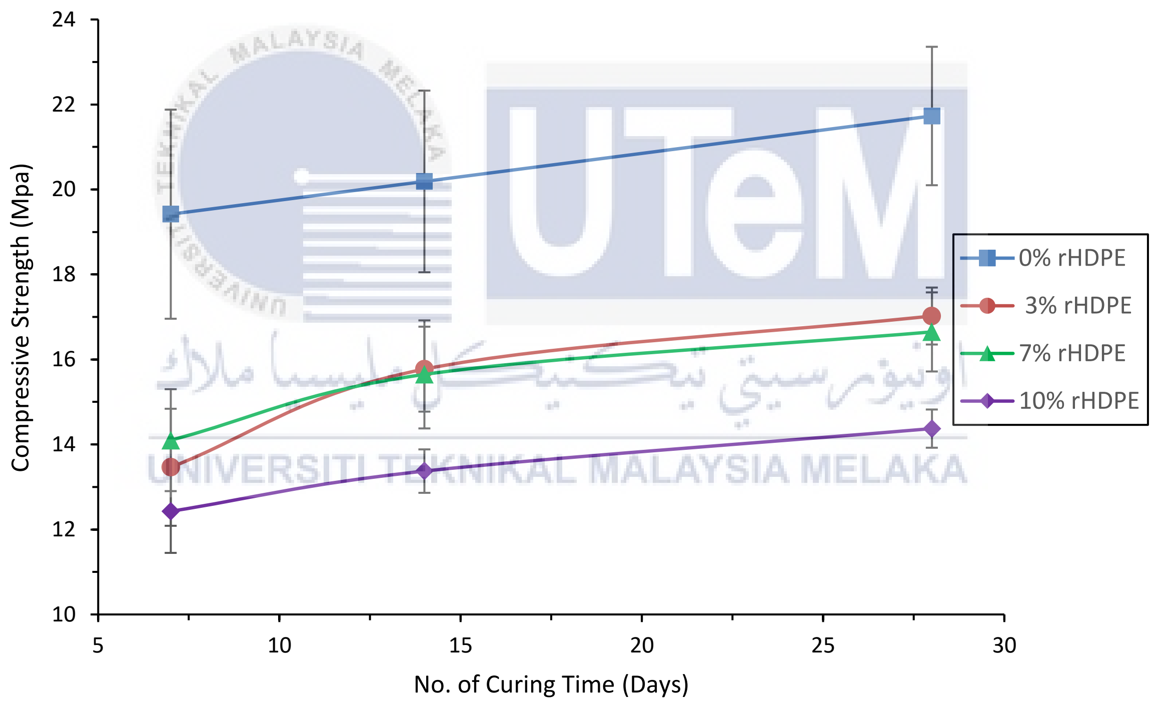

Figure 4.1: Compressive strength variation with the increase of curing period for different percentages of rHDPE aggregates

The compressive strength of concrete tiles incorporating recycled high-density polyethylene (rHDPE) aggregates were closely evaluated at 28 days of curing, as shown in Table 4.1 and Figure 4.2. The results indicate a decrease in compressive strength with increasing rHDPE content. Specifically, the average compressive strength for natural aggregates (0% rHDPE) was 21.73 MPa. For tiles with 3%, 7%, and 10% rHDPE, the average compressive strengths were 17.02 MPa, 16.65 MPa, and 14.37 MPa, respectively. These values surpassed the minimum required compressive strength for M10 concrete tiles of 10 MPa for all samples. The trend observed in Figure 4.2 further supports these findings, showing a consistent decline in compressive strength as the percentage of rHDPE increases over 7, 14, and 28 days of curing.

The observed reduction in compressive strength with increasing rHDPE content can be attributed to the inherent properties of HDPE. According to Abeysinghe et al. (2021), HDPE's hydrophobic nature and smooth surface texture result in weaker bonds and lower adhesion strength between the concrete mix and the HDPE aggregates. This weak bonding reduces the overall mechanical performance of the concrete. Additionally, the inclusion of HDPE increases the porosity and permeability of the concrete, as observed in Optical Microscopy and SEM analyses, which further contributes to the reduction in compressive strength (Abeysinghe et al., 2021). Despite the decrease in strength, the compressive strength values for all rHDPE-incorporated tiles remain above the minimum required threshold, indicating that these eco-friendly tiles are still viable for flooring applications. The findings align with Aocharoen & Chotickai (2023), highlighting the trade-off between sustainability and mechanical performance when using recycled plastic aggregates in concrete.

Table 4.1: Compression strength of concrete tiles at 28 days of curing

Batch No.	Sample	% of replacement with HDPE	Average compressive strength at 28 days (MPa)	Min Compressive Strength at 28 days (MPa)
1.	Natural Agregates (NA)	0	21.73	10
2.	rHDPE 3%	3	17.02	10
3.	rHDPE 7%	7	16.65	10
4.	rHDPE 10%	10	14.37	10

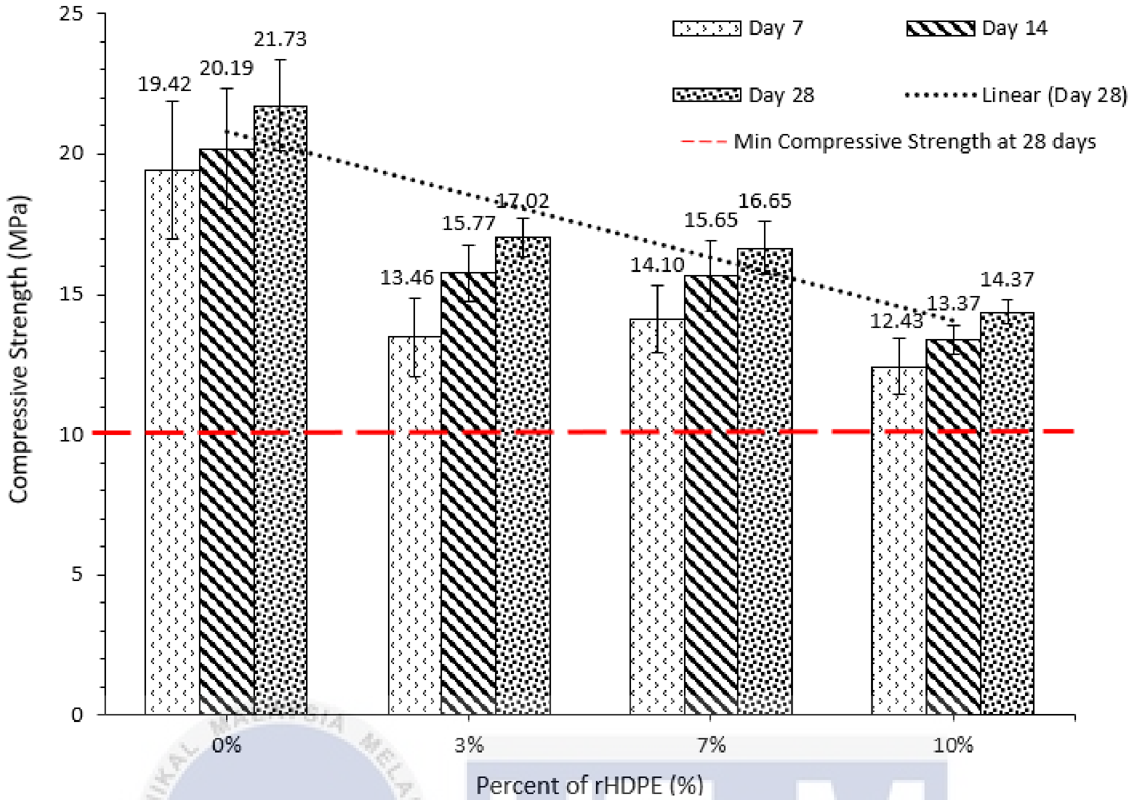

Figure 4.2: Compressive strength variation with the increase of rHDPE percentage at different curing periods

The data in Table 4.2 illustrates the percentage reduction in compressive strength of concrete tiles with varying percentages of recycled high-density polyethylene (rHDPE) replacement at 7, 14, and 28 days. At 3% rHDPE replacement, the compressive strength reduction is 28.84% at 7 days, 21.88% at 14 days, and 21.7% at 28 days. For 7% rHDPE replacement, the reduction is 25.46% at 7 days, 22.49% at 14 days, and 23.4% at 28 days. The most significant reduction is observed at 10% rHDPE replacement, with 34.32% at 7 days, 33.76% at 14 days, and 33.9% at 28 days.

The observed reduction in compressive strength with increasing rHDPE content is consistent with findings from previous studies. HDPE's hydrophobic nature and smooth surface texture lead to weaker bonds between the concrete matrix and the HDPE aggregates, resulting in decreased mechanical performance (Abeysinghe et al., 2021). This trend aligns with the literature, which indicates that increasing HDPE content generally results in lower compressive strength due to the non-reactive behavior of HDPE in the concrete mix (Tamrin & Nurdiana, 2021). The significant reduction at 10% rHDPE replacement is particularly notable, as it highlights the impact of higher plastic content on the structural integrity of concrete. These findings are supported by research that shows similar trends of reduced compressive strength with higher percentages of plastic aggregates (Tota-Maharaj et al., 2022). Therefore, while incorporating rHDPE in concrete can promote sustainability, it is crucial to balance the percentage of rHDPE to maintain the desired mechanical properties of the concrete tiles.

Table 4.2: Compressive strength reduction by rHDPE mix

% rHDPE Replacement	Reduction in Compressive Strength Compared to NA (%)		
	Day 7	Day 14	Day 28
3%	28.84	21.88	21.7
7%	25.46	22.49	23.4
10%	34.32	33.76	33.9

4.2 Dimensional Accuracy

The progressive dimensional changes of concrete tiles with varying percentages of recycled high-density polyethylene (rHDPE) content (0%, 3%, 7%, and 10%) were monitored over a curing period of 0 to 28 days, as shown in Figure 4.3. The results indicate that the percentage of dimensional changes increases as the rHDPE content increases. Specifically, the 0% rHDPE mixture exhibited the least dimensional change, remaining below 0.5% throughout the curing period. In contrast, the mixtures with 3%, 7%, and 10% rHDPE content showed progressively higher dimensional changes, reaching up to 1.5%, 2.0%, and 2.4%, respectively, by the end of the 28-day curing period. This trend suggests that higher rHDPE content in the concrete mix leads to greater dimensional instability over time.

