`

EXPLOITING RECYCLED PLASTIC WASTE AS AN ALTERNATIVE BINDER FOR MATERIALS USED IN THE CONSTRUCTION INDUSTRY

Thesis submitted to the Faculty of Engineering and the Built Environment in the fulfilment of the requirements for the degree of

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IN

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AT THE

DURBAN UNIVERSITY OF TECHNOLOGY

Prepared by

Kimendren Gounden

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DECLARATION

I, Kimendren Gounden, hereby declare that this thesis titled, ‘‘Exploiting recycled plastic waste as an alternative binder for materials used in the construction industry”, is my own work, that it has not been submitted in part or whole for any degree or examination to any other university or institution. All sources used in this dissertation have been acknowledged in the text and included in the complete list of references.

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DEDICATION

This work is dedicated to my dad Dr Balenthran Gounden, my mum Valerie Gounden, my sister Dr Lavaanie Gounden and my two grandparents Sakundalai Gounden and Parvathi Reddy for their overwhelming support and encouragement received during my studying journey.

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ABSTRACT

The population in the world is growing at an alarming rate and four local and global threats viz. plastic pollution, high unemployment, inadequate housing for all citizens and damage to the ozone layer causing climate change continue to emerge. The overwhelming demand for plastic goods in daily use resulting in plastic waste pollution has become an environmental challenge. Plastic waste is now becoming extremely dangerous due to their rapid accumulation in the environment and in landfills, and their improper disposal methods leads to many harmful effects on land, air, marine life and humans. Incineration of plastic waste is already posing several health risks.

Concurrently, the cement, building and construction industry is amongst the biggest contributor to carbon dioxide (CO_2) gas emissions, which poses an added environmental challenge. This creates a negative image on the use of cement-based masonry as construction materials, which renders it unsustainable. Hence, an alternative construction material is required. The manufacture and utilisation of burnt clay bricks have become an area of debate which led to a move towards greater sustainability. Therefore, there is need for a strategy to reduce plastic pollution, create job opportunities, provide alternate ways of constructing affordable eco-friendly houses, and reduce the depletion of the ozone layer for the benefit of all citizens. This strategy is explored in this research study that supports, enhances and promotes sustainability.

The efficacy of producing eco-friendly plastic-sand bricks as a feasible solution and an attractive alternative to cement or burnt clay bricks have been investigated in this study. This investigation encompasses an effort to combat issues related to plastic waste, high unemployment, rising building costs and climate change. In the first stage the study analyses the use of High-Density Polyethylene (HDPE) and river sand using six different ratios of sand(s): plastic(p) viz. 60s: 40p; 65s: 35p; 70s: 30p; 75s: 25p; 80s: 20p and 85s: 15p. The second stage consisted of the addition of 1%, 5% and 10% of Kaolin Clay DSF which was experimentally added to each of the different ratios of sand: plastic respectively to improve the mechanical and environmental properties towards producing eco-friendly plastic-sand bricks.

The mechanical tests showed significant improvement. Results revealed that the addition of 5% Kaolin Clay DSF, significantly increased the compressive strength from 21.4 MPa to 52.76

MPa in the 75s:25p ratio, the modulus of elasticity from 1109.35 gigapascal (GPa) to 2434.84 GPa and the short beam strength from 1.84 MPa to 2.27 MPa. The addition of 10% Kaolin Clay DSF, significantly increased the results for the impact test from 4.6 joules to 5 joules in the 75s:25p ratio. However, the addition of 5% Kaolin Clay DSF revealed an increase from 4.6 joules in the same ratio to 4.7 joules. The hardness test revealed that the impression of the nail did not affect the samples which implied that the plastic-sand bricks are durable and tough in all six ratios.

The environmental tests also showed significant improvement. Results revealed that the addition of 5% Kaolin Clay DSF decreased the rate of water absorption from day 1, being 0.78% to 0.43% on the 21st day. The plastic-sand brick as a composite material is an electrical insulator. The plastic-sand brick sample resisted the immediate absorption of water with respect to 0%, 1%, 5%, and 10% addition of Kaolin Clay DSF. No visible deposit of alkali was present when the efflorescence test was done. The fire test revealed that the addition of 10% Kaolin Clay DSF with an increase in sand content drastically reduced the linear burning rate significantly in the 75s:25p ratios from 10.52 mm/min to 2.10 mm/min respectively. This decrease in approximately 81% in the burning rate is significant.

The main conclusion of this research study is that HDPE plastics can be used to produce plastic-sand bricks that are durable, significantly high in strength and eco-friendly as compared to the conventional cement or burnt clay bricks. The addition of Kaolin Clay DSF improves both the mechanical and environmental properties of the plastic-sand brick. The manufacturing of plastic-sand bricks is an eco-friendly process. Thus, recycled plastic waste can be effectively used as an alternative binder material in the construction industry.

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LIST OF ABBREVIATIONS

Abbreviations	Particulars
ABS	Acrylonitrile Butadiene Styrene
Al_2O_2	Dialuminum dioxide
Al_2O_3	Aluminum oxide
ABMS	Alternative building materials and systems
ASTM	American Society for Testing and Materials
BC	Black carbon
BEE	Broad-based black economic empowerment
°C	Degrees Celsius
CaO	Lime
CH_4	Methane
CO_2	carbon dioxide
CO	Carbon monoxide
CFCs	chlorofluorocarbons
CE	Circular Economy
CMT	Construction Materials Testing
CSG	Child Support Grant
CTM	Compressive testing machine
DC	Direct Current
DDK	Down Draught Kiln
DEA	Department of Environmental Affairs
DHS	Department of Human Settlements
DIY	Do it yourself
DSC	Differential Scanning Calorimetry
DUT	Durban University of Technology
EDXRF	Energy Dispersive X-ray Fluorescence
EPS	Expanded polystyrene
EPWP	Expanded Public Works Programme
EPR	Extended Producer Responsibility
Fe_2O_3	Iron Oxide
FCKs	Fixed Chimney Kilns
FS	Foundry sand
Gt	Gigatonnes
GPa	Giga Pascal
GGBS	Ground Granulated Blast-furnace Slag
GHGS	Greenhouse gases
HDKs	High Draft Kilns
HDPE	High Density Polyethylene (C_2H_4) n
HKs	Hoffman Kilns
IEP	Informal Economy Policy
IEMS	Informal longitudinal Economy Monitoring Study
IP	Integrated Pollution
INC	Intergovernmental Negotiating Committee
K_2O	Potassium oxide
kg/cm^2	Kilogram per Square Centimetre

kN	Kilonewton
LDPE	Low Density Polyethylene
MCKs	Mobile Chimney Kilns
MDGs	Millennium Development Goals
MgO	Magnesia
MJ	Megajoules
MP	Microplastic
Mpa	Megapascal
MPRDA	Mineral and Petroleum Resources Development Act
MSDS	Material Safety Data Sheet
MSW	Municipal solid waste
MW	Megawatts
NDP	National Development Plan
NEMA	National Environmental Management Act
NEMLA	National Environmental Management Laws Amendment Act
NEMWA	National Environmental Management Waste Act
NEM: AQA	National Environmental Management: Air Quality Act
NEM:BA	National Environmental Management: Biodiversity Act
NEM: PAA	National Environmental Management: Protected Areas Act
NEM: WA	National Environmental Management: Waste Act
NFGBSA	National Framework for Green Building in South Africa
NFP	Non-Facing plastered
NFSD	National Framework for Sustainable Development
NGO's	Non-Governmental Organisation
NOx	Nitrogen Oxides
NO_2	Nitrogen dioxide
NSSD	National Strategy for Sustainable Development
NWMS	National Waste Management Strategy
NY	New York
O_3	Ozone
Pb	Lead
PE	Polyethylene
PET/ PETE	Polyethylene Terephthalate $(C_{10}H_8O_4)n$
PM	Particulate Matter
POP's	Persistent organic pollutants
PP	Polypropylene
PPGI	Public-Private Growth Initiative
PS	Polystyrene
PVC	Polyvinyl Chloride
PYEI	Presidential Youth Employment Initiative
RDP	Reconstruction and Development Programme
RQ	Research question
SA	South Africa
SABS	South African Bureau of Standards
SANS	South African National Standards
SASSAA	South African Social Security Agency Act
SD	Sustainable development
SDGs	Sustainable development goals

SEM	Scanning electron microscope
SiO_2	silicon dioxide (Silica)
SO_2	Sulphur dioxide
SONA	State of the Nation
SPM	Suspended Particulate Matter
SWM	Solid waste management
TGA	Thermogravimetric Analysis
TiO_2	Titanium dioxide
TKs	Tunnel Kilns
µL	Microlitres
µm	Micrometres
UN	United Nations
UNCED	United Nations Global Conference on Environment and Development
UNCSD	United Nations Conference on Sustainable Development
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
USA	United States of America
UVB	Ultraviolet B
VSBKs	Vertical Shaft Brick Kilns
WM	Waste Management
YES	Youth Employment Service
ZZKs	Zigzag Kilns

