INFLUENCE OF WASTE GLASS AND EFFECTIVE MICROORGANISM ON THE MECHANICAL PROPERTIES OF CONCRETE

ISA MALLUM

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2022

DEDICATION

I dedicate this work to the memory of my parents, Late Alhaji Muhammad Mallum and Late Hajiya Fadimatu Muhammad Mallum (Hajja Barkindo), whose prayers have brought me this far. In addition, I'd like to thank my brother, Engineer Umar Muhammad Mallum, for inspiring me to seek a doctorate, which has enabled me to reach this level.

ACKNOWLEDGEMENT

First and foremost, praises and thanks to Allah SWT, the beloved, the Sustainer of the entire universe; who taught man with a pen what he did not know. With his permission, I was able to complete this research work successfully. I prayed to Almighty Allah to grant peace and blessings to our beloved prophet Muhammad SAW, his family, and companions.

I would like to express my deepest gratitude to my esteemed supervisor, Associate Professor Dr. Abd. Rahman Mohd. Sam, for his invaluable supervision, support, and tutelage throughout my Ph.D. studies. His words of encouragement and guidance, combined with a perfect blend of insight, have helped shape who I am today. I would admit that his dedication and a keen interest in the research work at every stage, with timely suggestions, kindness, enthusiasm, and dynamism, has not only resulted in timely success but has also resulted in an understanding of what the entire research work is all about. I say a big thank you to him. I also express my gratitude to my co-supervisor Dr. Nor Hasanah binti Abdul shukor Lim for her time sparing, useful comments and suggestions throughout the period of my study.

I would like to offer my special thanks to the staff of Structures and Materials Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia for their support towards undertaken my laboratory work. I would also like to appreciate the effort of my colleagues Nathaniel Omolayo, Musa Muhammed, Mujedu, Tobi, and NurHaliza for their understanding and support. The same goes for my friends: Shahid Muhammad Dodo, Bashiru Buba, Mahmud Aliyu, Usman Dahiru Namtari, Mohammed Dahiru Zakari, Bubakari Joda, Rabiu Salihu, Abdussamad Muhammed Mukhtar, Isa Buba Lere, Kabiru Salihu, and many others whose names are not mentioned here for their encouragement and support in pursuing my studies. Thank you very much.

I am deeply grateful to the management of Adamawa State Polytechnic, Yola for selecting me from a large pool of applicants and provide me the opportunity to pursue my doctorate through the Tertiary Education Trust Fund (TETFUND) of Nigeria. I am grateful for the financial assistance provided by TETFUND.

Finally, I'd like to express my heartfelt gratitude to all of my brothers and sisters for their understanding and assistance with these studies. I am extremely grateful to my lovely wife Raihanatu Mohammed and my children - Mohammed Auwal Isa, Fatima Isa Mallum, Zainab Isa Mallum, Abdurrahman Isa Mallum, and Khadija Isa Mallum, for their patience, support, encouragement, and sacrifices for us to achieve this goal; it would not have been possible without their help. I am grateful to them for this big sacrifice.

ABSTRACT

The high demand for concrete in construction leads to the depletion of natural resources such as natural aggregates and clay. The use of waste material in concrete could assist in reducing natural resource depletion and carbon footprints. The use of waste glass in concrete as fine aggregate replacement affects the Interfacial transition zone (ITZ) of glass aggregate concrete and using glass powder as a cement substitute results in low early strength. The purpose of this research was to investigate the properties of concrete with windscreen waste glass as cement and fine aggregates replacement together with effective microorganism (EM) and to establish the appropriate mix proportion that will contribute to enhancing the properties of windscreen glass fine aggregate concrete. Concrete ingredients were altered to contain glass powder (GP) from windscreen glass waste as partial cement replacement (20%) and glass fine aggregate (GFA) as fine aggregate replacement in a proportion of 0-100% (in 20% increments) with EM as water substitute (10%). The laboratory work involves the characterization of waste glass materials and formulation of the size particle of glass aggregate to be used in concrete as fine aggregate replacement. The characterization includes sieve analysis, strength activity index, X-ray Fluorescence (XRF), X-ray diffraction (XRD) and Thermo-gravimetric analysis (TGA). The fresh and hardened properties of glass fine aggregate effective micro-organism concrete (GFAEMC) were investigated. The properties assessed include the workability, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and water absorption. Further studies were carried out on the microstructural properties of concrete using scanning electron microscopy (SEM), Energy dispersive x-ray analysis (EDX), X-ray diffraction (XRD), and Thermo-gravimetric analysis (TGA) to ascertain the filling mechanism and bonding effect at the micro-scale level. In addition, three reinforced concrete beams containing waste glass with two containing EM and one without EM, as well as a control concrete beam, were cast and tested to assess the behaviour of reinforced concrete beams under flexure. Based on the findings, the use of waste glass as fine aggregate and cement replacement in concrete improved concrete properties. Adding waste glass with EM in concrete mix improved the compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity (MOE) by 3.37%, 3%, 6%, and 1%, respectively compared to the control, after 28 days. Also, the water absorption of GFAEMC with a 100% GFA as fine aggregate substitute is slightly lower by 2% than that of the control concrete. The microscale analysis showed that GFAEMC samples had a denser microstructure with more CSH gel when compared to the control. In addition, the ultrasonic pulse velocity (UPV) of GFAEMC samples also indicates a denser microstructure. In addition, the ultimate loads of beams glass fine aggregate effective microorganism (BGFAEM), glass powder (BGP20), glass fine aggregate – glass powder effective microorganism (BGFAGPEM) were all higher than BC (control beam). Beam BGFAEM recorded higher stiffness value than beam BC by 18%. The flexural behaviour of reinforced concrete beams with windscreen glass waste and EM is comparable with the control beam. Based on the findings of this study, it can be concluded that incorporating windscreen waste glass as cement and fine aggregates replacement with EM show positive effects and enhanced concrete properties.

ABSTRAK

Permintaan yang tinggi terhadap konkrit dalam pembinaan menyebabkan pengurangan sumber asli seperti agregat dan tanah liat. Penggunaan bahan buangan dalam konkrit boleh membantu mengurangkan masalah ini dan jejak karbon. Penggunaan kaca buangan sebagai pengganti agregat halus dalam konkrit memberi kesan kepada zon peralihan antara muka konkrit agregat kaca dan penggunaan debu kaca sebagai pengganti simen menghasilkan kekuatan awal yang perlahan. Tujuan kajian ini adalah untuk menilai sifat-sifat konkrit yang mengandungi bahan buangan daripada kaca cermin depan sebagai pengganti sebahagian daripada simen dan agregat halus berserta mikroorganisma efektif (EM) dan menentukan kadar campuran yang akan menyumbang kepada peningkatan sifat konkrit menggunakan agregat halus kaca. Ramuan konkrit diubah menggunakan debu kaca (GP) dari bahan buangan kaca cermin depan sebagai pengganti simen (20%) dan agregat halus kaca (GFA) sebagai pengganti agregat halus dengan kadar 0 – 100% (peningkatan penambahan 20%) dengan mikroorganisma efektif sebagai pengganti air (10%). Ujikaji makmal yang dijalankan termasuk mengenalpasti ciri bahan kaca buangan dan rumusan saiz zarah agregat kaca yang akan digunakan sebagai agregat halus. Kajian pengenalpastian yang dijalankan termasuk analisis ayak, indek aktiviti kekuatan, *X-ray Flourescence* (XRF), *X-ray diffraction* (XRD) dan Analisa Thermogravimetri (TGA). Sifat segar dan mengeras konkrit yang mengandungi agregat halus kaca dan mikroorganisma efektif (GFAEMC) telah dikaji. Sifat yang dikaji termasuk kebolehkerjaan, kekuatan mampatan, kekuatan pemisahan tegangan, kekuatan lenturan, modulus elastik, pengecutan pengeringan, dan penyerapan air. Kajian selanjutnya dijalankan terhadap sifat mikrostruktur konkrit menggunakan *scanning electron microscopy* (SEM), analisa *Energy dispersive x-ray* (EDX), *X-ray diffraction* (XRD), dan analisa Thermogravimetrik (TGA) untuk melihat mekanisma pengisian dan kesan lekatan pada skala mikro. Sebagai tambahan, tiga rasuk konkrit bertetulang mengandungi kaca buangan dengan dua rasuk mengandungi EM dan tiada EM serta rasuk kawalan telah dibuat dan diuji bagi menentukan kelakunan lenturan rasuk. Berdasarkan kepada dapatan kajian, pengunaan kaca buangan dalam konkrit sebagai agregat halus dan pengganti simen dapat meningkatkan sifat konkrit. Penambahan kaca buangan dan EM dalam bancuhan konkrit meningkatkan kekuatan mampatan, kekuatan lenturan, kekuatan pemisahan tegangan dan modulus elastik (MOE) masing-masing sebanyak 3.37%, 3%, 6% dan 1% berbanding kawalan selepas 28 hari. Disamping itu penyerapan air bagi GFAEMC dengan 100% GFA sebagai penganti agregat halus adalah rendah sebanyak 2% berbanding konkrit kawalan. Analisis skala mikro menunjukkan sampel GFAEMC mempunyai mikrostruktur yang lebih padat dengan gel kalsium silakat terhidrat (CSH) yang lebih berbanding kawalan. Disamping itu halaju denyutan ultrasonik (UPV) bagi sampel GFAEMC adalah lebih tinggi bebanding konkrit kawalan menunjukkan mikrostruktur yang lebih padat. Beban muktamad bagi rasuk konkrit bertetulang BGFAEM, BGP20, dan BGFAGPEM adaah lebih tinggi berbanding BC (rasuk kawalan). Rasuk BGFAEM merekodkan nilai kekukuhan yang lebih tinggi daripada rasuk BC sebanyak 18%. Kelakunan lenturan rasuk konkrit bertetulang yang mengandungi kaca buangan cermin depan dan EM adalah setanding dengan rasuk kawalan. Berdasarkan kepada penemuan kajian boleh dinyatakan bahawa mengabungkan kaca buangan cermin depan sebagai pengantian sebahagian daripada simen dan agregat halus serta EM menunjukkan kesan yang positif dan meningkatkan sifat-sifat konkrit.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABS	-	Australia Bureau of Statistics
ACI	-	American Concrete Institute
ASR	-	Alkali silica reaction
ASTM	-	American Society for Testing and Materials
BSEN	-	British Standard European union
Ca	-	Calcium
$Ca(OH)_2$	-	Calcium hydroxide
$CaCO_3$	-	Calcium carbonate
CaO	-	Calcium oxide
CH	-	Calcium hydroxide
CO_2	-	Carbon dioxide
CRT	-	Cathode Ray Tube
C-S-H	-	Calcium silicate hydrate
DTA	-	Differential Thermal Analysis
E	-	Differential Thermal Analysis
EDX	-	Energy Dispersive X-ray Analysis
EM	-	Effective micro-organism
EVA	-	Ethylene-vinyl acetate
FA	-	Fly ash
Fe_2O_3	-	Ferric oxide
GA	-	Glass aggregate
GAIN	-	Global aggregate information network
GFA	-	Glass fine aggregate
GFAEMC	-	Glass fine aggregate effective micro-organism concrete
GGBS	-	Ground Granulated blast furnace slag
GP	-	Glass powder
GPa	-	GigaPascal
GPC	-	Glass powder concrete
GPEMC	-	Glass powder effective micro-organism concrete
H_2O	-	Water