The observed increase in dimensional changes with higher rHDPE content can be attributed to the inherent properties of plastic aggregates, which differ significantly from natural aggregates. The plastic aggregates may introduce more voids and less rigidity in the concrete matrix, leading to greater expansion and contraction during the curing process. These observations agree with the optical and SEM microscopy analyses in subsections 4.5

and compressive strength in subsection 4.1. Consistent dimensions in the 0% rHDPE mixture suggest a controlled mix and compaction process, likely resulting in a more uniform density across the tiles. This uniformity is crucial for ensuring the structural integrity and stability of the tiles during installation and use. Accurate dimensions may also correlate with a uniform microstructure, as observed in SEM analysis, which can provide insights into the material's internal structure and its impact on dimensional stability (Saxena & Gupta, 2022).

Furthermore, studies on using recycled plastic in concrete support the correlation between dimensional accuracy and microstructural uniformity. For instance, research has shown that including plastic waste in concrete can lead to a more porous structure, which affects the material's mechanical properties and dimensional stability (Sau et al., 2023). The findings from this study align with the broader literature on sustainable construction materials, highlighting the importance of optimizing the mix design to balance the benefits of using recycled materials with the need for maintaining structural performance and dimensional accuracy (Alqahtani & Zafar, 2023). This study underscores the potential of using rHDPE in concrete while emphasizing the need for careful formulation to achieve the desired balance between sustainability and dimensional stability.

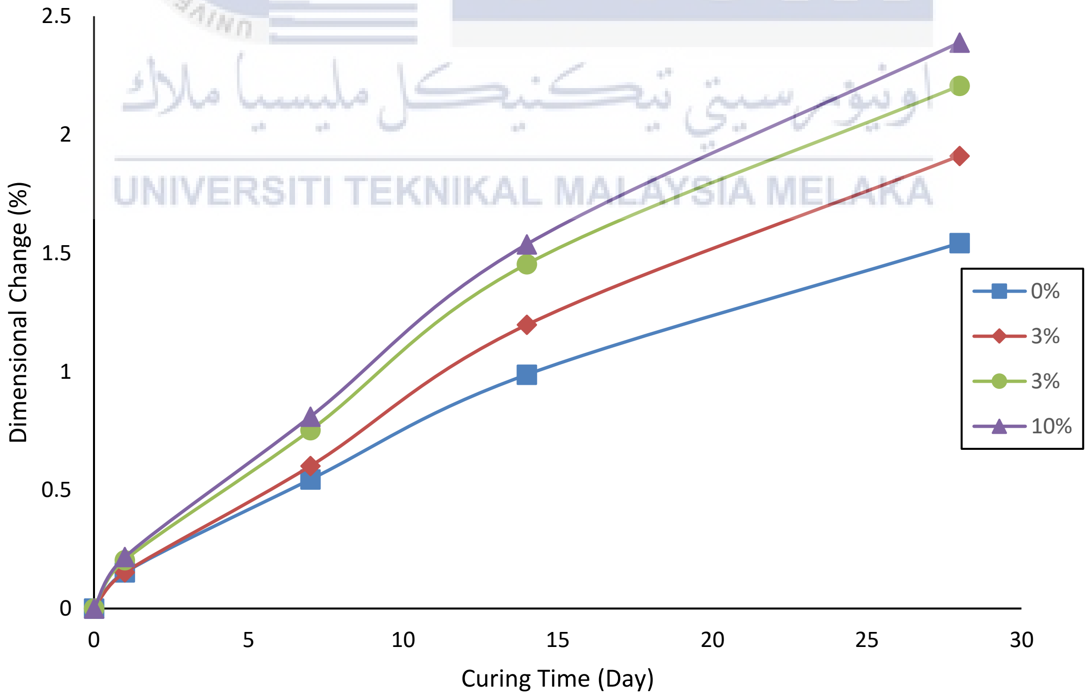

Figure 4.3: Dimensional changes of different percentages of rHDPE (3%, 7%, 10%) with natural aggregates (0%) from 0 to 28 day of curing

4.3 Surface Roughness

The surface roughness of green concrete tiles incorporating varying percentages of recycled High-Density Polyethylene (rHDPE) was measured over different curing periods (7, 14, and 28 days). The results are presented in Figures 4.3 and 4.4, which show the Ra (arithmetic average roughness) and Rz (maximum peak-to-valley height) values, respectively. The 0% rHDPE line begins just below a Ra value of 8 micrometers and exhibits a slight decrease over time, suggesting a minor improvement in smoothness as the concrete cures. The 3% rHDPE line starts at a Ra value of 8 micrometers and shows a slight increase before stabilizing, indicating a potential initial roughening followed by a plateau in texture. The 10% rHDPE line, starting above a Ra value of 8.5 micrometers, remains relatively stable, suggesting that higher rHDPE content may lead to a consistently rougher surface.

As illustrated in Figure 4.4, the Ra values decrease with higher percentages of rHDPE, indicating a smoother surface texture. Specifically, the Ra values for 0% rHDPE (natural aggregates) were higher than those for 3%, 7%, and 10% rHDPE across all curing periods. Similarly, Figure 4.5 shows a decrease in Rz values with increasing rHDPE content, further confirming the trend towards smoother surfaces. Additionally, for the natural aggregates (0% rHDPE), both Ra and Rz values decrease over the curing periods from 7 to 28 days, indicating an improvement in surface smoothness over time. Notably, the Ra values for all samples, including those with rHDPE, fall within the 6-9 µm range, which is considered optimal for balancing slip resistance and aesthetic appeal in flooring applications (Kim, 2018).

The observed increase in surface roughness (both Ra and Rz) with higher percentages of rHDPE can be attributed to the mismatch between the coarser surface of natural aggregates to smoother texture and hydrophobic nature of rHDPE aggregates. Contradicts data reported by Abeysinghe et al. (2021) and Tamrin and Nurdiana (2021), where the inclusion of plastic aggregates results in smoother concrete surfaces due to weaker bonds between the concrete matrix and the plastic aggregates. The increase in roughness over the curing period from 7 to 28 days for rHDPE mixes may be due to microstructural changes within the concrete matrix, possibly related to the interaction between the plastic aggregates and the cement paste, as shown in Optical Microscopy and SEM analysis. This could lead to differential shrinkage or swelling of the plastic aggregates, creating micro-cracks or surface irregularities, as observed in optical microscopy analysis (Qudoos et al., 2018).

Additionally, variations in curing conditions, such as humidity and temperature, could affect the surface characteristics, leading to increased roughness over time (Homkhiew et al., 2023). For the natural aggregates (0% rHDPE), the decrease in both Ra and Rz values over the curing periods suggests that the concrete surface becomes smoother as it cures. This can be explained by the continued hydration process of the cement, which fills in the pores and micro-cracks on the surface, leading to a denser and smoother surface texture (Abeysinghe et al., 2021). Next, the improvement in surface smoothness over time for natural aggregates is consistent with studies from Qudoos et al. (2018), which indicate that the surface roughness of concrete decreases as the curing process progresses. The concrete matrix becomes more compact and well-formed. The Ra values for all samples, including those with rHDPE, falling within the 6-9 µm range, are significant. This range is optimal for balancing slip resistance and aesthetic appeal, making the tiles suitable for flooring applications (Kim, 2018). This supports the hypothesis that green concrete tiles with surface roughness values within the 6-9 µm range are ideal for modern flooring applications.