LIST OF PUBLICATIONS

1. Gounden, K.; Mwangi, F.M.; Mohan, T.P. A Perspective on Four Emerging Threats to Sustainability and Sustainable Development. Earth 2022, 3, 1207–1236. https://doi.org/10.3390/earth3040069 (MDPI Editor's choice)

2. Gounden K, Mwangi FM, Mohan TP, Kanny K. The use of recycled high-density polyethylene waste to manufacture eco-friendly plastic sand bricks. SPEPolym. 2023;1-15. doi:10.1002/pls2.10106

3. Gounden, K.; Mwangi, F.M.; Mohan, T.P.; Kanny, K. Optimisation of environmental properties of HDPE plastic sand brick using Kaolin Clay DSF- Environment, Development and Sustainability- Springer- *Submitted.* ***ID: ENVI-D-23-06448***

4. Gounden, K.; Mohan, T.P.; Mwangi, F.M. Strengthening the socio-economic integration of waste pickers in South Africa: Environment and Urbanization- Springer- *Submitted.* ***ID: EAU-23-0217.***

ABSTRACTS ACCEPTED ARISING FROM THIS STUDY

1. Gounden, K.; Mwangi, F.M.; Mohan, T.P. Perspectives on the four emerging threats to sustainable development. Paper presented in the 16th Bridging Ages International Conference, Theme: Environment, Water use, Climate, Biodiversity and Life, Giresun, Turkey 29 June-1 July 2022.

2. Gounden, K.; Mwangi, F.M.; Mohan, T.P.; Kanny, K. Manufacturing and testing of plastic-sand bricks. Presentation at the Faculty Research Day hosted by the Faculty of Engineering and Built Environment, Musgrave, Durban 27th of October 2023.

ENCYCLOPEDIA ENTRY

1. Kimendren Gounden, Festus Maina Mwangi, Turup Pandurangan Mohan. Entry on "Threat to Sustainability" in MDPI Encyclopedia, https://encyclopedia.pub/entry/38503

CHAPTER ONE

INTRODUCTION

Sustainability has been a buzz word in sociology, economics, science, technology, travel and tourism and not forgetting in the construction industry. This research has originated from the vast reading on the concept of sustainability, which emerged since the commencement of the First World Conferences on Sustainability and Development in 1972. The four interlocking crises which have been identified are directly linked to the present research study. These crises pose a serious threat to sustainability in our country, Africa and globally. They have also seized public's concern as separate and individual crises over the past few decades. It can be argued that they are not separate crises but are all interlocked into one crisis of sustainability. Our planet is undergoing a period of increased growth and critical change. The facts of the world are therefore presented as they are. According to the United Nations (UN) [1], the world population projection is said to average out to 8 billion (from 4 billion) in the coming century. In this grim and doom picture portrayed, 90% of our population growth will take place in the poorest countries more especially in already over populated cities.

This sad state of affairs highlight poverty recreating itself simply working contrary to the promotion of sustainability. The human race has never faced such serious challenges as we are going to experience in the coming decades. So, the fundamental question is, how do we promote sustainable development that satisfies the basic needs of all individuals in the present without compromising the needs of the future generations to follow? The consequence of a world in (man-made) poverty will automatically be vulnerable to environmental, social and economic challenges and will lead to untold damage or to a catastrophe. Hence, this study in part creates an urgent awareness of these crises, showing the extent, context-specificity, and more importantly the problematic implications that these four crises will have environmentally, socially and economically.

This research is a micro aspect of sustainability which is undertaken for a specific purpose of making a substantial contribution at a theoretical and practical level. It proposes an engineering strategy of addressing the four crises as well as enhancing the concept of sustainability through the manufacturing of eco-friendly plastic-sand bricks. Therefore, chapter one explains the research background, problem statement, significance of the research, aims and objectives, research questions, scope of the study, overview of research methodology and outline of thesis.

1.1 Research background

An evaluation made on all the Sustainability World Conference proceedings from 1972 to 2022 (*Appendix A*) sparked an interest on the topic of sustainability and sustainable development. After researching and evaluating the issues over 50 years, four national and global crises were identified which must be given immediate attention before they reach levels of disastrous proportions. Currently, their collective negative impact is affecting our society at large and will have a snowballing effect onto future generations if sustainability is not taken seriously. The world leaders and all relevant stakeholders need to work honestly and collaboratively with shared principles and commitments as indicated in the World Conference on Sustainability held in 2015, New York (NY) in order to overcome these crises. This will be briefly explained in section 1.2 and expanded on in much detail in Chapter 2.

1.2 Problem statement

Kothari [2] explains that a research problem refers to some challenge which a researcher experiences in the context of either a theoretical or practical context and sets out a plan or a journey to seek solutions. He further states that a research problem allows the researcher to think of ways in which to arrive at the most suitable and appropriate solutions for the identified problem. Creswell [3] also contends that a research problem is a specific problem or critical issue that leads to a need for a study to be undertaken. He also highlights that the problem can originate from many potential sources such as the researcher's experiences at a personal level or from their workplaces. It may also emerge from an extensive debate for example on sustainability or issues that have appeared in the literature and conferences. Therefore, to actively elevate this research topic cannot be over-emphasised.

We are experiencing extra-ordinary challenges and society has no option but to react to several major threats such as food, security, pollution, unemployment, diseases, shortage of affordable housing, poverty, climate change, global warming and political changes [4]. These global threats have made it difficult for majority of the people in all countries which lead to a lower standard of lifestyle. However, prominence is given to four global crises currently affecting

South Africa (SA). Many studies [5] [6] [7] [8] [9] indicate that taking action with immediate effect can secure our future as a country.

The problem indicated as "four interlocking global crises" has seized public concern over the last few decades is really complex. Arguably, these are not separate crises. Rather, they are all one sustainability challenge. However, these are briefly explained below. *Firstly*, Sadan and de Kock [10] forewarn us that "*the amount of unmanaged plastic at end of life entering the environment, particularly the ocean, has reached crisis level*." Plastic plays an important role in the daily life of human beings. It is durable, compact in shape, light weight and serves multiple functions. By its importance it is a common material and is widely used by everybody. There are many applications of plastics that are used on a daily basis such as plastic bags, cups, utensils, shampoo bottles, medical devices, containers, food packages, appliances, furniture and chairs [11]. Sanchez-Echeverri [12] argues that there is a constant need to ensure that the continuous demand for building materials and the potential of reusing plastic contribute positively to the critical environmental crisis. This provides a solution by utilizing recycled plastic waste to revolutionize the building industry, turning valuable waste materials into valuable resources for a greener economy.

The challenge of plastic accumulation is becoming a serious concern locally due to dumping by citizens, industries and shops as seen in *Figure 1.1 (a-d)*. As per estimations, the rate of expansion of plastic waste is alarming and is projected to double in every 10 years. Our environment is being contaminated by the increase in plastic and this is a result of current expansion, movement of people to urban areas, growing population, change in people's behaviour and their life style [13].