HVFA	-	High Volume Fly ash
K_2O	-	Potassium oxide
LVDT	-	Linear Variable Differential Transformer
MgO	-	Magnesium oxide
MOE	-	Modulus of Elasticity
MSW	-	Municipal solid waste
Na_2O	-	Sodium Oxide
NaOH	-	Sodium Hydroxide
OPC	-	Ordinary Portland cement
PVB	-	Polyvinyl butyral
Q	-	Quartz
RFA	-	Recycled fine aggregate
SAI	-	Strength activity index
SCM	-	Supplementary cementitious material
SEM	-	Scanning Electron Microscope
SF	-	Silica fume
SiO_2	-	Silica
TGA	-	Thermo Gravimetric Analysis
TiO_2	-	Titanium oxide
TPU	-	Thermoplastic Polyurethane
UNEP	-	United Nations environment programme
UPV	-	Ultrasonic Pulse Velocity
USEPA	-	United State Environmental Protection Agency
USGS	-	United State geological survey
WG	-	Waste glass
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence Spectrometer

LIST OF SYMBOLS

d_1 and d_2	-	Lateral dimension of specimen
ε_L	-	Longitudinal strain
ε_T	-	Transverse strain
Ec	-	Modulus of elasticity
F_{cf}	-	Flexural Strength
F	-	Maximum Load
L	-	Distance between the lower roller
ΔL_x	-	length Change of specimen at any age
S	-	Stress
μ	-	Poisson ratio
Wa	-	Percentage of water absorption
Ww	-	Weight of wet specimen
Wd	-	Weight of dry specimen
W_L	-	Percentage weight loss between 400°C and 600°C
M_{CH}	-	Molecular weight of water
Mw	-	The molecular weight of CH

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Concrete is an indispensable material that is made from cement, aggregates, and water and is used in infrastructure development. Construction industries are the largest consumers of construction materials in developing countries, and the majority of construction projects require massive amount of concrete due to urbanization which has increased the demand for concrete. It has been reported that over 30 billion tonnes of concrete are used annually (Monteiro et al., 2017), such volumes require vast amounts of natural resources such as aggregate and cement for concrete production. Attempts to improve concrete's sustainability are critical if the commodity's environmental impact is to be reduced. However, using waste as aggregate and cement replacement materials, on the other hand, can make cost-effective and sustainable concrete. The use of waste material in concrete lowers the cost of production while also affecting the concrete's qualities (Suliman et al., 2019).

Nowadays, construction industries are becoming increasingly aware and interested in using recycled or waste materials to promote sustainable and green concrete (Al-Mansour et al., 2019). However, the impact of the recycled or waste materials on mechanical properties and durability, such as porosity and water absorption are the most affected factors, which must be taken into account (Collivignarelli et al., 2020). Similarly, various types of industrial by – products were employed in making concrete as a partial or complete fine aggregate replacement material, and their qualities were compared to control concrete (Dash et al., 2016). As a result, for long-term sustainability, materials and ingredients capable of making effective and high-quality concrete should be used. Therefore, green materials, such as industrial wastes, are widely available, inexpensive and they might be used to relieve the burden on natural resources, thereby promoting sustainability (Saran and Singh, 2021).

1.2 Background of the study

The global requirement to conserve natural resources and reduce CO_2 emissions to ensure the long-term sustainability of concrete structures has fuelled the search for alternative materials. Research showed that many waste materials such as tin slag, crushed glass, construction debris, plastic waste, and ceramic waste are used as partial fine aggregate replacement in concrete and has been found to improve the properties of concrete (Sandanayake et al., 2020). Therefore, emphasis has been placed on using waste material to replace fine aggregate. Also, the use of fly ash, GGBS, silica fume, glass powder, palm oil fuel ash, rice husk ash as cement replacement has been shown to improve the strength of concrete (Mark et al., 2019). Thus, the use of alternative materials for cement and fine aggregate replacement will assist in saving the available natural resources.

In relation to that, waste glass could provide an equal alternative to conventional aggregate in concrete, and using waste glass as fine aggregate in concrete not only benefits the environment but also decreases the demand for natural raw materials extraction. Although much of the waste glass is reused to create new glass products, a significant part is still discarded in landfills. Glass is an important yet non-biodegradable material that takes up considerable landfill space. New reuse methods should be researched to effectively manage the waste glass that is being disposed of in order to improve the sustainability of the construction industries (Harrison et al., 2020). The use of waste glass in cementitious materials is a low-cost way to reduce waste while also improving the qualities of cementitious composites.

Tamanna *et al.*, (2020) investigated the performance of mixed bottle waste glass as fine aggregate replacement in concrete in a ratio of 20% to 60% recycled glass sand (RGS) with particle size between 2.36 mm to150 µm. The result indicated that fine glass can be replaced up to 20% using RGS which shows about 7% higher strength compared to control after 28 days. However, it was recorded that 40% RGS and 60% RGS also achieved 86% and 96% of the control concrete strength, respectively, after 28 days. Similarly, the study conducted by Ibrahim, (2017) shows improvement on the properties of concrete up to 40% fine aggregate replacement with waste glass, which is about 5% increment in compressive strength after 28 days compared to control concrete. Furthermore, Olofinnade *et al.*, (2018) studies proved that window and container waste glass could also be used as a fine aggregate replacement for up to 50%. The results showed that concrete mixes with 25% and 50% glass content as a fine aggregate replacement recorded 20% increase in compressive strength after 28 days, compared to the control. After 90 days of curing, the compressive strength of 25% and 50% glass aggregate improved by 10% and 4%, respectively. While 75% fine aggregate replacement had the lowest compressive strength of 6% and 3% lower than the control concrete at 28 and 90 days, respectively. It was also reported that the compressive strength for 100% waste glass as fine aggregate replacement decreases by 32% and 13% at 28-day and 90-day when compared to the control concrete, respectively. The decline in the compressive strength is most likely attributed to the poor interfacial transition zone of glass aggregate.

Previous studies have also reported that waste glass in finely powdered form has been used as a partial substitute for Portland cement in concrete up to 20% (Yassen et al., 2019; Patel et al., 2020). Other studies also found that concrete with 20% mixed coloured glass powder with 20 μm particle size as a cement replacement material performed better than the control concrete after 90 days of curing (Nassar et al., 2021). The test result shows that at 90 days of concrete age, concrete containing glass powder had a 43% increase in compressive strength between 28 days and 90 days and a 28% increase in flexural strength when compared to control concrete. The improvement of the strengths is due to the development of calcium silicate hydrate gel at later ages. It is therefore evident from the literature that glass powder potentially could be used as cement replacement materials in concrete.