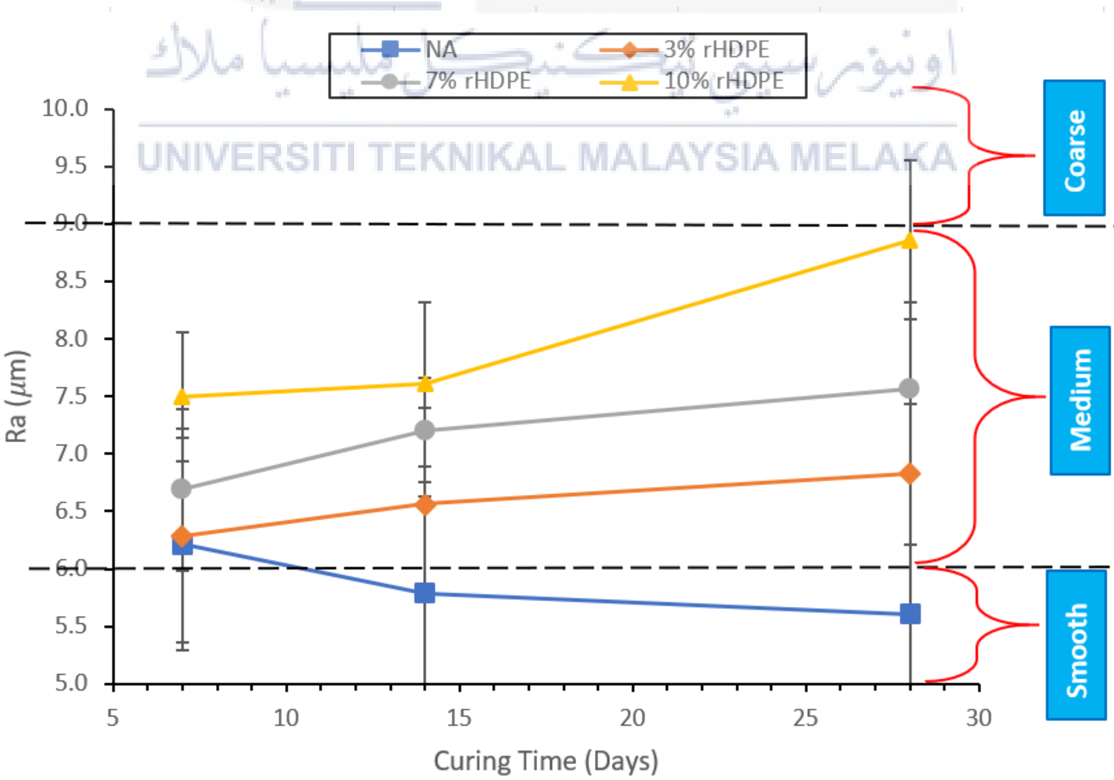

Figure 4.4: Ra values over the curing periods for each percentage of rHDPE

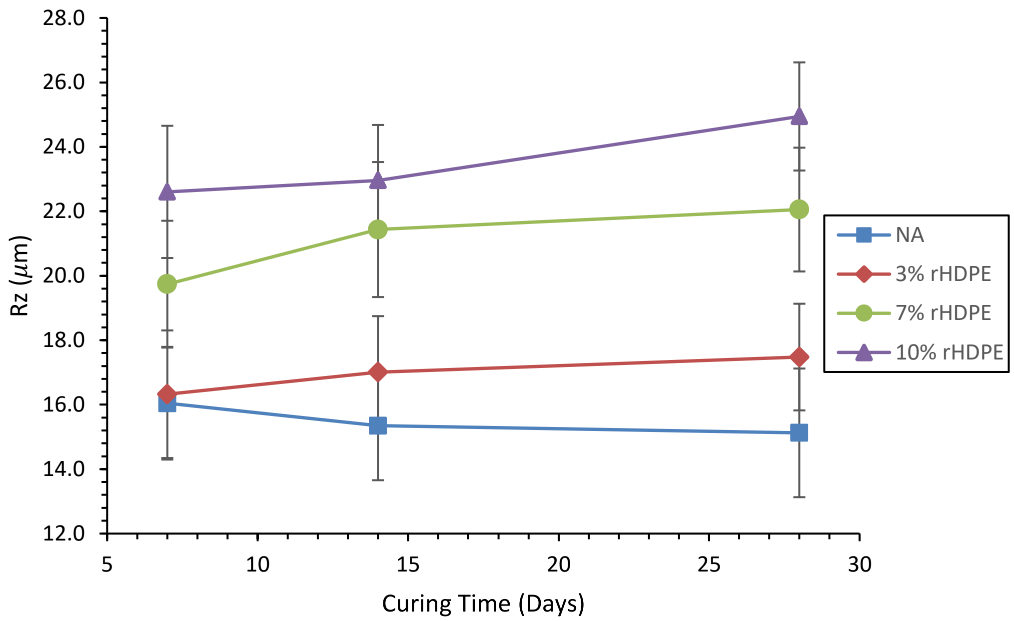

Figure 4.5: Rz values over the curing periods for each percentage of rHDPE

4.4 Unit Weight/Density

The unit weight or density of the green concrete tiles was evaluated to understand the impact of incorporating recycled High-Density Polyethylene (rHDPE) waste aggregates. The graph in Figure 4.6 illustrates the density of concrete tiles at 28 days, with varying percentages of recycled high-density polyethylene (rHDPE) content. The density of the concrete tiles decreases as the percentage of rHDPE increases. Specifically, the density values are 0.37 kg/m³ for 0% rHDPE, 0.36 kg/m³ for 3% rHDPE, 0.34 kg/m³ for 7% rHDPE, and 0.32 kg/m³ for 10% rHDPE. This trend indicates a linear reduction in density with the increase in rHDPE content, suggesting that the incorporation of rHDPE aggregates results in lighter concrete tiles.

The observed reduction in density with increasing rHDPE content aligns with the morphological analysis in subsection 4.5 and findings from previous studies on the use of recycled plastic aggregates in concrete. According to Guo et al. (2023) and Abeysinghe et al. (2021). The decrease in density can be attributed to the lower specific gravity of rHDPE compared to natural aggregates, which results in a lighter overall concrete matrix. For instance, rHDPE plastic has a specific gravity ranging from approximately 0.94 to 0.97 g/cm³, whereas natural aggregates typically range from 2.45 to 2.57 g/cm³. Furthermore, Aldahdooh et al. (2018) and Sau et al. (2023) state that adding plastic waste aggregates decreases concrete density. Moreover, Murts et al. (2021) indicated that the density of concrete tiles made with plastic and eggshell waste was lower than that of conventional concrete tiles. The reduction in density was attributed to the lower density of plastic aggregates and the improved workability due to the plastic particles' smooth texture and non-absorbent nature. This reduction in density can be advantageous for flooring applications, as it can lead to easier handling and installation of the tiles. However, it is important to consider that while the reduction in density can enhance certain properties like ductility and energy absorption capacity, it may also lead to a decrease in compressive strength and durability, as the weaker bond between the concrete matrix and the rHDPE aggregates can compromise the mechanical properties of the concrete (Abeysinghe et al., 2021; Tamrin and Nurdiana, 2021). In our case, the decrease in density is also contributed by the number of voids forming in the concrete tiles, as discussed in subsection 4.5. Meanwhile, higher density often indicates fewer voids and the potential for greater compressive strength, as observed in optical microscopy and SEM analysis (Berardi, 2023). Therefore, optimizing the balance between density reduction and maintaining adequate strength is crucial for the practical application of rHDPE-incorporated concrete tiles in a flooring application.

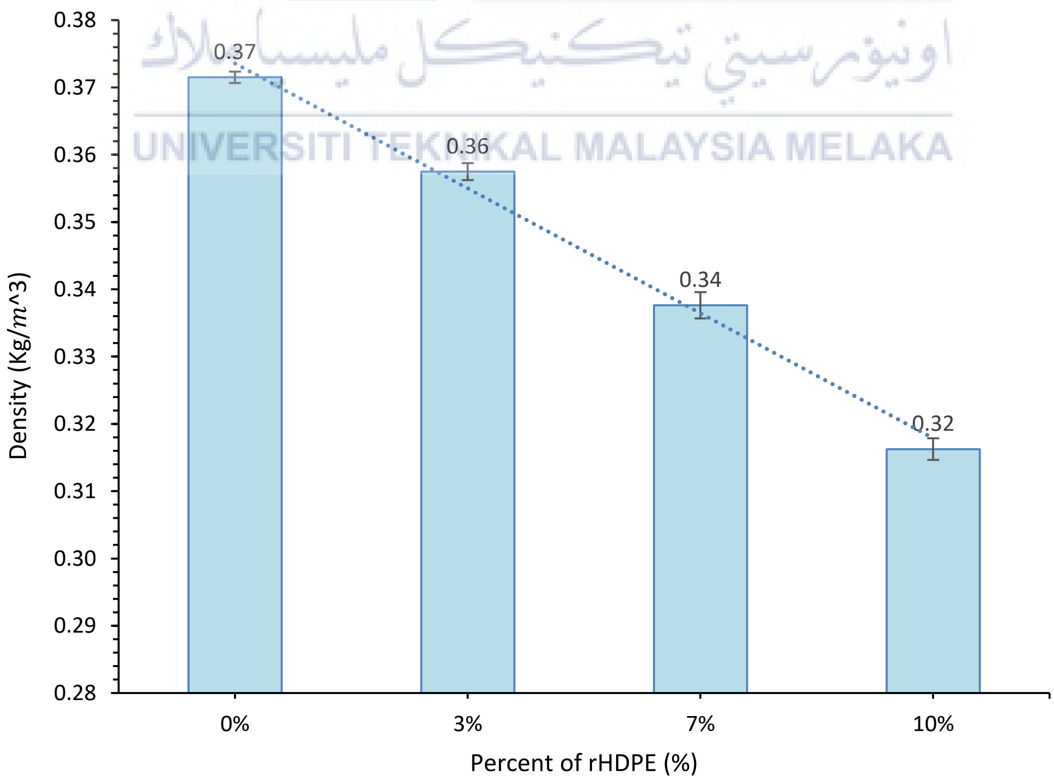

Figure 4.6: Density of concrete tiles at 28 days

4.5 Morphological Analysis

The morphological analysis of the green concrete tiles is a crucial component of this study, providing a deeper understanding of the microstructural characteristics that influence their physical and mechanical properties. The preceding sections have detailed the compressive strength, dimensional accuracy, surface roughness, and density of the tiles, highlighting the impact of varying percentages of recycled high-density polyethylene (rHDPE) aggregates. These analyses have shown that while incorporating rHDPE can enhance sustainability, it also affects the tiles' mechanical performance and dimensional stability. To further elucidate these findings, the morphological analysis in this section employs Physical Fracture Criteria, Optical Microscopy, and Scanning Electron Microscopy (SEM). These techniques provide comprehensive insights into the internal and surface structures of the tiles, which are pivotal for understanding the observed variations in compressive strength, dimensional accuracy, and surface roughness.

4.5.1 Physical Fracture Characteristics

The physical attributes of fractures in concrete tiles offer vital information about their structural robustness and ability to withstand compressive forces. A comparative analysis of fracture imagery, captured before and after the execution of compression tests, can highlight the relationship between fracture patterns and the structural vulnerabilities that arise from the incorporation of plastic waste. Figures 4.7 to 4.10 illustrate the physical fracture images of concrete tiles with different aggregate compositions before and after compression tests. The images provide a visual comparison of the fracture patterns and the impact of recycled HDPE (rHDPE) content on the structural integrity of the tiles. The physical fracture images of concrete tiles with natural aggregates before and after the compression test are shown in Figure 4.7. Before the compression test, the tiles exhibit a uniform and dense structure with minimal visible cracks or defects. After the compression test, the tiles show a well-defined fracture pattern with clean breaks, indicating a strong interfacial bond between the cement matrix and natural aggregates. This suggests that the natural aggregates provide a robust structure capable of withstanding significant compressive forces.

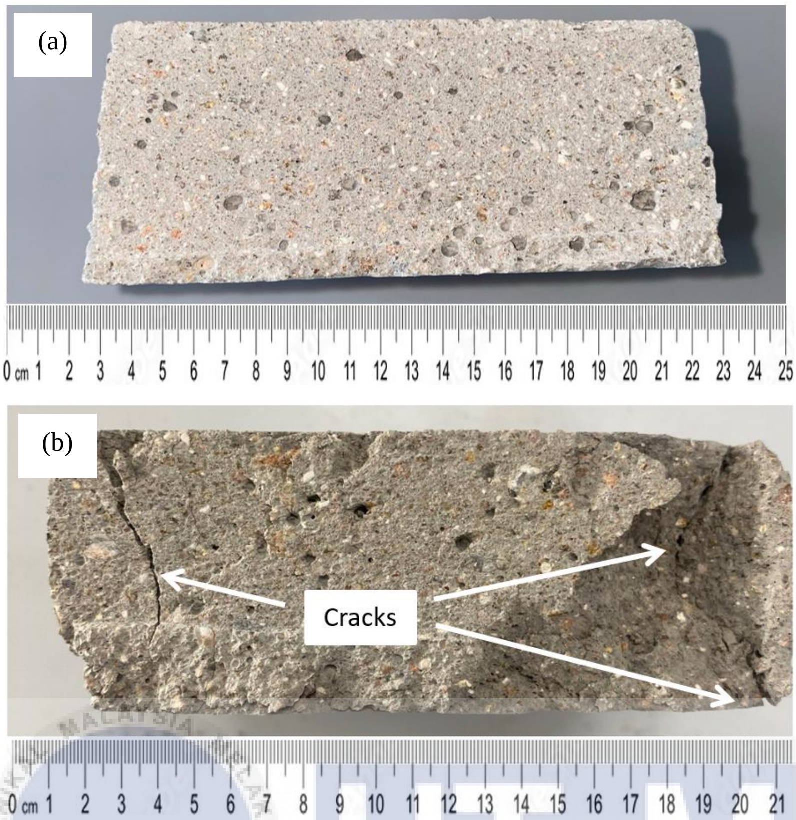

Figure 4.7: Physical Fracture Images of concrete tiles with Natural Aggregates (a) before compression test and (b) after compression test.