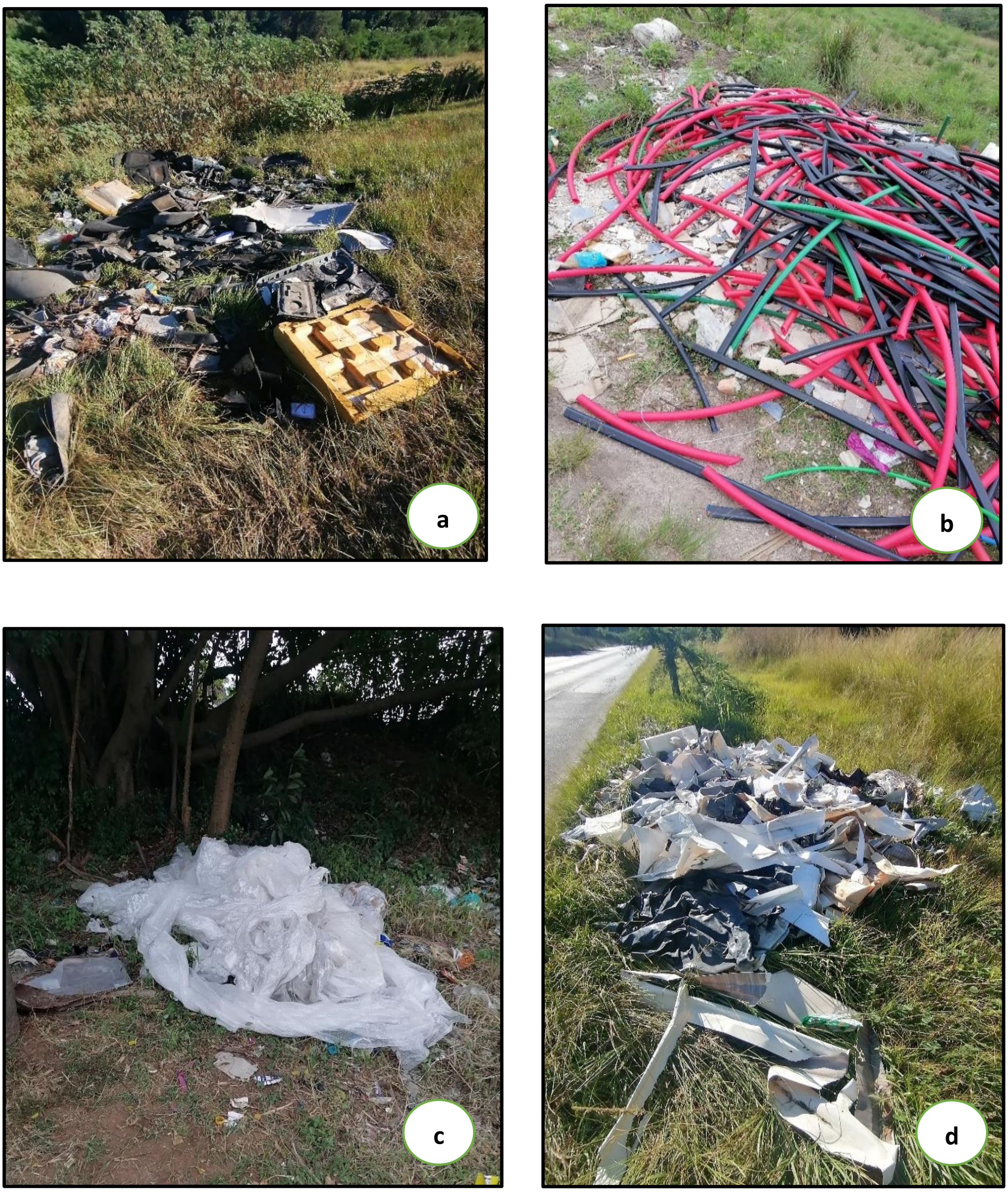


Figure 1. 1: (a-d) Environmental pollution

Secondly, Page [14] warns us that "*the growing population of more educated and urbanized youth encountering few jobs is a crisis in the making*." Stats South Africa [15] indicated that the unemployment rate among the youth in South Africa is very high irrespective of their education levels. It was found that the graduate unemployment rate was dreadful at 40,3% for those aged 15–24 and 15,5% among those aged 25–34 years. At the same time, the rate among adults (aged 35–64 years) was 5,4%. The existence of unemployment at a national and global level have many negative effects such as mental health challenges, increased depression, increased violence and crime rates, lower economic activity and poor consumption, decline in volunteerism, and loss of skills [16]. Therefore, the problem of unemployment has to be discussed and debated at a national and global platform since it directly affects sustainability and sustainable development. Unemployment has become a global problem and it is left to the will of the politicians to be urgently addressed in almost all nations [17].

Thirdly, as Favilukis et al. [18] warns that "*the increasing appeal of major urban centers has brought on an unprecedented housing affordability crisis*." This housing problem is also identified by Henley [19] who stated that "*The problem of inadequate or non-existent housing has reached crisis proportions globally*." UN habitat [20] explains that there is a correlation between housing and a sustainable future. There is constant demand to ensure that decent, suitable and more affordable housing is made available to millions of citizens in a way that would ensure a sustainable future. This calls for a redress in housing policy and practice.

De Villiers and Boshoff [21] contend that there is a definite need for alternative techniques to tackle housing shortages. Despite alternative building materials and systems (ABMS) being introduced at a commercial level, there is still much room for implementation of ABMS in South Africa. The population in the world is increasing at a rapid rate resulting in inadequate affordable housing for all citizens. Currently, the manufacture and utilisation of clay bricks have become an area of debate because there is a move towards greener housing projects.

Lastly, as announced by UN Environment Programme, Maria Tsakona et al. [22] "*our triple planetary crisis- climate change, biodiversity loss and pollution including plastic pollution – is having the greatest impacts on the world's poorest and most vulnerable populations*." Currently, there are visible signs of environmental damage such as air and water pollution, climate change, poor water quality, land contamination, and global warming. The weakening of the ozone layer has serious consequences to the quality of life on this planet. The consequences of climate change around the world has long-term challenges in temperature and weather patterns [23]. Climate change has been known as one of the major challenges to sustainability in the 21st century since it has resulted in major catastrophes. These devastating weather patterns are now increasing risk management strategies and assistance is required from all stakeholders [24] [25].

Therefore, there is need for a *strategy* to reduce plastic pollution in order to find a solution to the four local and global threats that are posing dangers to the whole of mankind.

1.3 Research questions

The steps outlined in Ratan et al. [26] for designing the RQ for this study has been followed. They indicated that an excellent RQ would commence by identifying a broader subject of interest (such as sustainability) that allows for a possible investigation. The follow up step would be to initially engage in a wide process of reading on this general topic. Thereafter, finding out what research or projects have already been completed and the body of literature that already exists in this field. Therefore, the study began with what is already known about the problem of sustainability followed by the identified` "information gaps." The outcome of this research would contribute to the solutions for plastic pollution, housing, unemployment and greenhouse gas (GHG) emission. The desire to know more about the problem of sustainability has led to few implied or sub-questions. Hence, the main RQ is:

How can <u>sustainability</u> be encouraged and promoted by introducing an alternative eco-friendly plastic-sand brick in the construction industry?

To appropriately address the issues surrounding the main research question, attention and due consideration has been given to the following sub-questions as set out below:

1. What can be done to reduce the huge acceleration of plastic pollution?
2. How can the unemployment rate be decreased?
3. What are alternatives to address the housing demand, affordability and high escalation costs in the building industry?
4. What strategy can be used to prevent the depletion of the ozone layer?

1.4 Aim and objectives of the research

The aim of the research is to develop an alternative building material from waste plastic that could satisfy the requirements of producing eco-friendly bricks for the construction industry and to feed a solution into the four crises as alluded to. The objective of this research emerges from a need to develop an efficient way to utilize plastic waste which is a great threat to the ecological balance. The problem of plastic waste directly affects food security and the purity of water at the water bed. Not only does it affect life on land but life below water as well as countless marine life deaths are caused by plastic pollution.

This research work is guided by the following objectives:

a) To identify the most optimal ratio of a suitable plastic to be mixed with sand in manufacturing a plastic-sand brick that is durable, high strength, less water absorption.

b) To settle on a suitable additive and quantity that could enhance the binding capacity of plastic in molten state and to achieve a mix with better binding quality.

c) To reduce plastic waste through plastic-sand brick production that causes pollution on air, land, seas, and rivers because it is a great threat to the sustainability of all ecological systems.

d) To reduce the consumption of natural resources such as river sand and clay for the manufacturing of bricks that resulted in the depletion of natural resources and environmental damage through greenhouse gas emission.

Hence, the collective objective is to develop a scientific way of reusing waste plastic, sand and the utilization of a fortifying ingredient that would result in the best alternative building material.

1.5 Significance of the research

The significance of this study is to:

a) produce an eco-friendly and durable brick for the construction industry.

b) contribute towards reducing the high demand and rising costs of building materials in South Africa using alternate plastic-sand bricks.

c) provide employment in the form of "waste collectors and sorters" of waste plastic and to create jobs during the production of eco-friendly bricks.

d) improve the management of waste disposal in our country through industrial outlets before it reaches landfills, oceans and the environment.

e) make it possible for recycling of waste plastic which will bring about significant relief in plastic pollution in South Africa and globally. When recycling is implemented, the effects can be enormous in respect of creating an awareness of the negative impacts of plastic which will assist in preventing dumping of plastic waste into rivers, and oceans. Hence, the recycling process will provide an economic boost to everyone more especially the disadvantaged and vulnerable people. The recycling process will also sustain the future generations from the harmful effects of plastic waste.

f) strengthen the functioning of earth ecosystems, to allow for a much healthier living environment for human, fauna and flora sectors.

g) contribute significantly to current and ongoing discourse and debates on issues of sustainability in general and more specifically to building, construction and environment sectors.

h) interrogate previous research and offer a unique approach of providing sustainable and affordable housing for all citizens. This study could provide relief to the demand for affordable houses by using plastic-sand bricks.

1.6 Scope of the study

The current study will encompass the following aspects:

a) The waste material as an alternative binding material will be explored towards assisting the construction industry to become more sustainable.
b) The research study will be conducted within the parameters of the Durban University of Technology (DUT) and all lawful legislations concerning pollution, chemicals and hazardous materials and the latest National Environmental Management: Waste Amendment Act, 2014 will be adhered to.
c) The samples of this study are specific. They are sand as a natural resource, plastic as a recyclable material and a fortifying ingredient.
d) The topics or theories will be guided by three pillars of sustainability i.e. environmental, social and economic dimensions.

e) This study basically focusses on sustainability via the manufacturing of alternate eco-friendly bricks for the building and construction industry.

1.7 Ethical considerations

The following ethical considerations are relevant to the current study and have been satisfied:

a) The purpose of the study was disclosed to my supervisors Dr FM Mwangi and Dr TP Mohan.

b) The post graduate guidelines for the DUT's Faculty of Engineering and the Built Environment.

c) The proposal has been approved by the Post Graduate Review Committee for Research at both departmental and faculty level.

d) The necessary permission was obtained from respective authorities for the retrieval of sample materials such as the sand from Malik Brick and Block, Port Shepstone, South Africa, and recycled plastic from KM Plastic in Amanzimtoti, Durban. Kaolin Clay DSF was procured from Kaolin Group from Cape Town.

e) The raw data and other materials obtained will be kept for future reference.