Many researchers have conducted numerous experiments on the partial replacement of fine aggregate with different type of waste glass and found that it is feasible. The most common type of glass waste used is Soda-lime glasses such as bottle glass, container glass, and float glasses with a few of lead silica glass. However, with various types of glass waste used in previous literature still the windscreen glass waste is not being explored as fine aggregate or cement replacement in concrete. Due to the variations in their thermal properties, windscreens built of laminated glasses have been found to be stronger than other glass types utilized in the literature. Windscreens are manufactured from two sheets of soda-lime glasses (tempered) that have been found to be four to five times stronger than annealed soda-lime glasses made using the annealing process. When correctly processed, it can thus have the potential to be used as a fine aggregate alternative in concrete.

The only few studies that utilize windscreen glass, are as coarse aggregates in concrete (Arabi et al., 2019; Paiz. et al., 2019). It has been established that only a partial replacement of 10% windshield glass might be used as coarse aggregate replacement in concrete (Paiz et al., 2019). However, Arabi et al., (2019) study showed that the use of windshield glass as coarse aggregate in self-compacting concrete in a ratio of 25, 50, 75, and 100 percent replacement had a decrease in strength in all replacements. This decrease could be attributed to the weak bonding between the aggregate and the cement paste as a result of the smooth surface of the glass.

Although grinding glass aggregate creates a rough fracture surface, it has minimal influence on the qualities of aggregate and bonding to cement matrix. However, further decrease in the size of crushed glass aggregate can increase the rough fracture surface, which improves the compressive strength of concrete (Song et al., 2019). Thus, the aspect of bonding between waste glass aggregate and cement matrix needs further study on how to improve the interfacial transition zone (ITZ) which could be done by reducing the sizes of the glass aggregate to smaller sizes and subsequent addition of effective microorganism (EM) to the concrete. Similarly, past research has shown that using glass powder as a cement substitute results in low early strength due to low early pozzolanic reactivity (Kalakada et al., 2019). In relation to this, more research on how to increase early strength is also required.

It is normally assumed that decreasing the size of aggregate to smaller sizes improve the surface area accessible for bonding (i.e. increasing roughness) which increases interfacial bond strength; nevertheless, the aggregate must be mechanically strong enough at its bonded surface to sustain this increase in bond strength. This shows that differences in aggregate mechanical strength, and internal structure are the major factors influencing bond strength and failure mode at the interface (Tasong et al., 1998).

Likewise, the need for sustainability has led to the use of environmentally beneficial materials like microorganisms. Previous studies showed that the use of effective microorganism (EM) in cement paste contributes to higher compressive strength and dense internal microstructure with less void compared to control cement paste (Ismail and Mohd Saman, 2014). Similarly, other studies verified that the inclusion of EM improves concrete properties in terms of workability, strength and durability of concrete (Isa et al., 2016; Rizwan et al., 2017; Mohd.Sam et al., 2019). EM has also been shown to improve the early and later ages strength of concrete with supplementary cementitious composite (Huseien et al., 2021).

Based on the shortcomings of previous research, this study proposes to utilize EM to adjust the characteristics of concrete and improve the interfacial transition zone of waste glass aggregate concrete. In addition, this study also looks into on how to mitigate the effect of low early strength of glass powder concrete when used as a cement replacement material that will contribute to sustainable technology and waste reduction. Therefore, further research into the properties of concrete containing glass fine aggregate (GFA) as a fine aggregate replacement and glass powder (GP) as cement replacement with EM can contribute to the wider acceptance of waste glass used in concrete. It may also help to reduce the use of natural aggregate as a fine aggregate in concrete to minimise natural resource depletion. As a result, waste valorisation in concrete may be a viable option for ensuring the long-term sustainability and cost-effectiveness of concrete. Due to this impact, the qualities of waste glass concrete will be improved.

1.3 Problem Statement

A considerable amount of waste glass is disposed of in landfills or discarded in open spaces. For example, every year, Malaysians throw away over 3,000,000 kg of windscreen glass (Glass Mechanic Sdn Bhd, 2012). Many people assume that glass is recyclable. Almost all windscreens currently on the market are laminated using tampered glass, but the layers of polyvinyl butyral film sandwiched between the glasses make windscreens non-recyclable or, at the very least, uneconomical to recycle. As a result, the only way to dispose of unused windscreens is to bury them or throw them in a landfill.

Several studies have focused on the use of waste glass in concrete as a partial replacement for natural aggregate only. However, incorporating waste glass powder as cement replacement in the same concrete mixture with the glass aggregate could create sustainable development due to abundant glass waste generated. However, few studies incorporate waste bottle and float glasses as fine aggregate and glass powder as cement replacement (Afshinnia and Rangaraju, 2016; Kiliçoglu and Çoruh, 2017; Shen *et al.*, 2020). It has been established that the use of bottle waste glass and float glass as aggregate and supplementary cementitious material (SCM) in the same mixture could only be used up to 10 to 20% fine aggregate replacement and 5% to 20% cement replacement due to poor bonding between the smooth surface of glass particles and Portland cement paste.

Based on the previous works, weak interfacial transition zone of glass aggregate has been identified by many authors as the primary contributor of low strength at a higher fine aggregate replacement in concrete due to smooth surface of the glass. Therefore, this study intended to overcome these effects (bonding) by providing increase rough fracture surface texture of glass aggregate through the reduction of the particle size of the aggregate, and subsequent application of EM to improve the performance of the concrete matrix. At present there is no published research employs windscreen waste glass as a fine aggregate and/or cement substitution with effective micro-organisms. The use of EM to improve the bonding effect of waste glass aggregate concrete could result in the maximum use of windscreen waste glass as a fine aggregate (100%) and cement replacement in concrete. This will contribute not only enhancing the properties of concrete but also reducing the load on landfills and saving available natural resources. Thus, this study focuses on the application of windscreen waste glass as a fine aggregate and cement replacement with effective microorganisms (EM-1) in concrete.

1.4 Aim and Objectives

The aim of this study is to evaluate the properties of concrete containing windscreen waste glass as a replacement for fine aggregate and cement with effective micro-organism (EM) in concrete.

1.4.1 Research Objectives

The objectives of the research are as follows:

i) To characterize the properties of waste glass and establish the appropriate mix proportion that will contribute to enhancing the properties of glass aggregate concrete.

ii) To evaluate the influence of effective microorganism and glass powder on the interfacial transition zone of waste glass aggregate and its effect on fresh and hardened properties of concrete.

iii) To examine the properties of glass fine aggregate effective microorganism concrete at microscale level and evaluate the factors affecting the microstructure development of interfacial transition zone of the glass concrete.

iv) To assess the implication of using windscreen waste glass as a fine aggregate and cement replacement with effective microorganism on the flexural behaviour of reinforced concrete beams.

1.5 Scope of the Research

The research emphasis is on the performance of concrete with windscreen waste glass as fine aggregate and cement replacement and improvement of ITZ of glass aggregate concrete. The waste glass was used in concrete as fine aggregate replacement with a ratio of 20%, 40%, 60%, 80%, and 100% with the aggregate's particle size of 1.18mm -150µm and glass powder of less than 45µm was used as cement replacement at 20% and EM (10%). The properties of waste glass as fine aggregate and cement replacement was characterized through physical, chemical, and mineralogical properties and the glass aggregate particles were formulated by decreasing the sizes to smaller size before applying it as fine aggregate replacement in concrete in order to improve the properties of concrete. The characterization, include sieve analysis, strength activity index, X-ray Fluorescence (XRF) for determination of the chemical composition of glass powder, and X-ray diffraction (XRD) for phase identification using glass powder sample and further studies of the pozzolanic reactivity of glass powder paste sample were determine through X-ray diffraction and Thermogravimetric analysis (TGA). The fresh and hardened properties of the glass fine aggregate effective micro-organism concrete (GFAEMC) were investigated. The properties include the slump test, compressive strength test, splitting tensile strength test, flexural strength test, modulus of elasticity, drying shrinkage, and water absorption. The study further checked on the microstructural analysis using scanning electron microscopy (SEM), Energy dispersive x-ray analysis (EDX), X- ray diffraction (XRD), and Thermogravimetric analysis (TGA) to ascertain the filling mechanism and bonding effect at the micro-scale level. Furthermore, three reinforced concrete beams were used to assess the effect of using waste glass with effective microorganism (EM) in concrete in terms of flexural behaviour and then compared with the control reinforced concrete beam.

1.6 Significance of the study

The importance of this study is to provide sustainable and greener concrete through the use of waste material (windscreen waste glass) with the potential of enhancing the properties of concrete by improving the ITZ of glass aggregate concrete. Many of the waste materials disposed of have the potential to improve the properties of concrete when used as either fine aggregate or cement replacement as the case may be. The use of waste glass as fine aggregate and cement replacement will assist in saving the available natural resources and also reduce the carbon dioxide footprint through the use of less cement. Finer particles of waste glass when used as cement replacement is proven to improve strength properties as a result of the production of more calcium silica hydrates (C-S-H) gel. The use of waste glass as cement replacement will reduce costs and prolong the service life of the concrete structure.