Figure 4.8 compares the physical fracture of concrete tiles with natural aggregates and those with 3% rHDPE before and after the compression test. Before the test, the natural aggregate tiles maintain a dense and uniform structure, while the 3% rHDPE tiles show a slightly less dense structure with minor visible voids. After the compression test, the natural aggregate tiles exhibit clean and well-defined fracture patterns, whereas the 3% rHDPE tiles display more irregular fracture patterns with visible micro-cracks. This indicates that the introduction of 3% rHDPE results in a weaker interfacial bond and reduced structural integrity.

The physical fracture images of concrete tiles with natural aggregates and those with 7% rHDPE before and after the compression test are shown in Figure 4.9. Before the test, the natural aggregate tiles continue to show a dense and uniform structure, while the 7% rHDPE tiles exhibit increased porosity and visible voids. After the compression test, the natural aggregate tiles maintain consistent fracture patterns, whereas the 7% rHDPE tiles show more pronounced micro-cracks and irregular fracture patterns. This suggests that increasing the rHDPE content to 7% further weakens the interfacial bond and reduces the structural integrity of the tiles.

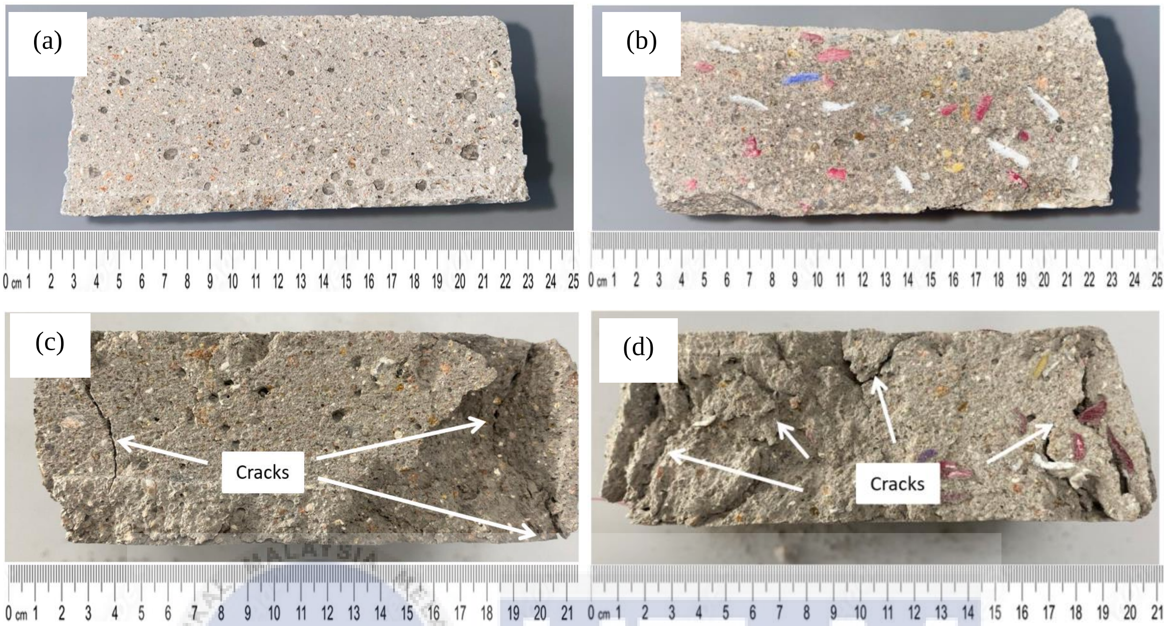

Figure 4.8: Comparison of Physical Fracture of concrete tiles with (a) Natural Aggregates before compression test, (b) 3% rHDPE before compression test, (c) Natural Aggregates after compression test, and (d) 3% rHDPE after compression test

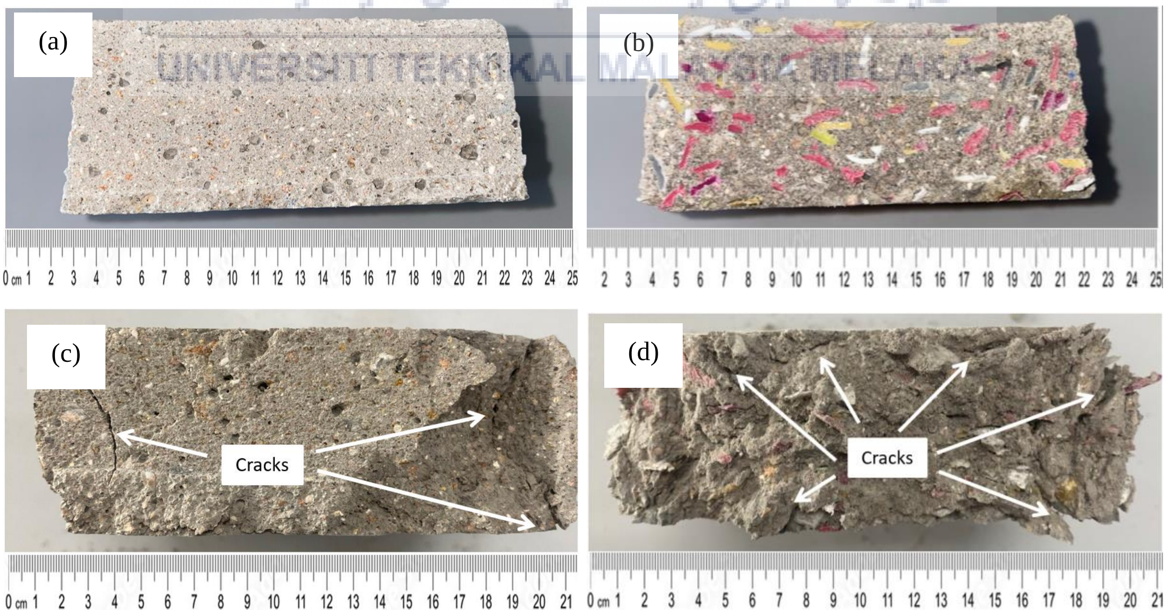

Figure 4.9: Comparison of Physical Fracture of concrete tiles with (a) Natural Aggregates before compression test, (b) 7% rHDPE before compression test, (c) Natural Aggregates after compression test, and (d) 7% rHDPE after compression test.

Figure 4.10 compares the physical fracture of concrete tiles with natural aggregates and those with 10% rHDPE before and after the compression test. Before the test, the natural aggregate tiles remained dense and uniform, while the 10% rHDPE tiles exhibit significant porosity and larger voids. After the compression test, the natural aggregate tiles show consistent fracture patterns, whereas the 10% rHDPE tiles display extensive micro-cracks and highly irregular fracture patterns. This indicates that the inclusion of 10% rHDPE results in a substantial reduction in structural integrity, making the tiles less suitable for applications requiring high compressive strength.

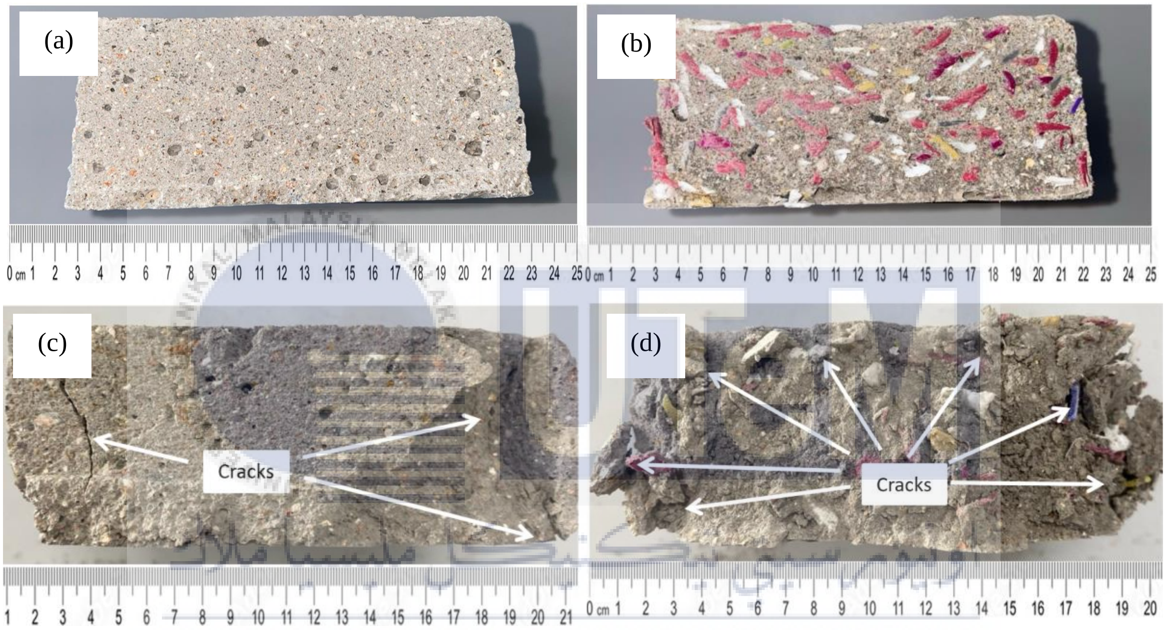

Figure 4.10: Comparison of Physical Fracture of concrete tiles with (a) Natural Aggregates before compression test, (b) 10% rHDPE before compression test, (c) Natural Aggregates after compression test, and (d) 10% rHDPE after compression test.

The morphological analysis findings indicate that the inclusion of rHDPE in concrete tiles affects both the physical fracture characteristics and the microstructural integrity. As the rHDPE content increases, the tiles exhibit increased porosity, larger voids, and more pronounced micro-cracks, resulting in a weaker interfacial transition zone (ITZ) and reduced compressive strength. Tiles with natural aggregates show the highest compressive strength and the most uniform microstructure, making them ideal for applications requiring high structural integrity. The inclusion of 3% rHDPE results in a slight reduction in compressive strength and increased porosity, but the tiles still maintain adequate structural integrity for flooring applications. However, tiles with 7% and 10% rHDPE exhibit further reductions in compressive strength and increased micro-cracks, making them less suitable for applications requiring high compressive strength. The 10% rHDPE tiles, while meeting the minimum strength requirement, show greater dimensional changes and reduced compressive strength, but their lower density makes them ideal for applications prioritizing lightweight and sustainability.