1.8 Outline of the thesis

The structure of the thesis is represented in *Figure 1.2*:

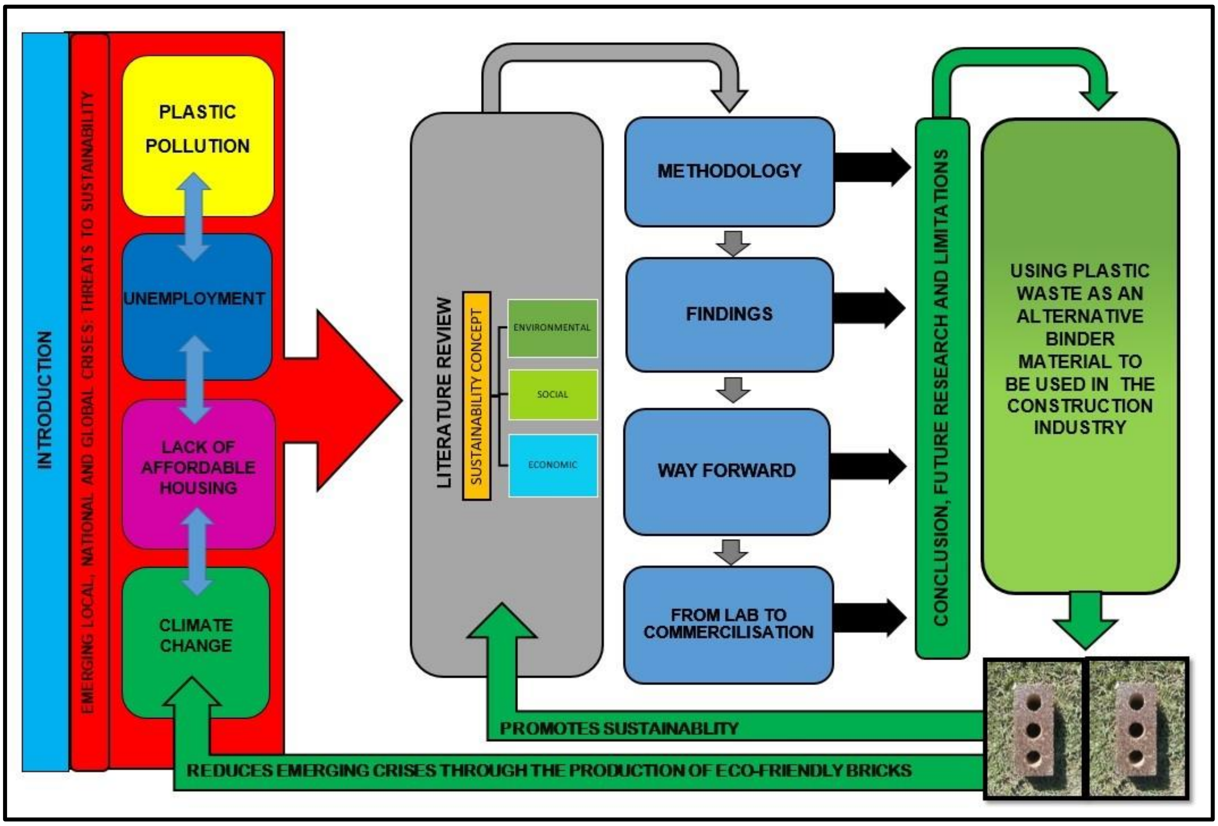


Figure 1. 2: Outline of thesis

Chapter One: Introduction

This chapter highlights the problem statement, the RQ, aim and objectives, significance of the study, scope of the study and ethical considerations.

Chapter Two: Four interlocking global crises

This is a special chapter which has a direct link to chapter one. It provides a deeper discussion of the critical national and global crises which are eluded to in the problem statement. It also explains how each of these crises are linked to this research study.

Chapter Three: Literature review

This chapter consists of two sections that provide an understanding and foundation for the current study at a global and South African context. It is used for the subsequent analysis and interpretation of the findings.

Section A: *Firstly*, it provides details of the durability of plastic, its types and valuable uses. *Secondly*, it hones in on the various accomplished writers on the feasibility of using plastic-sand bricks as alternative building material for the construction industry. *Thirdly*, it shares with the reader the gaps in the existing literature. *Fourthly*, the use of the extrusion machine in brick manufacturing and promoting sustainability are discussed. *Lastly*, it presents a pragmatic model demonstrating the envisaged impact of the plastic-sand bricks in reducing plastic waste, creating jobs, making affordable housing possible and reducing climate change.

Section B focuses on the theoretical and conceptual framework that forms the basis of this research. It delves into understanding the theory of sustainability, emergence of the concept of sustainability and sustainable development, understanding the complex nature and challenges of sustainability and provides an overview of how the South African National Framework for Sustainable Development (NFSD) is linked to the current study.

Chapter Four: Methodology

This chapter describes how the research study will be implemented and how it systematically addresses the research problem [2]. It provides a detailed outline of the research methodology used. Further, it provides an extensive explanation of the following processes in a step-by-step manner namely:

Pre-activities: The procurement of the standards clay brick, river sand, the recycled HDPE plastic and fortifying ingredient, determining testing standards and requirements was fulfilled. The machines, personal protective wear and various equipment for the study, design and manufacture of the mould were secured. The process of material preparation and ratios was determined at this stage.

During-activities: Plastic-sand brick preparation was completed for the six plastic sand ratios and varying additions of Kaolin Clay, mixing of materials and the mixing process, use of extruder, movement of composite from extruder into the moulds, use of the hydraulic press, cooling of brick samples and the cutting process.

Post-activities: Lab testing was conducted at DUT on the plastic-sand brick samples using reliable methods. A comprehensive methodology for the four tests for the mechanical properties viz. compressive, impact, short beam shear and hardness is discussed. Additionally, five tests for the environmental properties viz. water absorption, water contact angle, efflorescence, electrical resistance and fire resistance is also discussed.

Chapter Five: Mechanical properties: Findings and discussion

This chapter provides the four mechanical test results, comparisons, discussions, consolidated analysis and a summary.

Chapter Six: Environmental properties: Findings and discussion

This chapter provides the five environmental test results, comparisons, discussions, consolidated analysis and a summary.

Chapter Seven: Commercialization of plastic-sand brick

This chapter *firstly* highlights a pragmatic model explaining the advantages of using HDPE plastic waste to manufacture plastic-sand bricks and to reduce the negative impacts of the four global and local crises. It also explains how the production of eco-friendly bricks encourage and promote sustainability and sustainable development.

Secondly, it also explains how the envisaged need of the four crises are met, particularly within the South African context. It outlines the pathway for transitioning the material from a small-scale sample to full-scale production, facilitating its commercial introduction into the industrial market. The chapter also sheds light on the immediate concerns and challenges associated with establishing the composite material as a viable alternative in the construction industry. Furthermore, it identifies potential areas for improvement. *Finally*, it is proposed that the plastic-sand brick with 5% addition of Kaolin Clay and interlocking bricks using pressure fit can serve as alternate opportunities or an option to build sustainable houses at a quicker rate.

Chapter Eight: Conclusions

This chapter is presented in two sections. Section A provides a comprehensive explanation of how the developed composite material effectively addresses the research objectives.

Section B presents the conclusions of this study and how it aligns with the interventions required by the South African National Strategy for Sustainable Development at the local level. Furthermore, this section establishes a connection between the study's outcomes and the calls for action and mandates articulated in various UN World Conferences held between 1972 and 2022. The findings of the study demonstrate the feasibility of utilizing HDPE as an alternative binding material with Kaolin Clay for the production of eco-friendly bricks in the construction industry. The study culminates with final recommendations for future research.

CHAPTER TWO

FOUR INTERLOCKING LOCAL AND GLOBAL CRISES

2.0 Introduction

This is an expanded chapter that is specially written to provide the reader with a deeper understanding of the four crises which are present nationally and globally. These four crises as illustrated in *Figure 2.1* must be taken seriously and given urgent attention in order to promote sustainability and sustainable development.