The research focuses on the use of waste glass as both fine aggregate and cement replacement with effective microorganism in concrete for sustainable practices. The performance of glass fine aggregate effective micro-organism concrete (GFAEMC) was evaluated in terms of strength, microstructure, and structural behaviour of beams. This knowledge will contribute to the development of environmentally friendly and low-cost materials for concrete production in various applications in the construction industry.

1.7 Thesis layout

The thesis was arranged following the UTM thesis manual 2018. The work was spread in eight different chapters as follows:

Chapter 1 The first chapter describes the general background on the number of natural resources consumed by construction industries and the need for using recycled materials to preserve the resources. A brief emphasis was made on the importance of using waste glass as fine aggregate and cement replacement to reduce the CO_2 footprint and cost. The chapter further presents the background of the problem, aim, and objectives, statement of the problem, the scope of the study, and significance of the research

Chapter 2 The second chapter presents previous literature relating to the use of waste glass as a fine aggregate and cement replacement in concrete and the use of effective microorganism in concrete. This chapter contains a review of the performance of waste glass in concrete and effective microorganism.

Chapter 3 The chapter describes the method and the material used along with the test conducted for the research. The procedures that are followed in conducting the research work.

Chapter 4 In this chapter the analysis of the results on the characterization of waste glass powder and waste glass aggregate were described and the trial mixes of concrete containing waste glass as aggregate and cement were discussed.

Chapter 5 The chapter explains the fresh and hardened properties of concrete with waste glass and effective microorganism (EM) on the slump test, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity (MOE), drying shrinkage, and water absorption.

Chapter 6 The chapter discusses the microstructural analysis of waste glass and EM concrete under the following test conducted scanning electron microscopy (SEM), Energy Dispersive X-ray analysis (EDX), X-ray diffraction (XRD), and Thermo-Gravimetric Analysis (TGA).

Chapter 7 The chapter presents the results obtained for the flexural test on the reinforced concrete beams containing waste glass and effective microorganism (EM) and the control beam (without waste glass). The beams containing waste glass were compared with the control beam to evaluate the performance and the behaviour of the waste glass effective micro-organism concrete beams.

Chapter 8 In this chapter conclusions were drawn based on the findings from the research work and a recommendation was outlined for future studies for maximum utilization of waste glass as fine aggregate and cement replacement with effective microorganism in construction industries.

REFERENCES

Abdallah, S., and Fan, M. (2014). Characteristics of concrete with waste glass as fine aggregate replacement. *International Journal of Engineering and Technical Research (IJETR)*, *2*(6), 11–17.

ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02), American Concrete Institute, 2002.

Adam Wellsey. (2015). *The Properties of Glass*. https://go.koppglass.com/properties-of-glass-ebook

Adaway, M., and Wang, Y. (2015). Recycled glass as a partial replacement for fine aggregate in structural concrete -Effects on compressive strength. *Electronic Journal of Structural Engineering*, *14*(1), 116–122.

Afshinnia, K., and Rangaraju, P. R. (2016). Impact of combined use of ground glass powder and crushed glass aggregate on selected properties of Portland cement concrete. *Construction and Building Materials*, *117*, 263–272. https://doi.org/10.1016/j.conbuildmat.2016.04.072

Ahmad, J., Aslam, F., Martinez-Garcia, R., De-Prado-Gil, J., Qaidi, S. M. A., & Brahmia, A. (2021). Effects of waste glass and waste marble on mechanical and durability performance of concrete. *Scientific Reports*, *11*(1), 1–17. https://doi.org/10.1038/s41598-021-00994-0

Al-bawi, R. K., Kadhim, I. T., & Al-kerttani, O. (2017). Strengths and Failure Characteristics of Self-Compacting Concrete Containing Recycled Waste Glass Aggregate. *Advances in Materials Science and Engineering.Hindawi*, *2017*, 1–12. https://doi.org/https://doi.org/10.1155/2017/6829510

Al-Mansour, A., Chow, C. L., Feo, L., Penna, R., and Lau, D. (2019). Green concrete: By-products utilization and advanced approaches. *Sustainability (Switzerland)*, *11*(19), 1–30. https://doi.org/10.3390/su11195145

Ali, E. E., and Al-Tersawy, S. H. (2012). Recycled glass as a partial replacement for fine aggregate in self compacting concrete. *Construction and Building Materials*, *35*(October), 785–791. https://doi.org/10.1016/j.conbuildmat.2012.04.117

Ali, S., Iqbal, S., Room, S., Ali, A., Rahman, Z. (2021) Value added usage of granular steel slag and milled glass in concrete production, J. Eng. Res., 9, (2021), 73–85. doi: https://doi.org/10.36909/jer.v9i1.8214.

Aliabdo, A. A., Elmoaty, A., Elmoaty, M. A., and Aboshama, A. Y. (2016). Utilization of waste glass powder in the production of cement and concrete. *Construction and Building Materials*, *124*, 866–877. https://doi.org/10.1016/j.conbuildmat.2016.08.016

Almesfer, N., and Ingham, J. (2014). Effect of Waste Glass on the Properties of Concrete. *Journal of Materials in Civil Engineering*, *25*(7), 864–870. https://doi.org/10.1061/(ASCE)MT.1943-5533

Arabi, N., Meftah, H., Amara, H., Kebaïli, O., and Berredjem, L. (2019). Valorization of recycled materials in development of self-compacting concrete: Mixing recycled concrete aggregates – Windshield waste glass aggregates. *Construction and Building Materials*, *209*, 364–376. https://doi.org/10.1016/j.conbuildmat.2019.03.024

Asa, E., Anna, A. S., and Baffoe-twum, E. (2019). An investigation of mechanical behavior of concrete containing crushed waste glass concrete. *Journal of Engineering, Design and Technology*, 1–19. https://doi.org/10.1108/JEDT-01-2019-0020

ASTM C136 (2014) 'Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates'. Annual book of ASTM standards, American Society for Testing and Materials.

ASTM C150 (2016) 'Standard Specification for Portland Cement', ASTM International, west Conshohocken, 04 (01), 2020, 1–9. doi: 10.1520/C0150/C0150-20 .www.astm.org.

ASTM C33/33M (2018) 'Standard specification for concrete aggregate', ASTM International, west Conshohocken, 04 (02),(2018), 1–11. doi: 10.1520/C0033_C0033M-18.www.astm.org.

ASTM C618 (2019) 'Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete', ASTM International, West Conshohocken, 04(2), (2019), 3–6. doi: https://doi.org/10.1520/C0618-19. www.astm.org

ASTM C109 / C109M (2020) 'Standard Test Method for Compressive Strength of hydraulicCement Mortars (Using 2-in. or [50 mm] Cube Specimens) ', ASTM International, West Conshohocken, PA, 2020, doi: 10.1520/C0109_C0109M-20B. www.astm.org

ASTM C1602 / C1602M (2018) 'Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete', ASTM International, West Conshohocken, 04(02), (2018), 1–11. doi: 10.1520/C1602_C1602M-18. www.astm.org.

ASTM C192/192M (2018) 'Standard practice for making and curing concrete test specimens in the laboratory', ASTM International, West Conshohocken, 04(02), (2018), 1–11. doi: 10.1520/C0192_C0192M-19. www.astm.org.

ASTM C 311/311M (2018) 'Standard test method for sampling Fly ash or Natural pozzolans use for portland cement concrete', ASTM International, West Conshohocken, 04(02), (2018), 1–11. doi: 10.1520/C0311_C0311M-18.. www.astm.org.

ASTM-C511(2019) 'Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes', ASTM International, West Conshohocken, 04(01), 2019, doi: 10.1520/C0511-19. www.astm.org.

ASTM C143/143M (2020) 'Standard Test Method for Slump of Hydraulic-Cement Concrete', ASTM International, West Conshohocken, 04(02), 2020, doi: 10.1520/C0143_C0143M-20. www.astm.org.

ASTM C496/ C496M (2017) 'Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete specimen', ASTM International, West Conshohocken, 04(01), (2017), 1-5. doi: 10.1520/C0496_C0496M-17.www.astm.org.

ASTM C469/469M (2014) 'Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in compression', Am. Soc. Test. Mater., 04, (2014), 1–5.

ASTM C597 (2016) 'Standard Test Method for Pulse Velocity Through Concrete',
ASTM International, West Conshohocken, PA, 2016, doi: 10.1520/C0597-16.
www.astm.org

ASTM C157 / C157M (2017) 'Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete', ASTM International, West Conshohocken, PA, 2017, www.astm.org, (2017), doi: 10.1520/C0157_C0157M-17

Atoyebi, O. D., and Sadiq, O. M. (2018). Experimental data on flexural strength of reinforced concrete elements with waste glass particles as partial replacement for fine aggregate. *Data in Brief*, *18*, 846–859. https://doi.org/10.1016/j.dib.2018.03.104

Azreen, N. M., Rashid, R. S., Haniza, M., Voo, Y. L., and Amran, Y. M. (2018). Radiation shielding of ultra-high-performance concrete with silica sand, amang and lead glass. *Construction and Building Materials*, *172*, 370-377.