4.5.2 Optical Microscopy

The optical microscopy analysis of the concrete samples with varying ratios of recycled high-density polyethylene (rHDPE) aggregates (3%, 7%, and 10%) compared to natural aggregates was conducted at 70x magnification. The optical microscopy images in Figures 4.11(a) and 4.11(b) show the optical microscopy images of concrete tiles made with natural aggregates before and after compression testing, respectively. The pre-compression image in Figure 4.11(a) reveals a dense and uniform microstructure, with minimal visible pores or defects. This indicates a well-compacted mixture and proper bonding between the natural aggregates and the cement matrix. After compression testing, as seen in Figure 4.11(b), the fractured surface appears rough and irregular, which is typical of concrete failure under compressive loading. The fracture pattern suggests a relatively homogeneous distribution of stresses within the material, leading to a more uniform failure mode.

Figures 4.12(a) and 4.12(b) depict the concrete tiles with 3% rHDPE before and after compression testing, respectively. Compared to the natural aggregate sample, the pre-compression tile in Figure 4.12(a) exhibits a slightly more porous microstructure, with some visible air voids or gaps. This could be attributed to the introduction of rHDPE aggregates, which may have affected the compaction and interfacial bonding with the cement matrix. After compression testing, as shown in Figure 4.12(d), the fractured surface appears rougher and more porous compared to the natural aggregate sample. Micro-cracks and voids are more visible, suggesting a weaker interfacial transition zone (ITZ) between the rHDPE aggregates and the cement matrix. This could potentially lead to a reduction in compressive strength and overall integrity of the concrete tiles.

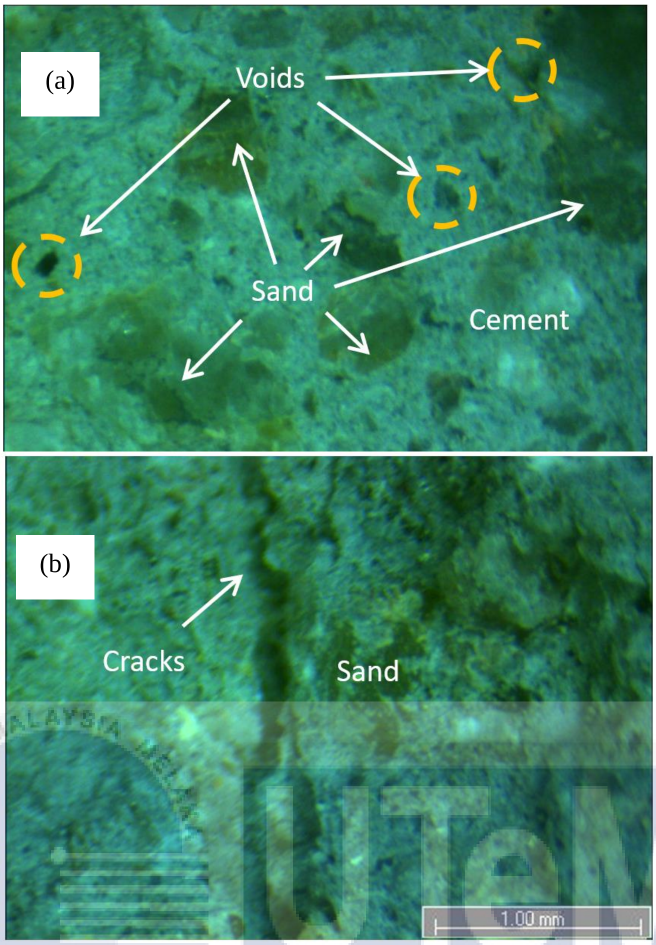

Figure 4.11: Optical microscopy images of concrete with Natural Aggregate (a) before compression test and (b) after compression test at 70x magnification.

Figures 4.13(a) and 4.13(b) show the concrete tiles with 7% rHDPE before and after compression testing, respectively. The pre-compression sample in Figure 4.13(a) exhibits an increased number of visible pores and air voids compared to the 3% rHDPE sample, indicating a further decrease in compaction and density due to the higher rHDPE content. After compression testing, as seen in Figure 4.13(d), the fractured surface appears even rougher and more porous, with larger and more numerous micro-cracks visible. This suggests that the 7% rHDPE content further compromised the compressive strength and integrity of the concrete tiles compared to the lower rHDPE percentages.

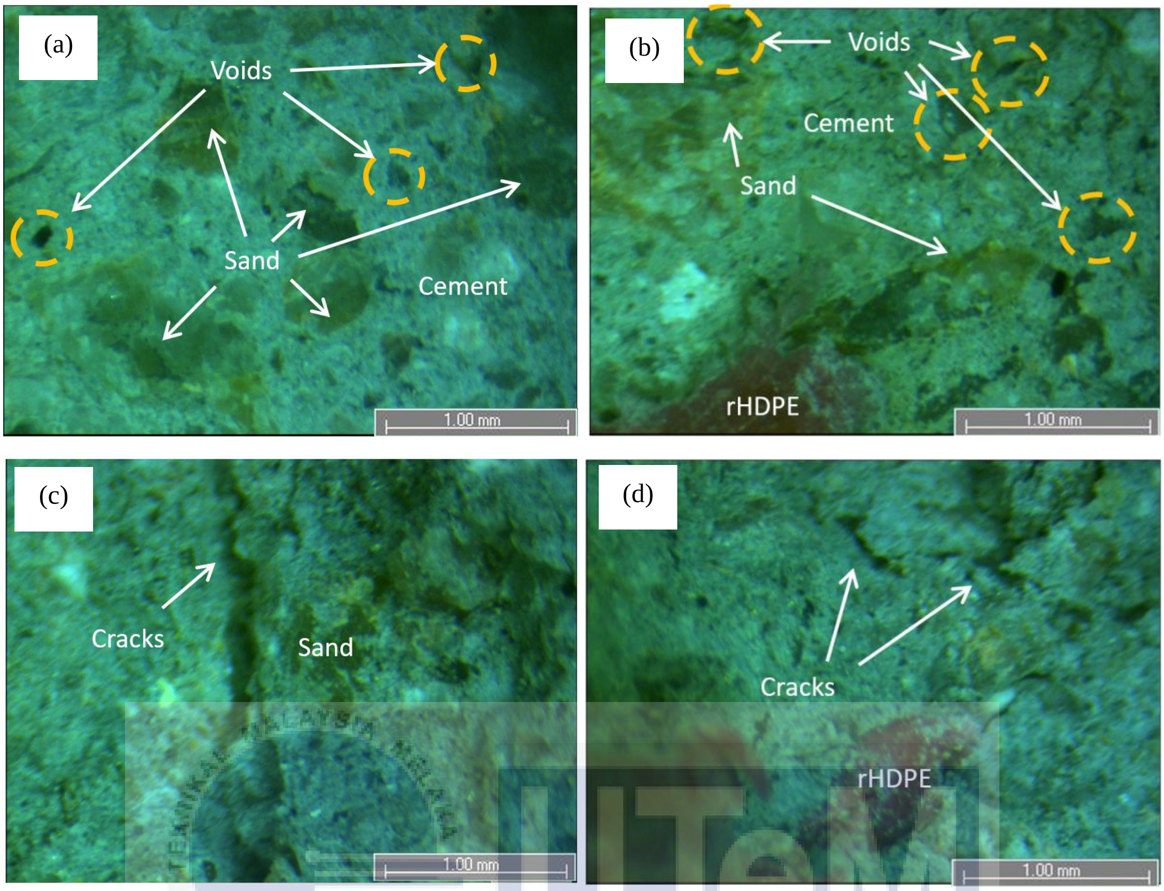

Figure 4.12: Optical microscopy images of of concrete tiles with (a) Natural Aggregates before compression test, (b) 3% rHDPE before compression test, (c) Natural Aggregates after compression test, and (d) 3% rHDPE after compression test at 70x magnification.

Figures 4.14(a) and 4.14(b) depict the concrete tiles with 10% rHDPE before and after compression testing, respectively. The pre-compression sample in Figure 4.14(a) exhibits a highly porous and non-uniform microstructure, with numerous visible air voids and gaps. This indicates a significant decrease in compaction and density due to the high rHDPE content, which may have hindered proper bonding between the aggregates and the cement matrix. After compression testing, as shown in Figure 4.14(d), the fractured surface appears highly irregular and porous, with extensive micro-cracking and potential delamination visible. This suggests that the 10% rHDPE content severely compromised the compressive strength and structural integrity of the concrete tiles, likely due to the weak ITZ between the rHDPE aggregates and the cement matrix.