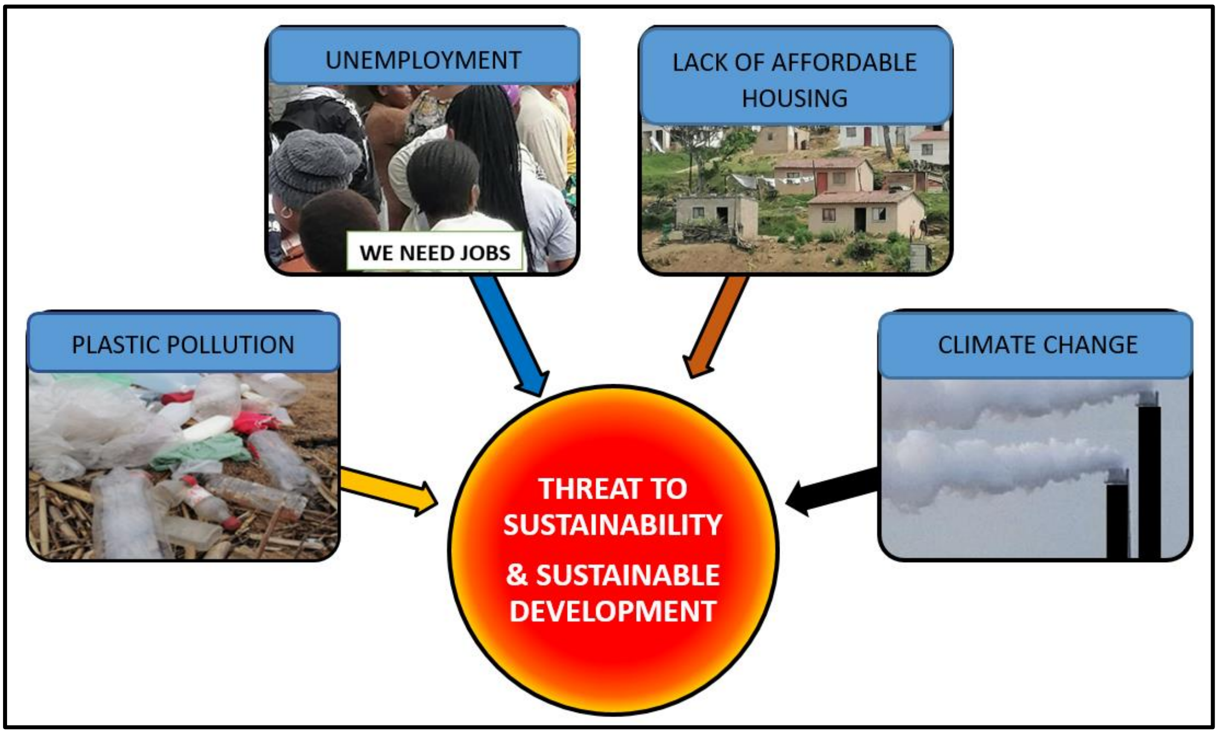


Figure 2. 1: Four national and global crises

It is necessary to obtain a comprehensive understanding of the four distressing scenarios that are growing rapidly. It must be emphasized that the four crises are written separately. However, they are integrated and directly interconnected to the three pillars of sustainability viz. pollution (environmental), housing (social) and employment (economic) [27] [28] [29] [30]. The four crises are intentionally written separately in order to present a deeper analysis of each one and to show them as one common challenge to sustainability. Each of the four threats to sustainability is elaborated in three broad categories namely: its impact globally, in Africa and South Africa.

Hence, a comprehensive discussion of these four crises is presented as an extended chapter in order to provide a deeper understanding of how these crises are seriously affecting sustainability.

2.1 A global plastic pollution crisis - A threat to sustainability

Victory [31] warns that over the last few decades, plastic pollution has reached crisis levels that require combined efforts to protect the planet and its inhabitants from further damage. Plastic pollution is now becoming extremely dangerous to the environment due to the related rapid accumulation, and improper disposal methods that are leading to many harmful effects to the environment and humans [32] [33]. Waste plastic found on land and water cause harmful effects to the living species in the marine ecosystem and also cause detrimental effects such as flooding [34].

2.1.1 Global plastic problem

Plastic pollution has developed as one of the most urgent environmental threats due to its rapid increase in production and poor waste disposable systems being implemented. Plastics have increased from 2 million metric tons in 1950 to a projected figure of 34 billion metric tons by 2050. This is indicated in *Figure 2.2*. The total plastic waste in 2015 was 6.3 billion metric tons. This wastage is projected to 12 billion metric tons by the year 2050 [35]. The current study is necessary because waste plastic such as HDPE, Low Density Polyethylene (LDPE), Polyethylene terephthalate (PET) and others are increasing at a disastrous rate. There is a dire need for the accumulated waste plastic to be recycled, so that it can be used as alternate building and construction materials or products.

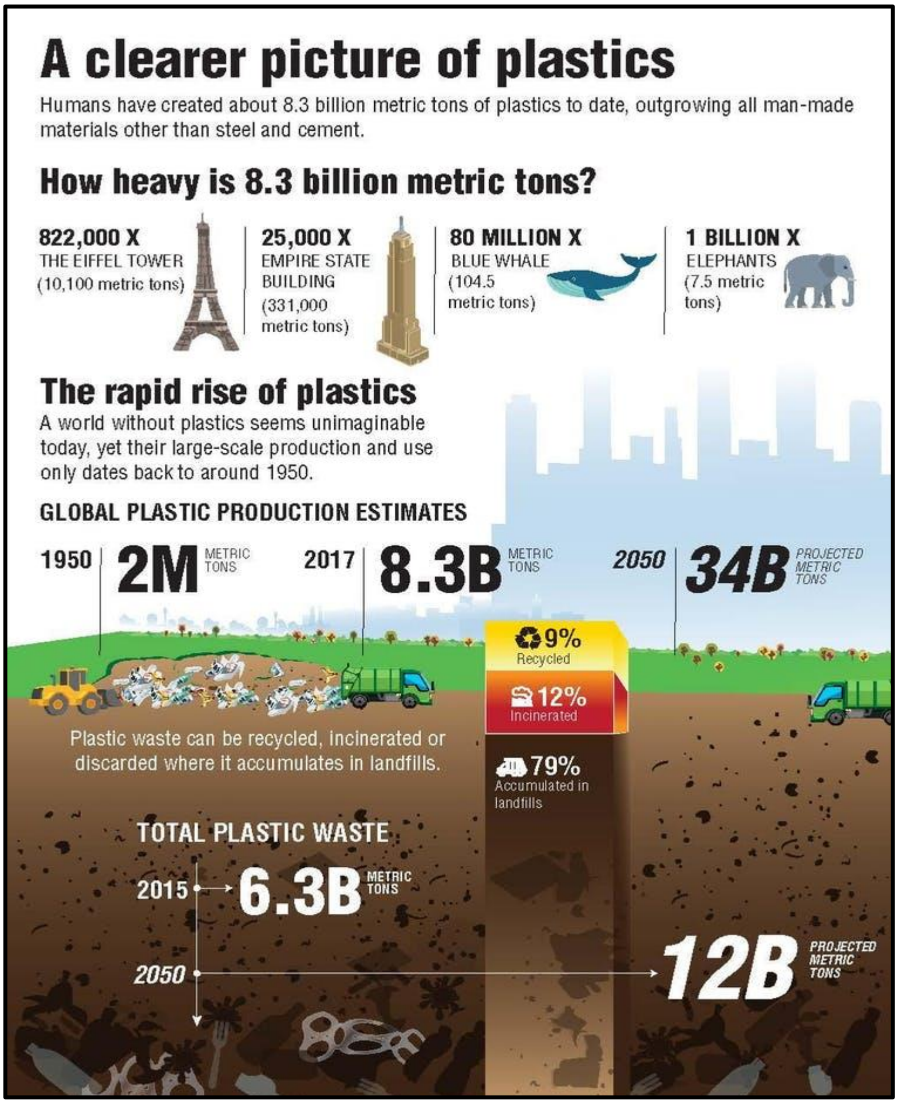


Figure 2. 2: Plastic pollution figures - projected to 2050 [35]

Global primary waste generation statistics indicated in *Figure 2.3* reveals that there is a rapid increase in all types of plastics over 60 years from 1955 to 2015. There has been a fast increase in plastic waste to over 300 million tons in PET, 150 million tons in PS, about 149 million tons in PP, over 100 million tons in HDPE and over 50 million tons in LDPE during 2015 [66]. It is estimated that this scary scenario will double every 10 years. A huge amount of plastic waste stems from municipal waste which infects all areas of society. Plastics by its very nature and the properties it possesses, can take between 400 and 500 years to decay in the environment [67]. Other researchers also confirm that plastics are not fully degradable wherever they lie in the natural environment and pose a life-threatening environmental hazard [68]. Thus ingenious, but radical strategies and techniques for discarding and making use of them are compulsory [69].