Balasubramanian, B., Krishna, G. V. T. G., Saraswathy, V., Srinivasan, K. (2021). Experimental investigation on concrete partially replaced with waste glass powder and waste E-plastic, Constr. Build. Mater., 278, 122400. doi: 10.1016/j.conbuildmat.2021.122400.

Bawab, J., Khatib, J., Jahami, A., Elkordi, A., and Ghorbel, E. (2021). Structural Performance of Reinforced Concrete Beams Incorporating Cathode-Ray Tube (CRT) Glass Waste. *Buildings*, *11*(67). https://doi.org/https://doi.org/10.3390/buildings11020067

Belebchouche, C., Moussaceb, K., Bensebti, S., and Aït-mokhtar, A. (2021). Mechanical and Microstructural Properties of Ordinary Concrete with High Additions of Crushed Glass. *MDPI Materials*, *April*. https://doi.org/10.3390/ma14081872

Bisht, K., and Ramana, P. V. (2022). Experimental investigation of strength, drying shrinkage, freeze and thaw and fire attack properties of concrete mixes with beverage glass waste as fine aggregate. *Structures*, *36*(December 2021), 358–371. https://doi.org/10.1016/j.istruc.2021.12.019

Bisht, K., and Ramana, P. V. (2018). Sustainable production of concrete containing discarded beverage glass as fine aggregate. *Construction and Building Materials*, *177*, 116–124. https://doi.org/10.1016/j.conbuildmat.2018.05.119

Bisikirske, D., Blumberga, D., Vasarevicius, S., and Skripkiunas, G. (2019). Multicriteria Analysis of Glass Waste Application. *Environmental and Climate Technologies*, *23*(1), 152–167. https://doi.org/10.2478/rtuect-2019-0011

Bostanci, S. C. (2020). Use of waste marble dust and recycled glass for sustainable concrete production. *Journal of, Cleaner Production*, *251*, 1–40. https://doi.org/10.1016/j.jclepro.2019.119785

BS EN 12390-3:2019 Testing hardened concrete - Part 3: Compressive strength of test specimens, Stand. by Br. -Adopted Eur. stanadad, 2009.

BS EN 12390-5 (2019) Testing hardened concrete Part 5- Flexural strength of test specimens. (2019), 1–5.

BS EN 12390-7 (2019) Testing hardened concrete. Density of hardened concrete. (2019), 1-3.

BS 1881-122:2011+A1 (2020) Testing concrete Part 122 : Method for determination of water absorption,"BSI Stand., (2011), 1–8.

BS EN 1992-1-1:2004+A1 (2014) Euro code 2: Design of concrete structures. General rules and rules for buildings. (2014),1-230.

Butler, J. H., and Hooper, P. D. (2019). Glass Waste. In *Waste* (2nd ed.). Elsevier Inc 307-322. https://doi.org/10.1016/b978-0-12-815060-3.00015-3.

Chaïd, R., Kenaï, S., Zeroub, H., and Jauberthie, R. (2015). Microstructure and permeability of concrete with glass powder addition conserved in the sulphatic environment. *European Journal of Enviromental and Civil Engineering*, *19*(October), 219–237. https://doi.org/10.1080/19648189.2014.939310

Chen, Z., Wang, Y., Liao, S., and Huang, Y. (2020). Grinding kinetics of waste glass powder and its composite effect as pozzolanic admixture in cement concrete. *Construction and Building Materials*, *239*(December 2019), 1–8. https://doi.org/10.1016/j.conbuildmat.2019.117876

Chua, H. S., Bashir, M. J. K., Tan, K. T., and Chua, H. S. (2019). A sustainable pyrolysis technology for the treatment of municipal solid waste in Malaysia. *AIP Conference Proceedings*, *2124*(July), 1–11. https://doi.org/10.1063/1.5117076

Collivignarelli, M. C., Cillari, G., Ricciardi, P., Miino, M. C., Torretta, V., Rada, E. C., and Abbà, A. (2020). The production of sustainable concrete with the use of alternative aggregates: A review. *Sustainability (Switzerland)*, *12*(19), 1–34. https://doi.org/10.3390/SU12197903

Dash, M. K., Patro, S. K., and Rath, A. K. (2016). Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete – A review. *International Journal of Sustainable Built Environment*, *5*(2), 484–516. https://doi.org/10.1016/j.ijsbe.2016.04.006

De Castro, S., and De Brito, J. (2013). Evaluation of the durability of concrete made with crushed glass aggregates. *Journal of Cleaner Production*, *41*, 7–14.

https://doi.org/10.1016/j.jclepro.2012.09.021

Deboucha, W., Leklou, N., Khelidj, A., and Oudjit, M. N. (2017). Hydration development of mineral additives blended cement using thermogravimetric analysis (TGA): Methodology of calculating the degree of hydration. *Construction and Building Materials*, *146*, 687–701. https://doi.org/10.1016/j.conbuildmat.2017.04.132

Devaraj, R., Jordan, J., Gerber, C., and Olofinjana, A. (2021). *Exploring the Effects of the Substitution of Freshly Mined Sands with Recycled Crushed Glass on the Properties of Concrete applied sciences Exploring the Effects of the Substitution of Freshly Mined Sands with Recycled Crushed Glass on the Properties of C. April*. https://doi.org/10.3390/app11083318

Drzymała, T., Zegardło, B., and Tofilo, P. (2020). Properties of Concrete Containing Recycled Glass Aggregates Produced of Exploded Lighting Materials. *Materials MDPI*, *226*(13), 1–16. https://doi.org/https://doi.org/10.3390/ma13010226

Du, H., and Tan, K. H. (2014a). Waste glass powder as cement replacement in concrete. *Journal of Advanced Concrete Technology*, *12*(11), 468–477. https://doi.org/10.3151/jact.12.468

Du, H., and Tan, K. H. (2014b). Concrete with recycled glass as fine aggregates. *ACI Materials Journal*, *111*(1), 47–57. https://doi.org/10.14359/51686446

Du, H., and Tan, K. H. (2015). Transport properties of concrete with glass powder as supplementary cementitious material. *ACI Materials Journal*, *112*(3), 429–437. https://doi.org/10.14359/51687363

Du, H., and Tan, K. H. (2017). Properties of high volume glass powder concrete. *Cement and Concrete Composites*, *75*, 22–29. https://doi.org/10.1016/j.cemconcomp.2016.10.010

Elaqra, H. A., Al-Afghany, M. J., Abo-Hasseira, A. B., Elmasry, I. H., Tabasi, A. M., and Alwan, M. D. (2019). Effect of immersion time of glass powder on mechanical properties of concrete contained glass powder as cement replacement. *Construction and Building Materials*, *206*, 674–682. https://doi.org/10.1016/j.conbuildmat.2019.02.110

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

https://doi.org/10.1016/j.conbuildmat.2018.05.263

Ellis, L. D., Badel, A. F., Chiang, M. L., Park, R. J. Y., and Chiang, Y. M. (2020). Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(23), 12584–12591. https://doi.org/10.1073/pnas.1821673116

García Del Toro, E. M., and Más López, M. I. (2018). Study of new formations of C-S-H in manufactured with glass powder as binder mortar. *Ingenieria e Investigacion*, *38*(3), 24–32. https://doi.org/10.15446/ING.INVESTIG.V38N3.67270

Ghayoor Khan, A., and Khan, B. (2017). Effect of Partial Replacement of Cement by Mixture of Glass Powder and Silica Fume Upon Concrete Strength. *International Journal of Engineering Works Kambohwell Publisher Enterprises*, *4*(7), 124–135.

Gimenez-Carbo, E., Soriano, L., Roig-Flores, M., and Serna, P. (2021). Characterization of glass powder from glass recycling process waste and preliminary testing. *Materials*, *14*(11). https://doi.org/10.3390/ma14112971

Glass Mechanic Sdn Bhd. (2012). *Glass Mechanic Sdn Bhd | Windscreen Repair Professionals | Malaysia*. Bhd Mechanics. http://www.glassmechanic.com.my/environment.html

Hama, S. M., Mahmoud, A. S., and Yassen, M. M. (2019). Flexural behavior of reinforced concrete beam incorporating waste glass powder. *Structures*, *20*(February), 510–518. https://doi.org/10.1016/j.istruc.2019.05.012

Han, W., Sun, T., Li, X., Sun, M., and Lu, Y. (2016). Using of borosilicate glass waste as a cement additive. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *381*, 11-15.