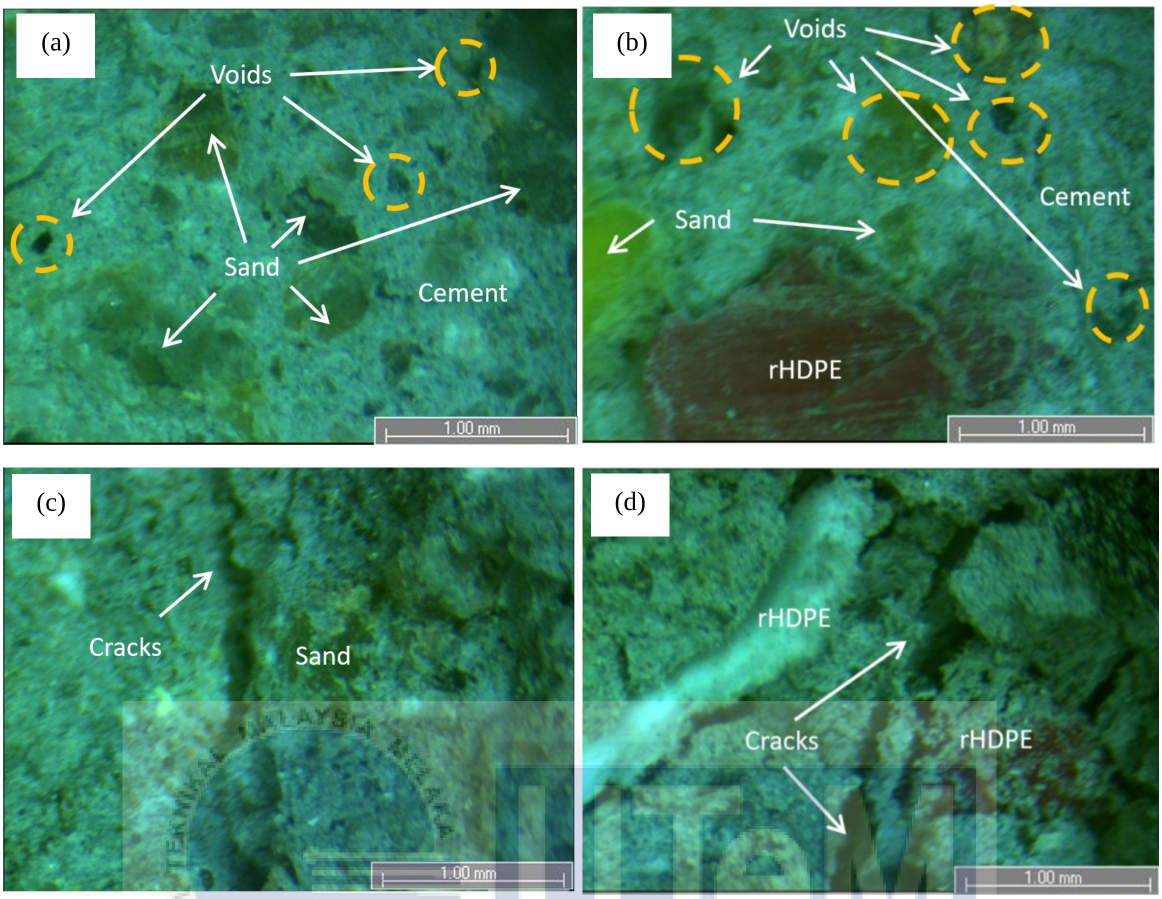

Figure 4.13: Optical microscopy images of of concrete tiles with (a) Natural Aggregates before compression test, (b) 7% rHDPE before compression test, (c) Natural Aggregates after compression test, and (d) 7% rHDPE after compression test at 70x magnification.

The morphological analysis of the concrete tiles reinforced with natural aggregates and hybrid natural/rHDPE aggregates reveals several key findings. The addition of rHDPE aggregates introduced porosity and air voids into the concrete mixture, which increased with higher rHDPE percentages. This can be attributed to the poor interfacial bonding between the hydrophobic rHDPE and the cement matrix, leading to a weaker interfacial transition zone (ITZ). The increased porosity and micro-cracking observed in the rHDPE-containing tiles after compression testing suggest a reduction in compressive strength and structural integrity compared to the natural aggregate tiles. This effect became more pronounced with higher rHDPE percentages. Futhermore, the rough and irregular fractured surfaces of the rHDPE-containing tiles, particularly at higher percentages (7% and 10%), indicate a more brittle failure mode compared to the natural aggregate tiles. This could be due to the weaker ITZ and the presence of micro-cracks acting as stress concentration points. The morphological observations align with the reduction in compressive strength and dimensional stability of the concrete tiles as the rHDPE content increases.

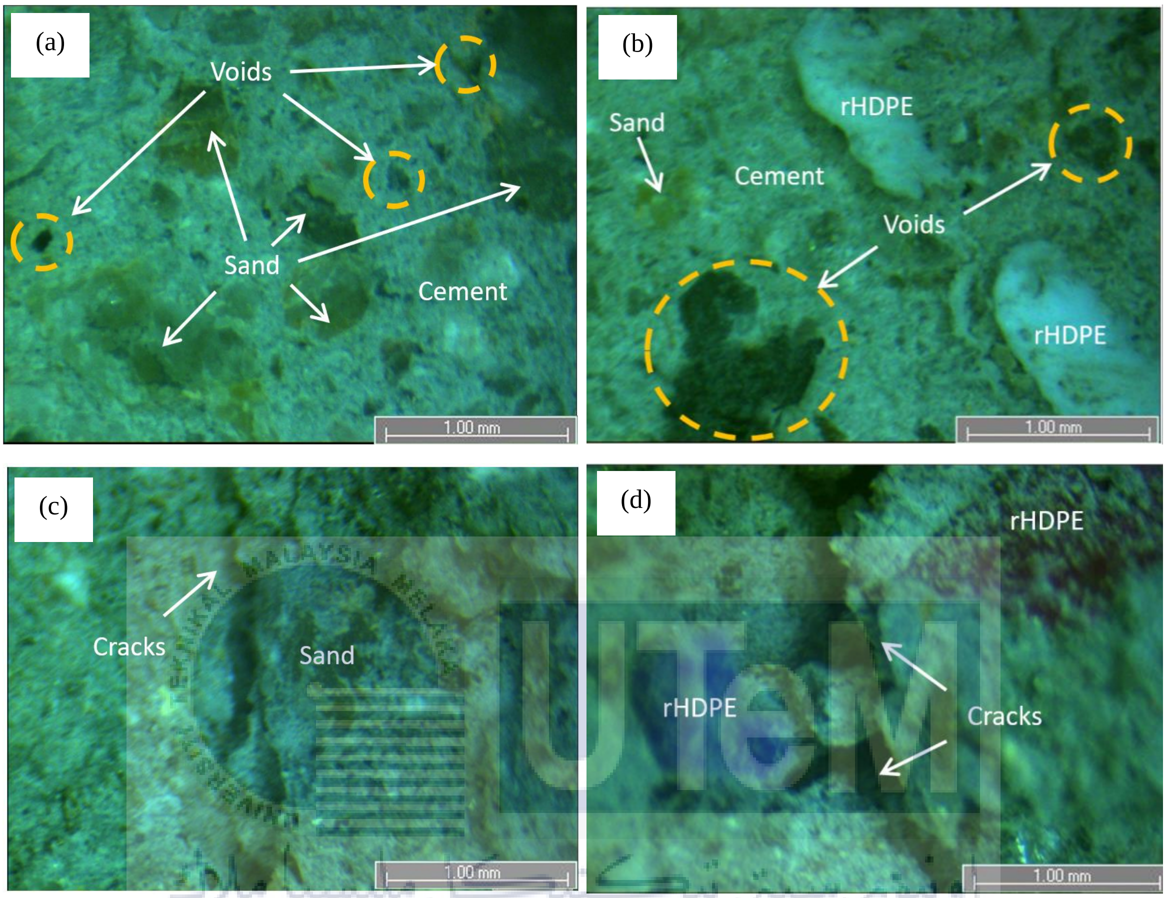

Figure 4.14: Optical microscopy images of of concrete tiles with (a) Natural Aggregates before compression test, (b) 10% rHDPE before compression test, (c) Natural Aggregates after compression test, and (d) 10% rHDPE after compression test at 70x magnification.

4.5.3 SEM Analysis

The SEM analysis of the concrete samples with varying percentages of recycled High-Density Polyethylene (rHDPE) aggregates reveals significant differences in their microstructure and morphology. The SEM micrographs in Figure 4.15 show the surface morphology of concrete containing only natural aggregates at 40x and 1000x magnifications. The microstructure appears dense and uniform, with a well-compacted matrix and a strong interfacial transition zone (ITZ) between the aggregates and the cement paste. The dense and homogeneous microstructure observed in the concrete with natural aggregates is a result of the effective bonding between the aggregates and the cement matrix. This strong ITZ contributes to the high compressive strength and dimensional stability of the concrete tiles, as evidenced by the experimental results. The uniform microstructure also suggests a consistent distribution of aggregates within the matrix, leading to a more uniform surface texture and roughness.

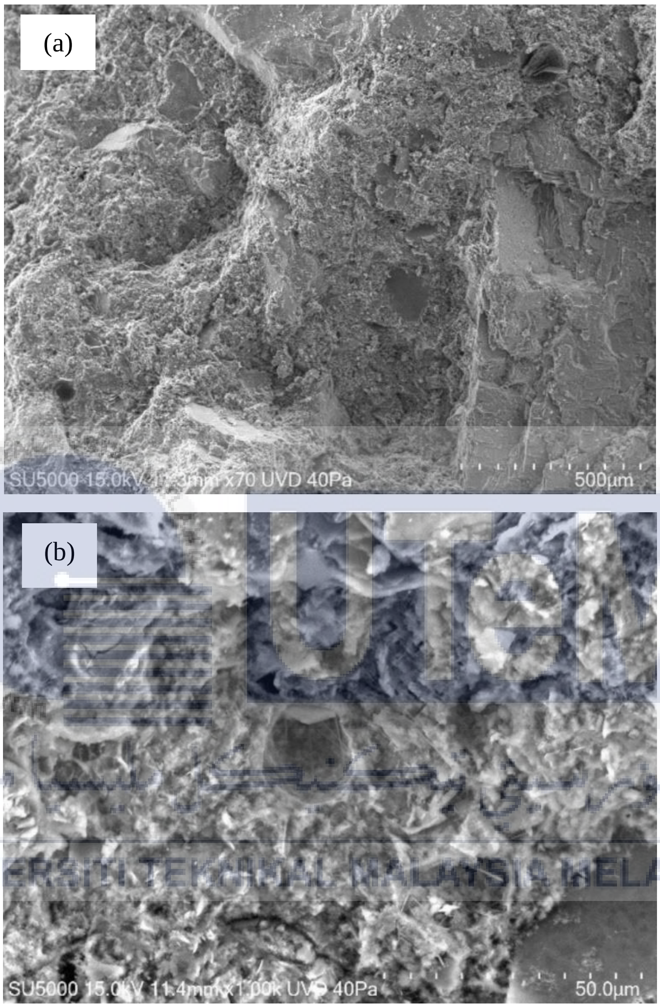

Figure 4.15: Surface Morphology of concrete with (a) Natural Aggregate at 40x magnification and (b) Natural Aggregate at 1000x magnification

Figure 4.16 compares the surface morphology of concrete with natural aggregates and concrete containing 3% recycled HDPE (rHDPE) aggregates at 40x and 1000x magnifications. While the microstructure of the natural aggregate concrete appears dense, the concrete with 3% rHDPE exhibits some porosity and micro-cracks, particularly visible at higher magnification. The introduction of 3% rHDPE aggregates into the concrete mixture leads to the formation of a slightly porous microstructure with micro-cracks. This can be attributed to the poor interfacial bonding between the hydrophobic HDPE particles and the cement matrix. The weaker ITZ and the presence of micro-cracks may contribute to a slight reduction in compressive strength and dimensional stability compared to the natural aggregate concrete. However, the impact on surface roughness is expected to be minimal at this low rHDPE content.