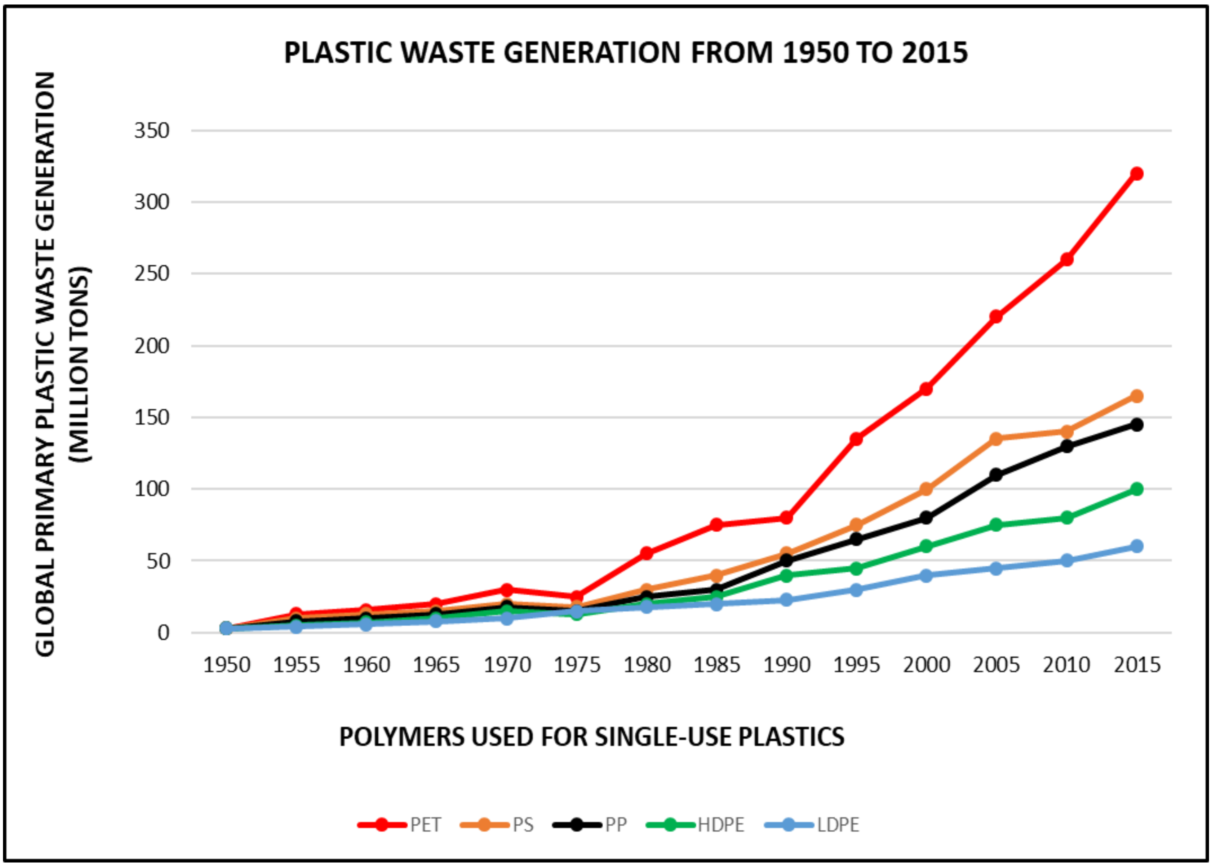


Figure 2. 3: Global primary plastic waste generation, 1950–2015 (Adapted from [36])

There are many materials that are recyclable. Unfortunately, plastic recycling is existing at a lowest rate, which contributes mainly to the rising problem of pollution [37]. More strategies and innovative ideas are required to tackle the global plastic pollution crisis. Therefore, there must be more focus on stimulating positive consumer behaviour, renewed environmental policies, increased awareness and advocacy to educate the citizens about pollution and the value of recycling waste into other new products [38].

2.1.1.1 Impact of plastic pollution

i) Long term food security

Zhang et al. [39] cautions about the dangers of plastic pollution to long term food security in aquatic and terrestrial habitats. Whilst plastic mulch is extensively used to increase crop yields worldwide, it has also demonstrated multiple negative impacts on plant growth such as crop yield, plant height, root weight, and soil properties such as soil water evaporation capacity, soil water infiltration rate and soil organic matter.

It is shocking to note that between 1950 and 2015, an estimate of about 4,900 metric tons of mostly non-biodegradable plastic waste, which is translated to about 60% of all plastic produced worldwide, ended up and accumulated in landfills, marine, and other environments. It has been noted that a large percentage of plastic film mulches which should have been used to increase crop productivity are not recovered at the end of the crop season. The scary situation is that once these phthalates are absorbed by plants, it then moves along the food chain and will be finally consumed by humans. Although, these are initial findings, this scenario signals an ever growing concern which threatens the sustainability of global crop production and food safety in the future [39].

In their study, Akankali and Elenwo [40] argued that the ocean is an important source of food, especially to the nation's poorest people. The majority of them live on fish as their source of protein; engage in activities within the fishing industry and also rely on aquaculture sport either directly or indirectly. In some cases beaches are closed to citizens since the water is unsuitable for engaging in sports or bathing. The people are directly affected by plastic pollution due to the accumulation of plastics, discharge of sewage, agricultural run-off, and release of nutrients and pesticides. This constitutes approximately 80% of marine pollution.

ii) Marine life

The marine environment is constantly subjected to the harmful effects of plastic waste pollution. The destructive effects on birds, fish and other sea life have been documented so that further action can be taken [41]. The research study conducted by Vegter et al. [42] also reiterated that plastic pollution has reached the oceans as well as all the coastal environments causing major threats to ocean life. It is discovered that plastic pollution is growing relentlessly and is a serious global concern reaching threshold levels and is pointing towards a global disaster in the future.

Nano and microparticles of polystyrene (PS) have been ingested by marine invertebrates, fish, seabirds, sea turtles and other marine mammals. It is clear that plastic pollution is impacting negatively on all food webs. The ingestion of these non-nutritive substances has led to gastrointestinal perforation which is caused unfortunately by swallowed hooks and hard plastic that cause chronic infection, septicemia, disorders and finally death [42].

iii) Environmental

Adeniran and Shakantu [43] highlight that plastic waste is a serious environmental issue because it has reached unprecedented levels and leads to waste pollution. The devastating and harmful effects of waste plastic on the immediate environment and its people is increasing on public platforms and is becoming important to talk about saving our ecosystems.

The danger of plastic pollution commences when they reach end of life since they escape into the land and marine environment and struggle to disintegrate. Plastics have become one of the most problematic items that are discarded in landfill sites or through illegal dumping into rivers and oceans causing damage to the environment and aquatic life. South Africa is currently addressing the challenge of plastic pollution and its impacts on humans and the environment. The study conducted by the Department of Forestry, Fishery and the Environment (DEA) in 2017 [11] provided evidence that packaging constituted the largest component of single-use plastic waste that is of serious concern in South Africa.

iv) Health

Adeniran and Shakantu [43] explains that due to the accumulation of waste plastics, most aquatic species in the marine ecosystem struggle to live in it and harmful plastics are ingested by them causing various health issues in people if such fish are consumed. This leads to a host of human ill-health problems ranging from the stomach to the lymphatic and circulatory problems. In order to find an effective way to manage waste plastic and improve the sustainability of our environment, the use of waste plastic for construction applications is a necessary initiative.

In the research conducted by Forrest et al. [44] it was concluded that plastic pollution had a negative impact on humans. It leads to different types of health difficulties such as thyroid dysfunction, obesity, diabetes, and reproductive impairment. It has been noted that plastic pollution does not only contribute to marine and environmental problems but it does attack the body, causing severe illness and dysfunction. Plastic contamination in humans is common and many cases have been recorded globally. Therefore, an effective recycling system is urgently required to prevent plastic pollution from increasing, endangering marine life and eventually people.

It was discovered that synthetic textiles are one of the main sources of airborne microplastics, and fibres found in the atmosphere. Due to their minute size, these airborne microplastics are unfortunately inhaled causing serious health risks to people. Furthermore, the release of dangerous chemical and microorganisms from the surface of microplastics pose a major risk factor to the health and well-being of all humans [45]. When plastic is discarded or disposed of in a careless manner, it gives rise to short- and long-term challenges that affect humans and their natural environment. The escalating plastic waste being disposed of in many South African townships is a serious cause for concern. [43].

2.1.2 Extent of plastic pollution in Africa

i) West African perspective

Adam et al. [46] evaluated 13 out of 16 countries of West Africa regarding plastic waste: Sierra Leone, Mali, Mauritiana Bernin, Burkina Faso, Guinea Bissau Cape Verde, Ghana, Guinea, Ivory Coast, Liberia, Nigeria, Niger, Senegal, Gambia and Togo. It was noticed that migration of rural people to urban areas was common. Approximately 47.3% of West Africa's population are now living in urban areas with a trend of increased population growth and urbanization. Hence, the use of plastic material has doubled and is forever increasing in an unsafe way. The accumulation of plastic waste is seen to have many poisonous effects on the environment and on humans in general. It causes water borne diseases, blockages on the roads and in storm water drains, poses a serious risk to human, plant, animal and marine life. There are also several damages to the fishing and tourism industry. The great challenge is that almost all plastic waste is mismanaged. The main reason for this is a lack of or poor waste management (WM) systems being in operation. This mostly leads to marine pollution in West Africa. Illegal waste dumping activities is also prevalent along the West African coast, which contributes significantly to the demise of marine life.

ii) Plastic problem in African states

Bashir [47] explains that the government of Nigeria is finding it difficult to place a ban on plastic bags since most of the population access water through these plastic sachets. An estimation of about 10% of the rubbish in Africa makes its way to the dumps. Unfortunately, the rest of the waste material is left to decay in the neighbourhood or set alight in open bonfires posing a threat to sustainability.