Harrison, E., Berenjian, A., and Seifan, M. (2020). Recycling of waste glass as aggregate in cement-based materials. *Environmental Science and Ecotechnology*, *4*, 100064. https://doi.org/10.1016/j.ese.2020.100064

Hasanuzzaman, M., Rafferty, A., Sajjia, M., and Olabi, A.-G. (2016). Properties of Glass Materials. *Reference Module in Materials Science and Materials Engineering*, 1–12. https://doi.org/10.1016/b978-0-12-803581-8.03998-9

He., Zhan, P., Du, S., Liu, B., and Yuan, W. (2019). Creep behavior of concrete containing glass powder. *Composites Part B*, *166*(July 2018), 13–20. https://doi.org/10.1016/j.compositesb.2018.11.133

Hooi, L. S., and Min, P. J. (2017). Potential of Substituting Waste Glass in Aerated Light Weight Concrete. *Procedia Engineering*, *171*, 633–639. https://doi.org/10.1016/j.proeng.2017.01.398

Huseien, G., Fahim, Z., Hafizah, N., Khalid, A., Rahman, A., Sam, M., Tahir, M., Hasanah, N., Shukor, A., Alyousef, R., and Mirza, J. (2021). Durability performance of modified concrete incorporating fly ash and effective microorganism. *Construction and Building Materials*, *267*, 120947. https://doi.org/10.1016/j.conbuildmat.2020.120947

Ibrahim, K. I. M. (2017). The Effect of Using Waste Glass [WG] as Partial Replacement of sand on Concrete. *IOSR Journal of Mechanical and Civil Engineering*, *14*(2), 41–45. https://doi.org/10.9790/1684-1402024145

Ibrahim, S., and Meawad, A. (2022). Towards green concrete: Study the role of waste glass powder on cement/superplasticizer compatibility. *Journal of Building Engineering*, *47*(September 2021), 103751. https://doi.org/10.1016/j.jobe.2021.103751

Idir, R., Cyr, M. and Tagnit-Hamou, A. (2011) Pozzolanic Properties of Fine and Coarse Color-Mixed Glass Cullet. Cement and Concrete Composites, 33, 19-29. https://doi.org/10.1016/j.cemconcomp.2010.09.013

Isa, M. N., Garba, M. M., and Kawu, A. L. (2016). Influence of Locally Made Effective Microorganisms On The Compressive Strength of Concrete. *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, *3*(4), 4425–4429.

Islam, G. M. S., Rahman, M. H., and Kazi, N. (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*, *6*(1), 37–44. https://doi.org/10.1016/j.ijsbe.2016.10.005

Ismail, N., and Saman, H. M. (2014). Microstructure Examination and Strength Characteristics of Effective Microbed Cement. *International Conference on Biological, Civil and Enviromental Engineering*, 82–87. https://doi.org/10.15242/iicbe.c0314161

Jang, B. K., Lee, J. C., Kim, J. H., and Chung, C. W. (2017). Enhancement of thermal neutron shielding of cement mortar by using borosilicate glass powder. *Applied Radiation and Isotopes*, *123*, 1-5.

Jim, O. . (2019). Global aggregates growth examined by global aggregate information net work (GAIN). *AggregateResearch.Com*, 1–4. https://www.aggregateresearch.com/news/global-aggregates-growth-examined-by-gain-convenor-jim-obrien/

Jostin, P., Priya, B., and Suganya, S. (2014). Use Of Glass Powder As Fine Aggregate In High Strength Concrete. *International Journal of Science and Engineering Research (IJ0SER)*, *2*(7), 1–7.

Kabeer, K. I. S. A., and Vyas, A. K. (2018). Utilization of marble powder as fine aggregate in mortar mixes. *Construction and Building Materials*, *165*, 321–332. https://doi.org/10.1016/j.conbuildmat.2018.01.061

Kalakada, Z., Doh, J. H., and Chowdhury, S. (2019). Glass powder as replacement of cement for concrete–an investigative study. *European Journal of Environmental and Civil Engineering*, 1–18. https://doi.org/10.1080/19648189.2019.1695149

Kamali, M., and Ghahremaninezhad, A. (2015). Effect of glass powders on the mechanical and durability properties of cementitious materials. *Construction and Building Materials*, *98*, 407–416. https://doi.org/10.1016/j.conbuildmat.2015.06.010

Kamali, M., and Ghahremaninezhad, A. (2016). An investigation into the hydration and microstructure of cement pastes modified with glass powders. *Construction and Building Materials*, *112*, 915–924. https://doi.org/10.1016/j.conbuildmat.2016.02.085

Kastiukas, G., Zhou, X., Castro-gomes, J., Huang, S., and Saafi, M. (2015). Effects of lactic and citric acid on early-age engineering properties of Portland / calcium aluminate blended cements. *Construction and Building Materials*, *101*(June 2021), 389–395. https://doi.org/10.1016/j.conbuildmat.2015.10.054

Keerio, M. A., Abbasi, S. A., Kumar, A., Bheel, N., Rehaman, K. ur, and Tashfeen, M. (2020). Effect of Silica Fume as Cementitious Material and Waste Glass as Fine Aggregate Replacement Constituent on Selected Properties of Concrete. *Silicon*. https://doi.org/10.1007/s12633-020-00806-6

Khalil, W., and Al Obeidy, N. (2018). Some properties of sustainable concrete containing two environmental wastes. *MATEC Web of Conferences*, *162*, 1–9. https://doi.org/10.1051/matecconf/201816202029

Khan., Sheikh, M. N., Mccarthy, T. J., Robati, M., and Allen, M. (2019). Experimental investigation on foam concrete without and with recycled glass powder : A sustainable solution for future construction. *Construction and Building Materials*, *201*, 369–379. https://doi.org/10.1016/j.conbuildmat.2018.12.178

Kiliçoglu, C., and Çoruh, S. (2017). Recycling of waste glass in concrete plant as aggregate and pozzolan replacement. *International Journal of Global Warming*, *11*(3), 250–262. https://doi.org/10.1504/ijgw2017.082771

Kim, I. S., Choi, S. Y., and Yang, E. I. (2018). Evaluation of durability of concrete substituted heavyweight waste glass as fine aggregate. *Construction and Building Materials*, *184*, 269–277. https://doi.org/10.1016/j.conbuildmat.2018.06.221

Kim, S. K., Kang, S. T., Kim, J. K., and Jang, I. Y. (2017). Effects of particle size and cement replacement of LCD glass powder in concrete. *Advances in Materials Science and Engineering*, *2017*(1). https://doi.org/10.1155/2017/3928047

Kushartomo, W., Bali, I., and Sulaiman, B. (2015). Mechanical behavior of reactive powder concrete with glass powder substitute. *Procedia Engineering*, *125*, 617–622. https://doi.org/10.1016/j.proeng.2015.11.082

Lee, H., Hanif, A., Usman, M., Sim, J., and Oh, H. (2018). Performance evaluation of concrete incorporating glass powder and glass sludge wastes as supplementary cementing material. *Journal of Cleaner Production*, *170*, 683–693. https://doi.org/10.1016/j.jclepro.2017.09.133

Li, L. G., Lin, C. J., Chen, G. M., Kwan, A. K. H., and Jiang, T. (2017). Effects of packing on compressive behaviour of recycled aggregate concrete. *Construction and Building Materials*, *157*, 757–777. https://doi.org/10.1016/j.conbuildmat.2017.09.097

Lim, A. (2019). ASEAN vehicle to population list – the correct facts. In *International News* (p. 1). https://paultan.org/2019/09/26/asean-vehicle-to-population-list-the-correct-facts/

Lim, A. (2020). Vehicles Registrations in Malaysia – 31.2 mil as of 2019. *Paultan.Org*, *April*, 1. https://paultan.org/2020/04/02/vehicles-registrations-in-malaysia-31-2-mil-as-of-2019/

Ling, T. C., and Poon, C. S. (2014). Use of CRT funnel glass in concrete blocks prepared with different aggregate-to-cement ratios. *Green Materials*, *2*(1), 43–51. https://doi.org/10.1680/gmat.13.00013

Ling, T. C., Poon, C. S., and Wong, H. W. (2013). Management and recycling of waste glass in concrete products: Current situations in Hong Kong. *Resources, Conservation and Recycling*, *70*, 25–31. https://doi.org/10.1016/j.resconrec.2012.10.006

Liu, S., Xie, G., and Wang, S. (2015). Effect of glass powder on microstructure of cement pastes. *Advances in Cement Research*, *27*(5), 259–267. https://doi.org/10.1680/adcr.13.00100

Liu, T., Wei, H., Zou, D., Zhou, A., and Jian, H. (2020). Utilization of waste cathode ray tube funnel glass for ultra-high performance concrete. *Journal of Cleaner Production*, *249*, 119333. https://doi.org/10.1016/j.jclepro.2019.119333

Lu, J. X., Zheng, H., Yang, S., He, P., and Poon, C. S. (2019). Co-utilization of waste glass cullet and glass powder in precast concrete products. *Construction and Building Materials*, *223*, 210–220. https://doi.org/10.1016/j.conbuildmat.2019.06.231

Mardani-Aghabaglou, A., Tuyan, M., and Ramyar, K. (2015). Mechanical and durability performance of concrete incorporating fine recycled concrete and glass aggregates. *Materials and Structures/Materiaux et Constructions*, *48*(8), 2629–2640. https://doi.org/10.1617/s11527-014-0342-3

Mark, O. G., Ede, A. N., Olofinnade, O., Bamigboye, G., Okeke, C., Oyebisi, S. O., and Arum, C. (2019, November). Influence of Some Selected Supplementary Cementitious Materials on Workability and Compressive Strength of Concrete–A Review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 640, No. 1, p. 012071). IOP Publishing.