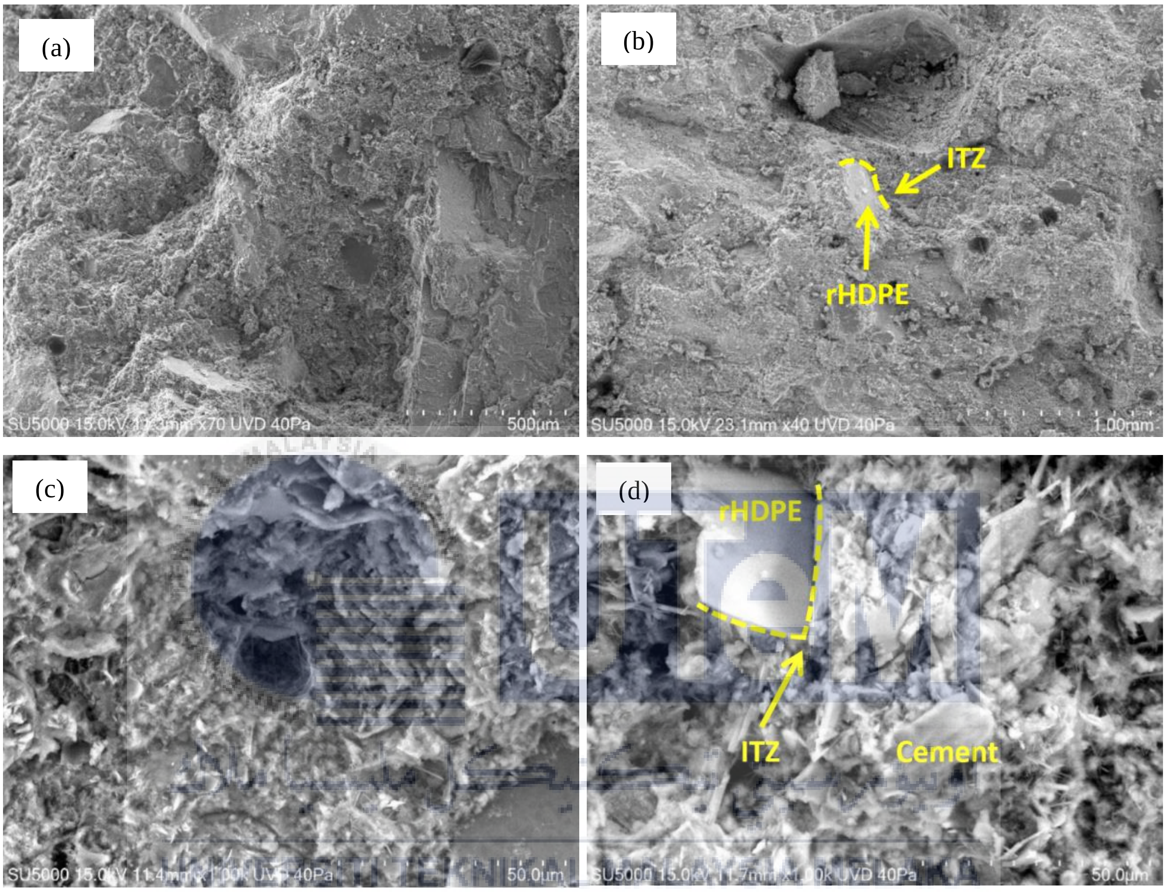

Figure 4.16: Comparison of surface morphology of concrete with (a) Natural Aggregate at 40x magnification, (b) 3% rHDPE at 40x magnification (c) Natural Aggregate at 1000x magnification, and (d) 3% rHDPE at 1000x magnification

Figure 4.17 shows the surface morphology of concrete with 7% rHDPE aggregates in comparison to the natural aggregate concrete at 40x and 1000x magnifications. The concrete with 7% rHDPE exhibits a more porous microstructure with visible micro-cracks and voids, particularly evident at higher magnification. As the percentage of rHDPE aggregates increases to 7%, the microstructure becomes increasingly porous, and the number of micro-cracks and voids increases. This can be attributed to the poor adhesion between the HDPE particles and the cement matrix, leading to a weaker ITZ. The porous microstructure and the presence of micro-cracks can adversely affect the compressive strength, dimensional stability, and potentially the surface roughness of the concrete tiles. The increased porosity may also contribute to a lower density of the concrete tiles with higher rHDPE content.

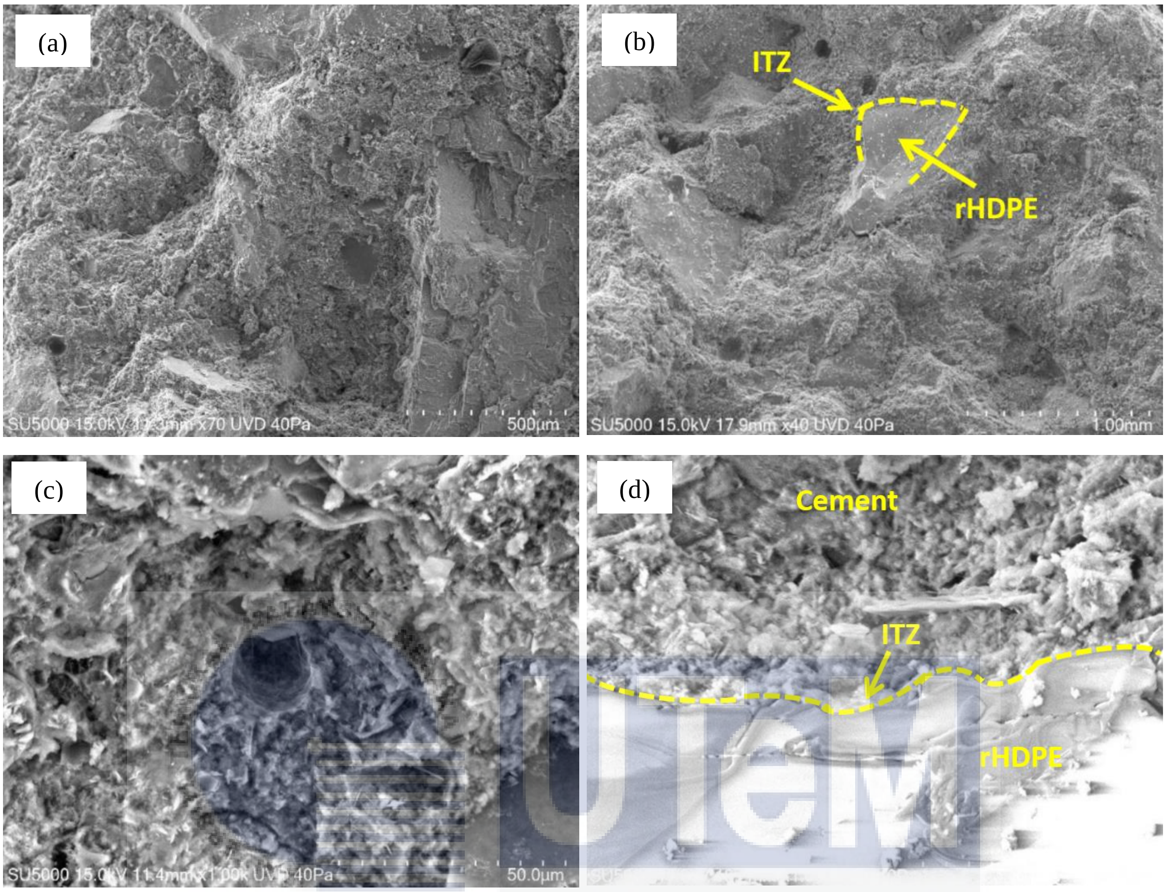

Figure 4.17: Comparison of surface morphology of concrete with (a) Natural Aggregate at 40x magnification, (b) 7% rHDPE at 40x magnification, (c) Natural Aggregate at 1000x magnification and (c) 7% rHDPE at 1000x magnification

Figure 4.18 compares the surface morphology of concrete with 10% rHDPE aggregates to the natural aggregate concrete at 40x and 1000x magnifications. The concrete with 10% rHDPE exhibits a highly porous microstructure with numerous micro-cracks and voids, particularly visible at higher magnification. At the highest rHDPE content of 10%, the microstructure of the concrete tiles shows significant porosity and a high density of micro-cracks and voids. This can be attributed to the poor interfacial bonding between the HDPE particles and the cement matrix, leading to a weak ITZ. The highly porous microstructure and numerous micro-cracks can significantly impact the concrete tiles' compressive strength, dimensional stability, and surface roughness, as detailed in subsections 4.1, 4.2 and 4.3. The increased porosity also contributes to a lower density of the concrete tiles with 10% rHDPE content, as observed in the experimental results.

The SEM images indicate that the ITZ between the rHDPE particles and the cement paste becomes more porous and less dense as the rHDPE content increases. This can be attributed to the hydrophobic nature of rHDPE, which hinders proper bonding with the cement paste, leading to a weaker interfacial bond. Increased porosity within the cement matrix, observed with higher rHDPE content, can negatively impact the concrete's strength, permeability, and durability. The distribution of rHDPE particles within the cement matrix becomes more concentrated with higher rHDPE content, leading to a higher probability of particle clustering and agglomeration, further weakening the interfacial bond and increasing porosity. The microstructural density of the concrete decreases with increasing rHDPE content, with samples containing higher rHDPE percentages exhibiting a less dense and more porous microstructure compared to the natural aggregate sample, which can adversely affect the mechanical properties and durability of the concrete. These observations support the reduction of compressive strength of the concrete tiles, as discussed in subsection 4.1.