Majority of the 48 million plastic bags manufactured in Kenya find its way directly into the environment. This accumulation of plastic waste causes many problems such as death of livestock, blocked sewer pipes, the spread of multiple diseases, and harms tourist activities. The Kenyan Government has legislated a 120% tax on all plastic carrier bags including a total ban on plastic bags that are <30μ thick.

Botswana

The Non-Governmental Organisations (NGO's) in Botswana have raised concerns regarding the widespread use of plastic, its management and disposal. A plastic campaign was launched which gave rise to government taking action on the use of plastic such as: shops to sell plastic bags thicker than 60μ and manufacturers to ensure that plastic bags are made such that they can be recycled [47]. The government of Botswana enacted a legislation on the use of plastic bags which began in 2007 with the possible outcome of reducing the plastic bag demand. The initial introduction of this legislation has led to a significant decrease in the demand for plastic bags [48]. The plastic levy in Botswana achieved short-term success. However, the results of the study conducted by Mogomotsi et al. [49] argues that the levy implemented in Botswana was partially achieved and indicated a short-term success.

Namibia

There is a definite problem with plastic trash accumulating on the beaches. This accumulation eventually leads to marine plastic pollution and finally affects tourism and aquatic life [47]. Curtis [50] stressed in his thesis that plastic pollution in the ocean is an ongoing debate. The plastic waste being harmful to the ocean and its surroundings due to the entanglement of many marine mammals such as dolphins and whales must be addressed.

Congo

The Republic of Congo has stood firm in their position to combat environmental pollution by prohibiting the production, importation, sale and the general use of plastic bags. Congo has faced major environmental pollution due to plastic bags being thrown in the environment, which resulted in serious problems of blocked drains. This resulted in many areas being continuously flooded and leading to other challenges of water borne diseases. Hence, Congo has huge challenges regarding the promotion of sustainability [47].

Ghana

Ghana is struggling to cope with waste plastic disposal. Plastic bags accumulate in city spaces, clogging public drainage, damaging the soil and have a negative impact on the beaches. It has been found that the political will including the change in people's behaviour was necessary to promote the capacity, scope and depth of recycling at a national level. The collection, sorting and distribution of waste to allocated centres and restricting the use of landfills for plastic dumping are other areas that need attention [51].

Ethiopia

It has been noted that plastic bag waste has become one of the major challenges contributing negatively to the environment thereby causing health challenges to humans and livestock. A survey study was conducted in Jimma City of Ethiopia to ascertain the impact of plastic bags on the environment. The results indicated that the pattern of using plastic bags is increasing all the time. One of the recommendations to decrease the problems with the increasing trend of the use of plastic bags was to at least educate all the citizens to avoid using it. Instead, they must use eco-friendly alternative bags manufactured from textile, natural fibers or ordinary paper that can be recycled [52].

Tanzania

Tanzania has also experienced challenges due to Microplastics (MPs) pollution in the marine environment due to a lack of or poor implementation of proper solid waste management (SWM) strategies. A study was conducted on the distribution and types of MPs in beaches and on the seabed of the coastline of Dar-es-Salaam and Zanzibar. A shocking figure of 641 MPs were recorded from all the sites investigated, of which a large percentage (84 %) and (16 %) were located from the beach and seabed, respectively [53].

iii) Other countries

Sudan, Gadarif and Gezira states have prevented the use of plastic bags for more than ten years now. Sudan, Chad, Erirea, Ethiopia, Central Republic of Africa, and Burkino Faso have unfortunately faced many challenges in respect of the disposal of plastic bags in the country side which directly impacts the cattle and other livestock [47].

2.1.3 The extent of plastic pollution in South Africa

i) Plastic pollution in five urban estuaries of KwaZulu-Natal, Durban

Naidoo et al. [54] argues that not much quantitative evidence of plastic pollution has surfaced in the literature. There is limited data published on plastic pollution even though there are problems in 73 estuaries in KwaZulu-Natal. Only five of the estuaries were sampled in respect of plastic pollution. It was interesting to note what samples were found in the three sections of the estuary at spring low tide: head, middle and mouth. Plastic particles were identified in all five estuaries. Altogether, there were 13 680 particles recorded in that study [54]. The highest mean concentration of plastic (159.9 $\pm$ 271.2 particles per 500ml) was recorded in Durban, followed by Umgeni and Isipingo estuaries respectively. The lowest concentration of plastic particles was recorded in Mdloti and Ilovu, which are away from the Durban Harbour. The pollution levels recorded were the highest around the metropolitan areas, such as the Durban Harbour. Fibres, fragments and films which were predominantly < 5mm constituted the main plastic waste disposal from the Durban estuaries and noting that plastic fragments indicated the greatest concern at the Bayhead region itself. Fibre was more of a concern at the remaining estuaries.

ii) Huge amount of waste in Umhlanga river

Research findings of the Litterboom Project published in the National Business Day on 12 January 2022 by Suthentira Govender [55] portray a more accurate consequence of plastic pollution in and around the Durban area. The Litterboom Project revealed that it was a blessing since the heavy rains were able to wash out the accumulation of waste that had collected along the banks of the Umhlanga River. It is believed that the plastic waste had been flowing from the local communities and industries. Most of the waste material had been collected before it made its way into the sea. Large pipes were used across the river to trap all plastics floating on the surface. The Project leader, Mr Josh Redman and his team had more than 300 tons of plastic waste removed from some rivers in KwaZulu-Natal and in the Western Cape before it landed in the ocean. A similar situation was prevalent three years ago which means that this is now becoming a recurring phenomenon.

iii) Historical review of waste management and recycling in South Africa

Godfrey and Oelofse [56] provided a detailed outline of the four stages of South African waste disposal and recycling during the last 3 decades. Rasmenia and Madyira [57] indicated that most municipalities in the South African provinces are currently facing a crises regarding solid waste disposal and management. This is due to the main concern of the lack of landfill capacity to accommodate all waste disposal. Hence, Municipal Solid Waste (MSW) management being a major environmental problem in South Africa has led to charting a way towards policy development on "Age of landfilling", "Emergence of Recycling", "Flood of Regulation", "The Drive for Extended Producer Responsibility (EPR)" and Circular Economy (CE).

Stage 1: The age of landfilling (1989-2001)

Disposal of general and hazardous waste material to landfills has been the general trend in South Africa and abroad. This disposal amounted to about 90% of all waste material into these unlicensed, uncontrolled and mismanaged dumpsites. Due to the heightened environmental and health risk arising from landfills, government has been forced to design policy and regulations that would allow landfills to operate in a safe way. It was found that 431 out of 581 landfills which made up 74%, were unlicensed. Government has made endeavors to get the landfill sites registered and licensed and was successful. Whether the operations of the landfill sites satisfied the requirements for compliance in respect of WM still remains questionable.

Stage 2: Emergence of recycling (2001-2012)

It is noted that recycling has been taking place in South Africa since 1976 from collecting to recycling of all the used beverage cans. Also, the sorting of waste material was prevalent in many urban areas in Johannesburg as well as Pretoria during the 1970's. Slowly, there was the emergence, development and growing of a local waste economy by industry, producers and manufacturers as well as within the economy. The informal sector of waste pickers was around 215 000 who made a living from work in the waste sector in South Africa. Although there has been a noticeable transition in the recycling landscape in South Africa, it was only possible to re-divert 10% of the waste generated away from the landfill sites to recycling.

Stage 3: Flood of legislation and other regulations (from 2008)

There has been a proliferation of waste legislation since 2008 with the publication of the Integrated Pollution (IP) & Waste Management White Paper. Later the NEMWA No. 59 of 2008 provided a regulatory framework in order to protect the health and the natural environment by outlining reasonable measures to prevent pollution and ecological degradation as well as providing sustainable development. These regulations essentially had an overarching controlling approach in the waste sector to minimise the negative environmental and health risks due to poor WM systems. The focus was to move away from waste disposal towards the 3 r's: reuse; recycling and recovery. Shah [58] also promoted the various techniques that are used in WM which he called the 5 R's: Reduce, Recycle, Reuse, Recover and Residual management which are acceptable WM techniques to be followed in order to bring about an ecological balance.

Stage 4: The drive for Extended Producer Responsibility (EPR) (from 2012)

EPR laws which have been amended on 5th May 2021 now require the manufacturer of products to be responsible for the life cycle of their products which they produced for the open markets, which includes final recycling, reuse or disposal processes. This shifted the burden of the costs of managing the product's end of life from taxpayers. South Africa and the rest of the world are now entering a fifth stage called "Circular Economy." Stahel [59] argues that a CE business model falls within two categories. *Firstly*, those that promote the reuse by engaging in repair, remanufacture and upgrades so that the life of the material or resource is extended. *Secondly*, those that make use of the waste or discarded material and turn them into a new resource material by engaging in the process of recycling.

iv) Scenario of plastic waste generation

South Africa is now regarded as one of the major contributors to plastic leakage on the African continent and this is a matter of great concern [60]. It is claimed that 43% of plastics in South

Africa is recycled while 57% of them is dumped in landfills, incinerated or makes its way into the ocean and other environments. Therefore, it is essential that WM systems are effective and functional in order to get rid of plastic waste within the country so that it does not reach levels which cannot be managed [61].