Mehdipour, I., and Khayat, K. H. (2018). Elucidating the Role of Supplementary Cementitious Materials on Shrinkage and Restrained-Shrinkage Cracking of Flowable Eco-Concrete. *Journal of Materials in Civil Engineering*, *30*(3), 04017308. https://doi.org/10.1061/(asce)mt.1943-5533.0002191

Memon, R. P., (2021). The effect of effective microorganism solution as self-curing agent on properties of concrete. PhD thesis, Universiti Teknologi Malaysia, Skudai.

Menéndez, E., Argiz, C., Recino, H., and Sanjuán, M. Á. (2022). Characterization of Mortars Made with Coal Ashes Identified as a Way Forward to Mitigate

Climate Change. *Crystals*, *12*(4), 557.

Miranda Junior, E. J. P., De Jesus Costa Leite Bezerra, H., Politi, F. S., and Paiva, A. E. M. (2014a). Increasing the compressive strength of Portland cement concrete using flat glass powder. Materials Research, 17, 45–50. https://doi.org/10.1590/S1516-14392014005000058

Miranda, E. J. P., Paiva, A. E. M., and Rodrigues, E. N. L. (2014b). Influence of waste glass on the physical properties of Portland cement concrete. *Materials Science Forum*, *798–799*(June), 576–581. https://doi.org/10.4028/www.scientific.net/msf.798-799.576

Mohajerani, A., Vajna, J., Ho, T., Cheung, H., Kurmus, H., and Arulrajah, A. (2017). Practical recycling applications of crushed waste glass in construction materials : A review. *Construction and Building Materials*, *156*, 443–467. https://doi.org/10.1016/j.conbuildmat.2017.09.005

Mohd.Sam, A. R., Khanom, F., Kamaruzzaman, M., Tahir, M., and Abdul, N. H. (2019). Fresh and hardened properties of concrete containing effective microorganisms. *IOP Conference Series: Earth and Environmental Science*, *220*, 012050. https://doi.org/10.1088/1755-1315/220/1/012050

Monteiro, P. J. M., Miller, S. A., and Horvath, A. (2017). Towards sustainable concrete. *Nature Materials*, *16*(7), 698–699. https://doi.org/10.1038/nmat4930

Nassar, R. U. D., Soroushian, P., and Sufyan-Ud-Din, M. (2021). Long-term field performance of concrete produced with powder waste glass as partial replacement of cement. *Case Studies in Construction Materials*, *15*(September), 1–14. https://doi.org/10.1016/j.cscm.2021.e00745

Neville, A. M., Brooks, J. J. (2004). Concrete technology, Longman scientific and technical. New York, NY: Longman Publisher

Ngene, B. U., Olofinnade, O., and Agomoh, C. (2019). *Effect of Magnetized Water on the Mechanical Properties of Concrete Containing Recycled Waste Glass Aggregate*. *February*. https://doi.org/10.4028/www.scientific.net/JERA.41.103

Olofinnade, O. M., Ndambuki, J. M., and Ede, A. N. (2017). *Application of Waste Glass Powder as a Partial Cement Substitute towards more Application of Waste Production*. *June*, 19–20. https://doi.org/10.4028/www.scientific.net/JERA.31.77

Olofinnade, Oluwarotimi M., Ede, A. N., Ndambuki, J. M., Ngene, B. U., Akinwumi, I. I., and Ofuyatan, O. (2018). Strength and microstructure of eco-concrete produced using waste glass as partial and complete replacement for sand. *Cogent Engineering*, *5*(1), 1–19. https://doi.org/10.1080/23311916.2018.1483860

Omran., and Tagnit-hamou, A. (2016). Performance of glass-powder concrete in field applications. *Construction and Building Materials*, *109*, 84–95. https://doi.org/10.1016/j.conbuildmat.2016.02.006

Omran, A., Harbec, D., Tagnit-Hamou, A., and Gagne, R. (2017). Production of roller-compacted concrete using glass powder: Field study. *Construction and Building Materials*, *133*, 450–458. https://doi.org/10.1016/j.conbuildmat.2016.12.099

Omran, A., Soliman, N., Zidol, A., and Tagnit-Hamou, A. (2018). Performance of Ground-Glass Pozzolan as a Cementitious Material—A Review. *Advances in Civil Engineering Materials*, *7*(1), 20170125. https://doi.org/10.1520/acem20170125

Osman, M. H., and Razali, N. F. (2017). Effectiveness of glass as a substitution for cement and aggregate in concrete mix. In Concrete Materials. series 1 (2017), 72–81.

Otunyo, A. W., and Okechukwu, B. N. (2017). Performance of concrete with partial replacement of fine aggregates with crushed waste glass. *Nigerian Journal of Technology*, *36*(2), 403. https://doi.org/10.4314/njt.v36i2.12

Paiz., Muhamad, M. S., Hamidon, N., Osman, M. H., and Lwi Mokhtar, M. H. M. (2019). The performance of windshield glass waste as a replacing material for coarse aggregate in concrete. *International Journal of Recent Technology and Engineering*, *7*(6), 1675–1682.

Patel, D., Shrivastava, R., Tiwari, R. P., and Yadav, R. K. (2020). The role of glass powder in concrete with respect to its engineering performances using two closely different particle sizes. *Structural Concrete*, *May 2019*, 1–17. https://doi.org/10.1002/suco.201900182

Piškur, J., and Compagno, C. (2014). Molecular mechanisms in yeast carbon metabolism. In *Molecular Mechanisms in Yeast Carbon Metabolism*. https://doi.org/10.1007/978-3-642-55013-3

Qin, R., Hao, H., Rousakis, T., and Lau, D. (2019). Effect of shrinkage reducing admixture on new-to-old concrete interface. *Composites Part B*, *167*(September 2018), 346–355. https://doi.org/10.1016/j.compositesb.2018.11.087

Rahma, A., El Naber, N., and Issa Ismail, S. (2017). Effect of glass powder on the compression strength and the workability of concrete. *Cogent Engineering*, *4*(1). https://doi.org/10.1080/23311916.2017.1373415

Rajagopalan, P., Balaji, V., Unnikrishnan, N., Jainul Haq, T., and Bhuvaneshwari, P. (2017). Study of Bond Characteristics of Reinforced Waste Glass Aggregate Concrete. *IOP Conference Series: Earth and Environmental Science*, *80*(1), 1–7. https://doi.org/10.1088/1755-1315/80/1/012006

Ramakrishnan, K., Pugazhmani, G., Sripragadeesh, R., Muthu, D., and Venkatasubramanian, C. (2017). Experimental study on the mechanical and durability properties of concrete with waste glass powder and ground granulated blast furnace slag as supplementary cementitious materials. *Construction and Building Materials*, *156*, 739–749. https://doi.org/10.1016/j.conbuildmat.2017.08.183

Rizwan, S. A., Khan, H., Bier, T. A., and Adnan, F. (2017). Use of Effective Micro-organisms (EM) technology and self-compacting concrete (SCC) technology improved the response of cementitious systems. *Construction and Building Materials*, *152*, 642–650. https://doi.org/10.1016/j.conbuildmat.2017.05.102

Romero, D., James, J., Mora, R., and Hays, C. D. (2013). Study on the mechanical and environmental properties of concrete containing cathode ray tube glass aggregate. *Waste Management*, *33*(7), 1659–1666. https://doi.org/10.1016/j.wasman.2013.03.018

Sandanayake, M., Bouras, Y., Haigh, R., and Vrcelj, Z. (2020). Current sustainable trends of using waste materials in concrete—a decade review. *Sustainability*, *12*(22), 9622.

Saran, D., and Singh, S. . (2021). A review on the contemporary innovations & advancements in the field of green concrete. *IOP Conference Series: Earth and Environmental Science*, *796*, 012002. https://doi.org/10.1088/1755-1315/796/1/012002

Seddik Meddah, M. (2019). Use of waste window glass as substitute of natural sand in concrete production. *IOP Conference Series: Materials Science and Engineering*, *603*(3). https://doi.org/10.1088/1757-899X/603/3/032011

Selvakumar, M., Geetha, S., Kasturi Rangan, S., Sithrubi, T., and Sathyashriya, K. (2021). Effect of glass powder as partial fine aggregate replacement on properties of basalt fibre reinforced concrete. *Materials Today: Proceedings*, *43*, 1460–1464. https://doi.org/10.1016/j.matpr.2020.09.299

Šerelis, E., Vaitkevičius, V., and Kerševičius, V. (2016). Mechanical Properties And Microstructural Investigation Of Ultra-High Performance Glass Powder Concrete. *Journal of Sustainable Architecture and Civil Engineering*, *14*(1), 5–11. https://doi.org/10.5755/j01.sace.14.1.14478

Serpa, D., De Brito, J., and Pontes, J. (2015). Concrete made with recycled glass aggregates: Mechanical performance. *ACI Materials Journal*, *112*(1), 29–38. https://doi.org/10.14359/51687366

Sharifi., Afshoon, I., Afshoon, Z., Firoozjaei., and Amin, M. (2016). Utilization of Waste Glass Micro-particles in Producing Self-Consolidating Concrete Mixtures. *International Journal of Concrete Structures and Materials*, *10*(3), 337–353. https://doi.org/10.1007/s40069-016-0141-z

Sharifi, Y., Afshoon, I., and Firoozjaie, Z. (2015). Fresh properties of self-compacting concrete containing ground waste glass microparticles as cementing material. *Journal of Advanced Concrete Technology*, *13*(2), 50–66. https://doi.org/10.3151/jact.13.50

Sharifi, Y., Houshiar, M., and Aghebati, B. (2013). Recycled glass replacement as fine aggregate in self-compacting concrete. *Frontiers of Structural and Civil Engineering*, *7*(4), 419–428. https://doi.org/10.1007/s11709-013-0224-8

Shen, P., Zheng, H., Liu, S., Lu, J., and Poon, C. S. (2020). Development of high-strength pervious concrete incorporated with high percentages of waste glass. *Cement and Concrete Composites*, *114*(July), 103790. https://doi.org/10.1016/j.cemconcomp.2020.103790

Simon, K. M., and Kishen, J. C. (2016). Influence of aggregate bridging on the fatigue behaviour of concrete. *International Journal of Fatigue*, *90*, 200-209.