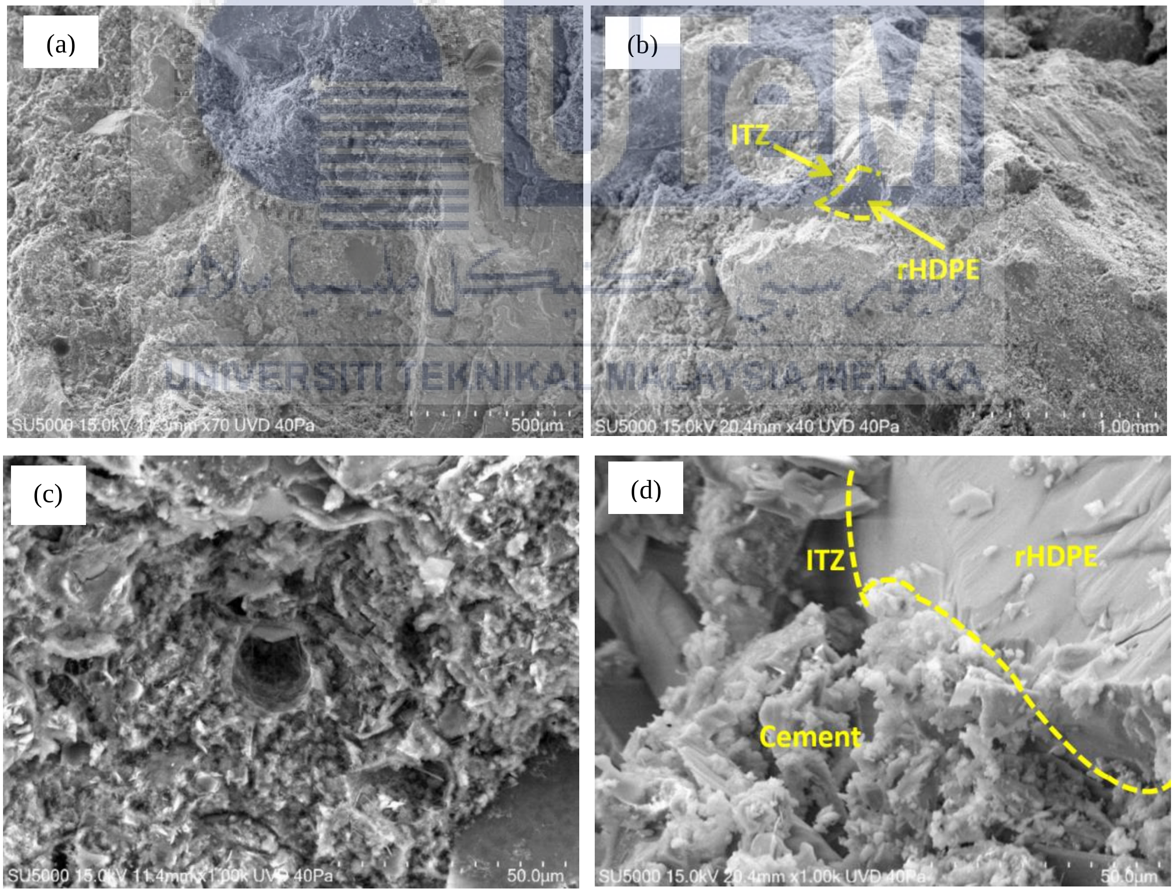

Figure 4.18: Comparison of surface morphology of concrete with (a) Natural Aggregate at 40x magnification, (b) 10% rHDPE at 40x magnification, (c) Natural Aggregate at 1000x magnification and (c) 10% rHDPE at 1000x magnification.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

To conclude, the production of detachable green concrete tiles for flooring applications using recycled high-density polyethylene (rHDPE) as a partial replacement for natural aggregates was successfully carried out following a comprehensive experimental program. The research objectives were achieved by evaluating the tiles' compressive strength and dimensional accuracy.

The compressive strength results revealed a decrease in strength with increasing rHDPE content, although all formulations met the minimum requirement of 10 MPa for flooring applications. The 0% rHDPE mix exhibited the highest compressive strength of 21.73 MPa at 28 days, while the 10% rHDPE mix had the lowest strength of 14.37 MPa. This reduction in strength can be attributed to the weaker interfacial transition zone (ITZ) between the rHDPE aggregates and the cement matrix, as observed in the morphological analysis.

The dimensional accuracy analysis showed an increase in dimensional changes with higher rHDPE content, reaching up to 2.4% for the 10% rHDPE mix. Notably, the Ra values for all mixes fell within the optimal range of 6-9 µm, ensuring adequate slip resistance and aesthetic appeal for flooring applications. The density of the concrete tiles decreased linearly with increasing rHDPE content, reaching 0.32 kg/m³ for the 10% rHDPE mix. This reduction in density can be advantageous for flooring applications, as it can lead to easier handling and installation of the tiles.

The morphological analysis, comprising Physical Fracture Criteria, Optical Microscopy, and Scanning Electron Microscopy (SEM), provided valuable insights into the microstructural behavior of the tiles. The natural aggregate tiles exhibited a dense and uniform microstructure, while the rHDPE-containing tiles showed increased porosity, micro-cracks, and a weaker ITZ with higher rHDPE percentages. These microstructural changes contributed to the observed reductions in compressive strength and dimensional stability.]

Overall, the incorporation of rHDPE in concrete tiles demonstrated a balance between sustainability and structural integrity. The 93:7 natural-to-plastic aggregate ratio exhibited the most promising performance, meeting the strength and dimensional requirements while incorporating a significant amount of recycled plastic waste. The 90:10 ratio mix, while meeting the minimum strength requirement, showed greater dimensional changes and reduced compressive strength, but its lower density makes it ideal for applications prioritizing lightweight and sustainability.

The significance of this study lies in its potential to revolutionize the construction industry by promoting the use of sustainable and recycled materials. By demonstrating the feasibility and benefits of using rHDPE in concrete tiles, this research paves the way for more environmentally friendly construction practices. It contributes to waste reduction and opens up new possibilities for developing lightweight, durable, and sustainable construction materials. This study, therefore, represents a significant step forward in our pursuit of a more sustainable future.

5.2 Recommendations

Based on this study, the following are the recommended topics for future studies for knowledge development in this field:

i. To explore higher percentages of rHDPE as hybrid aggregates in concrete tiles. Future studies could investigate using higher percentages of rHDPE, such as 15%, 20%, and 25%, in the composition of concrete tiles. The aim would be to determine the upper limits of rHDPE incorporation that can be achieved without significantly compromising the tiles' mechanical properties and dimensional stability.

ii. To investigate the thermal expansion properties of green concrete tiles with varying rHDPE content. Understanding how the inclusion of rHDPE affects the thermal expansion of concrete tiles could have significant implications for their performance in different climates and under varying temperature conditions. This could involve subjecting the tiles to a range of temperatures and measuring their dimensional changes.

iii. To study the effect on the properties of green concrete tiles with other recycled materials such as polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Each of these materials has unique properties that could influence the performance of the tiles in different ways. For instance, PP and PET are known for their strength and durability, while PVC has excellent resistance to environmental degradation. By studying the effects of these materials on the properties of green concrete tiles, researchers could develop new formulations that optimize performance while maximizing the use of recycled content. This could lead to the creation of even more sustainable and environmentally friendly construction materials.

5.3 Sustainable Elements

This research was motivated by the innovation of incorporating sustainable practices into various fields, particularly focusing on recycled plastic materials. The data and results obtained may contribute to society in numerous ways, especially in the engineering and construction fields. These fields were constantly evolving and seeking improvements to move forward into the future. At the same time, societies related to these fields were looking for potential research that benefits themselves and others. This research contributed to society as follows:

i. The research aims to reduce the amount of plastic waste that ends up in landfills. Recycling and reusing plastic waste aligns with the Sustainability Goal of Responsible Consumption and Production (SDG 12). This practice decreases the environmental burden of plastic waste and promotes a circular economy where materials are continuously reused, reducing the need for virgin resources.

ii. The use of lightweight materials, such as recycled plastic tiles, leads to lower transportation costs and fuel consumption. This contributes to the Sustainability Goal of Climate Action (SDG 13) by reducing carbon dioxide and carbon monoxide emissions. Reducing transportation emissions helps mitigate climate change and promotes more sustainable logistics and supply chains.

iii. The tiles made from plastic waste contribute to the construction of greener buildings. This supports the Sustainability Goal of Sustainable Cities and Communities (SDG 11) by promoting eco-friendly building materials. Greener buildings reduce urban development's environmental footprint and enhance communities' sustainability by using durable and environmentally friendly materials.

iv. Plastic tiles can be as strong and durable as traditional tiles but cheaper. This is an important part of the Sustainability Goals related to Industry, Innovation, and Infrastructure. Using cost-effective and durable materials promotes innovation in construction and infrastructure, making sustainable practices more accessible and economically viable.

5.4 Lifelong Learning Elements

Time management is the biggest challenge in balancing work and study. It's crucial to prioritize and allocate sufficient time for both academic pursuits and professional responsibilities to succeed in both realms. Learning new skills, such as operating machinery, requires recognizing and following the proper techniques. These skills can be mastered with practice and minimal supervision, ultimately enhancing one's overall competence.

5.5 Complexity Elements

In this study, determining the appropriate quantity and achieving homogeneity in the concrete tiles mix containing recycled HDPE aggregates proved challenging. This complexity also arose during the tiles curing process, requiring meticulous monitoring and strict timelines. Calculating the precise proportions to obtain the desired M10 grade concrete mix also presented difficulties. The complexity of producing the concrete mix according to standards involves using the correct tools and following the proper techniques. The data interpretation, analysis and evaluation require a complex understanding of materials' structure, processing, and properties relation to conclude the findings for the variables investigated in this work.

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APPENDICES

A Gantt Chart PSM 1

No.	Task	Weeks														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1.	Selection of PSM title															
2.	Implement and review PSM title selected and filled the synopsis of title with supervisor															
3	Research study and understand the synopsis of title															
4.	Find the related information, journal and references book															
5.	Implement and review of chapter 1 by supervisor															
6.	Make correction for chapter 1															
7	Implement and review of chapter 2 by supervisor															
8	Meet and discuss the progress of chapter 2 with supervisor															
9	Make correction for															

	chapter 2															
10	Implement and review ofchapter 3 with supervisor															
11	Meet and discuss the progress of chapter 3 by supervisor															
12	Make correction for chapter 3															
13	Preparation for poster presentation															
14	Poster Presentation															
15	Complete the report and summit to supervisor and panel															

Planning	
Actual	
Mid Semester Break	

B Gantt Chart PSM 2

No.	Task	Weeks														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1.	Preparation of raw material															
2.	Finalize paramaters settings for all testing															
3	Fabrication tiles for try and error															
4.	Dimensional accuracy test															
5.	Surface roughness test															
6.	Compression strength test															
7	Fabrication final tiles for testing and analysis															
8	Density test															
9	Optical microscopy															
10	SEM analysis															

11	Slide presentation preparation															
12	PSM 2 presentation															
13	Complete the report and submit to supervisor, panel															
14	Complete the technical paper and submit to supervisor															

Planning	
Actual	
Mid Semester Break	