Soliman, N. A., and Tagnit-Hamou, A. (2016). Development of ultra-high-performance concrete using glass powder – Towards ecofriendly concrete. *Construction and Building Materials*, *125*, 600–612. https://doi.org/10.1016/j.conbuildmat.2016.08.073

Song, W., Zou, D., Liu, T., Teng, J., and Li, L. (2019). Effects of recycled cathode ray tube glass fine aggregate size and content on mechanical and damping properties of concrete. *Construction and Building Materials*, *202*, 332–340. https://doi.org/10.1016/j.conbuildmat.2019.01.033

Sua-iam, G., and Makul, N. (2013). Use of limestone powder during incorporation of Pb-containing cathode ray tube waste in self-compacting concrete. *Journal of Environmental Management*, *128*, 931–940. https://doi.org/10.1016/j.jenvman.2013.06.031

Suliman, N. H., Atif Abdul Razak, A., Mansor, H., Alisibramulisi, A., and Mohd Amin, N. (2019). Concrete using sawdust as partial replacement of sand : Is it strong and does not endanger health? *MATEC Web of Conferences*, *258*, 01015. https://doi.org/10.1051/matecconf/201925801015

Slump test of concrete, slump cone for workability-procedure, Apparatus-cement concrete.https://cement concrete.org/how-to-guide/concrete-slump-test/2171/ Accessed: 2021-08-10

Taffese, W. Z., and Abegaz, K. A. (2019). Embodied energy and CO_2 emissions of widely used building materials: The Ethiopian context. *MDPI Buildings*, *9*(6), 1–15. https://doi.org/10.3390/buildings9060136

Tagnit-Hamou, A., Zidol, A., Soliman, N., Deschamps, J., and Omran, A. (2018). Ground Glass Pozzolan in Conventional, High, and Ultra-High Performance Concrete. *MATEC Web of Conferences*, *149*, 1–7. https://doi.org/10.1051/matecconf/201714901005

Tamanna, N., and Tuladhar, R. (2020). Sustainable Use of Recycled Glass Powder as Cement Replacement in Concrete. *The Open Waste Management Journal*, *13*, 1–13. https://doi.org/10.2174/1874347102013010001

Tamanna, N., Tuladhar, R., and Sivakugan, N. (2020). Performance of recycled waste glass sand as partial replacement of sand in concrete. *Construction and Building Materials*, *239*, 1–9. https://doi.org/10.1016/j.conbuildmat.2019.117804

Tanwar, V., Bisht, K., Ahmed, K. I. S., and Ramana, P. V. (2021). Experimental investigation of mechanical properties and resistance to acid and sulphate attack of GGBS based concrete mixes with beverage glass waste as fine aggregate. *Journal of Building Engineering*, *41*(November 2020), 1–12.

Tariq, S., Scott, A. N., Mackechnie, J. R., and Shah, V. (2020). Durability of High Volume Glass Powder Self-Compacting Concrete. *Applied Sciences*, *10*, 1–20. https://doi.org/10.3390/app10228058

Tasong, W. A., Lynsdale, C. J., and Cripps, J. C. (1998). Aggregate-Cement Paste Interface. II: Influence Of Aggregate Physical Properties. *Cement and Concrete Research*, *28*(10), 1553–1465.

Tonduba, Y. W. (2016). The Application Of Waste Glass As Partial Replacement For Cement In Concrete. *Masters Thesis, Universiti Teknologi Malaysia*, Skudai.

United Nations Enviroment Programme (2019). Sand and sustainability : finding new solutions for environmental governance of global sand resources.

United State Geological Survey (USGS-2020). Mineral commodity summaries. US Geological Survey, Reston, V. Mineral commodities summaries. 1–200. https://doi.org/https://doi.org/10.3133/mcs2020.

United State Enviromental Protection Agency (USEPA-2018). Facts and figures on materials. In Facts and figures about material, Waste Recycling. https://doi.org/https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

Vaitkevičius, V., Šerelis, E., and Hilbig, H. (2014). The effect of glass powder on the microstructure of ultra high performance concrete. *Construction and Building Materials*, *68*, 102–109. https://doi.org/10.1016/j.conbuildmat.2014.05.101

Wattanapornprom, R., and Stitmannaithum, B. (2015). Comparison of properties of fresh and hardened concrete containing finely ground glass powder, fly ash, or silica fume. *Engineering Journal*, *19*(3), 35–47. https://doi.org/10.4186/ej.2015.19.3.35

Wright, J. R., Cartwright, C., Fura, D., and Rajabipour, F. (2014). Fresh and hardened properties of concrete incorporating recycled glass as 100% sand replacement. *Journal of Materials in Civil Engineering*, *26*(10), 1–11. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000979

Xing, M., Fu, Z., Wang, Y., Wang, J., and Zhang, Z. (2017). Lead recovery and high silica glass powder synthesis from waste CRT funnel glasses through carbon thermal reduction enhanced glass phase separation process. *Journal of hazardous materials*, *322*, 479-487.

Yassen, M. M., Mahmoud, A. S., and Hama, S. M. (2019). Effectiveness of Glass Wastes as Powder on Some Hardened Properties of Concrete. *Al-Nahrain Journal for Engineering Sciences*, *22*(1), 14–17. https://doi.org/10.29194/njes.22010014

Yew, M. K., Bin, H., Chin, B., and Chian, M. (2014). Effects of heat treatment on oil palm shell coarse aggregates for high strength lightweight concrete. *Materials and Design*, *54*, 702–707. https://doi.org/10.1016/j.matdes.2013.08.096

Yu., Tao, Z., Song, T. Y., and Pan, Z. (2016). Performance of concrete made with steel slag and waste glass. *Construction and Building Materials*, *114*, 737–746. https://doi.org/10.1016/j.conbuildmat.2016.03.217

Zhao, H., Poon, C. S., and Ling, T. C. (2013). Utilizing recycled cathode ray tube funnel glass sand as river sand replacement in the high-density concrete. *Journal of Cleaner Production*, *51*, 184–190. https://doi.org/10.1016/j.jclepro.2013.01.025

Zheng, K. (2013). Recycled glass concrete. In *Eco-Efficient Concrete* (Vol. 2010). Woodhead Publishing Limited. https://doi.org/10.1533/9780857098993.2.241

Zheng, K. (2016). Pozzolanic reaction of glass powder and its role in controlling alkali-silica reaction. *Cement and Concrete Composites*, *67*, 30–38. https://doi.org/10.1016/j.cemconcomp.2015.12.008

LIST OF PUBLICATIONS

Isa Mallum, Abdul Rahman Mohd.Sam, Nor Hasanah Abdul Shukor Lim and Nathaniel Omolayo (2021), “Sustainable Utilization of Waste Glass in Concrete: A Review”. Silicon. Pp 1-16.

Isa Mallum, Abdul Rahman Mohd. Sam, Nor Hasanah Abdul Shukor Lim and Nathaniel Omolayo, Peter Loo (2021) “Properties of glass fine aggregate effective micro-organism concrete” Construction and Building Materials (under review). Pp 1-25.

Other publications

Nathaniel Olukotun, Abdul Rahman Mohd. Sam, Nor Hassana Abdul Shukur Lim, Muydeen Oladimeji Abdulkareem, **Isa Mallum**, Olukotun Adebisi (2021) “Mechanical Properties of Tin Slag Mortar” Recycling (MDPI) pp. 1-15

Abdulkareem, M., Ganiyu, A., Olukotun Nathaniel, **Isa Mallum**, Dunu, W (2021) “Interval analysis of mode shapes to identify damage in beam structures” Materials science and Engineering Technology. Special Issue: 6th international Conference on mechanical, Manufacturing and Plant Engineering (ICMMPE 2020). 10(52) PP 1064-1072.