South Africa has experienced a surge in its daily operations and expenditure regarding plastic generated in 2019 which amounted to R885.34 billion. This figure comprises damage to people and also the harmful effects to the health and welfare of the citizens. South Africa has been noted to be the 11th worst global lawbreaker in regard to plastic leaking into the oceans because it produces much more waste plastic in comparison to the world average. It produces an annual figure of 41 kg of plastic waste per capita as compared to the world average which is much lower at 28kg annually [62].

The single-use plastics in South Africa is becoming commonly used and expected to increase. This is due to the estimated population growth and a rapid movement of people to urban areas. The same scenario exists even though government has tried to prevent plastic pollution. Plastic waste continues to be thrown onto land, and somehow makes its way into rivers, lakes and streams, and is seen in illegal dumping and landfill sites. The sad situation is that the National State of Waste Report recorded that more than 50% of plastics produced in South Africa are dumped in landfill sites. The present WM policy instituted by government is problematic and a major challenge to implement in order to achieve the required outcomes [11].

v) Waste disposal

In general, waste is classified as dangerous to the natural environment and to the health and welfare of people because of its toxic nature [63]. Scientists and others have discovered that waste can be of value when changed or altered to form other useful products as long as they are carefully stored, suitably discarded or managed in a way that is acceptable to legislation. Eventually, all waste materials are a threat to human life and the environment (soil, air, water). Therefore, the manner in which dangerous waste is disposed of is important. The prudent use of environmentally friendly waste disposal technology, which must be economically viable, is welcomed [64]. The volume of plastic waste disposal during the last few years is a signal that plastic waste is growing at a terrifying rate. This situation seems to be difficult to change due to the general increase in population growth and the forced migration of individuals from unstable countries. It is projected that by 2050, a dreadful figure of 12 000 metric tons of plastic waste will find its way into landfills or be thrown onto land, oceans and rivers [65]. Regrettably, the disposal of plastic is seen to be a frequent occurrence and a general environmental issue which unfortunately damages the environment. The ineffective disposal methods affect land cultivation which is linked directly from its non-biodegradable properties and the emission of toxic substances as well as gases during the burning process [66].

Due to the pressing plastic waste problem, incineration has become another way of reducing the plastic from the environment and in landfills. Verma et al. [67] argues that the burning of plastic waste in an open area is now becoming a major health hazard and is a cause of air pollution. Waste incineration creates and releases harmful chemicals and pollutants into the atmosphere. The release of poisonous gases such as Dioxins, Furans, Mercury and Polychlorinated Biphenyls into the air poses a serious danger to people’s health such as heart disease, worsens respiratory problems, causes skin cancers and retards the central nervous system [67].

However, the rapid increase in solid waste and less land for disposal of waste material in South Africa means that the disposal of general and hazardous waste material to landfills will continue to increase and be a common pattern [56]. Statistics have recorded that South Africa produced about 108 million tons of waste in 2011 and a very high percentage (90%) had been discarded into landfills while a small percentage 10% had been recycled. More innovative ways of recycling waste material will change this current scenario. South Africa is experiencing many challenges regarding waste management ranging from a growing population that produces more plastic waste on a daily basis, to the absence of suitable, reliable and effective recycling infrastructure and WM equipment. Due to these challenges, there is still a reliance of using landfill as the convenient WM option. The continued use of landfilling options is not making it any easier for human survival and a strategy has to be implemented to resolve the pollution crises [68]. The absence of forceful strategies to decrease waste generation in South Africa will inevitably lead to waste generation that will be uncontrolled in future. Hence, deviation of plastic waste from landfill will be unimaginable and this situation is unsustainable [65].

The problem of illegal dumping and littering is still an ongoing problem in many municipalities in South Africa. Waste clean-up is a very time-consuming exercise, difficult in its operations and costly to the citizens of South Africa. Therefore, it is necessary to establish proper methods to dispose plastic waste in the environment, households, light and heavy industries [69]. There needs to be greater effort of an urgent and sustainable way for its reuse to safeguard and endure future generations. One of the ways is to start making a difference in our own home by learning how to reduce, reuse, and how to recycle certain materials [70]. The reality of limited land for landfilling exist and the constant increase in dumping fees will continue. Bearing this in mind, the recycling of waste plastic is an answer to the disposal problem [71].

Therefore, the constant challenge is to engage in different ways of how plastic can be disposed of in an acceptable manner from households and industries. The effort of an urgent and sustainable solution for its reuse is a necessary option to protect and sustain future generations.

2.2 A global unemployment crisis - A threat to sustainability

This section presents the details of how unemployment has become a national and global crisis. Unemployment is currently faced by many countries globally. However, the youth unemployment rate in South Africa is intensifying, regardless of several attempts and programmes implemented by government to curb high unemployment [15] [72]. Unemployment is constantly faced by citizens, it needs serious consideration, and conscious planning for it to be reduced. The unemployment situation in South Africa and abroad is presented and its direct bearing on the current study will be emphasized.

2.2.1 The unemployment globally and in Africa

Figure 2.4 below indicates a fearsome situation of the projected youth population. The size of the youth population has somewhat reached its peak in countries in Oceania, Northern America, Europe, Latin America and the Caribbean. On the other hand, *Figure 2.4* demonstrates that the size of the youth population of Asia is decreasing steadily in the age group 15-24 years from 780 million in 2015 to 690 million in the year 2060. Africa has indicated exponential growth in this category [73]. However, in Africa 226 million youth are recorded in 2015, in the age category of 15-24 years. Studying this projected trend, it is estimated to increase to approximately 500 million in 2060. The unemployment rate in other countries such as Saudi Arabia, Jordan and Iraq is no different. One of the greatest challenges is experienced in countries such as Greece, South Africa and Spain where youth unemployment is above 50% [73].

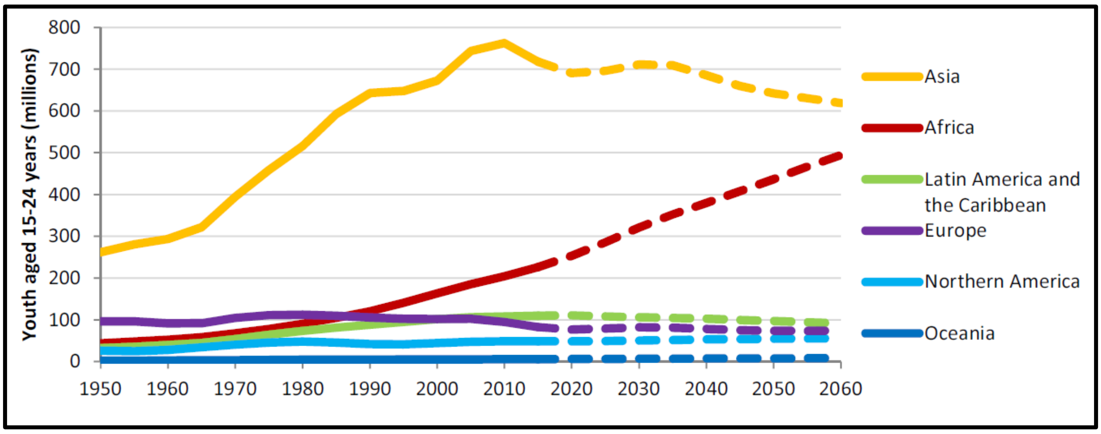


Figure 2. 4: Youth unemployment population [74]

The African Development Bank group [75] indicates that most of the youth in Africa continue to be disadvantaged in the labour market due to the weak economies. It is noted that about 33.33% of the 420 million youth aged between 15-35 years are facing unemployment and depression. It is noted that 10-12 million youth tried to make their way into the workforce each year but only 3.1 million jobs are available. Hence, there is a priority to provide employment prospects for youth in Africa for the coming years [75].

Studies show that Africa is one of the regions where the youth category shows a definite sign of growth at an exponential rate in the coming future. This situation reflects a picture of an impending disaster if governments do not reintroduce and implement new policies to boost job opportunities [76].

2.2.2 Unemployment in South Africa

i) Unemployment during the 1st quarter of 2021

Statistics South Africa [15] reveals the statistics of the 1st quarter of 2021 as presented in *Figure 2.5*. The worrying statistics shows that young adults (youth) aged 15-24 years and 25-34 years have been identified as the groups with the highest unemployment rates from the five categories, i.e. 63.3% and 41.3% respectively. Only a 7.6% absorption rate and a 20.6% labor participation rate in the 15-24 years' category have been recorded.

Unfortunately, the general unemployment rate in South Africa swings to an unprecedented rate of 32.6%. This implies that having a very high percentage of unemployment means that a large population of the country does not have work. The youth unemployment rate is frightening because it is beyond 63% in the age group between 15-24 years. South Africa is now vulnerable and has the potential of social and political unrest.

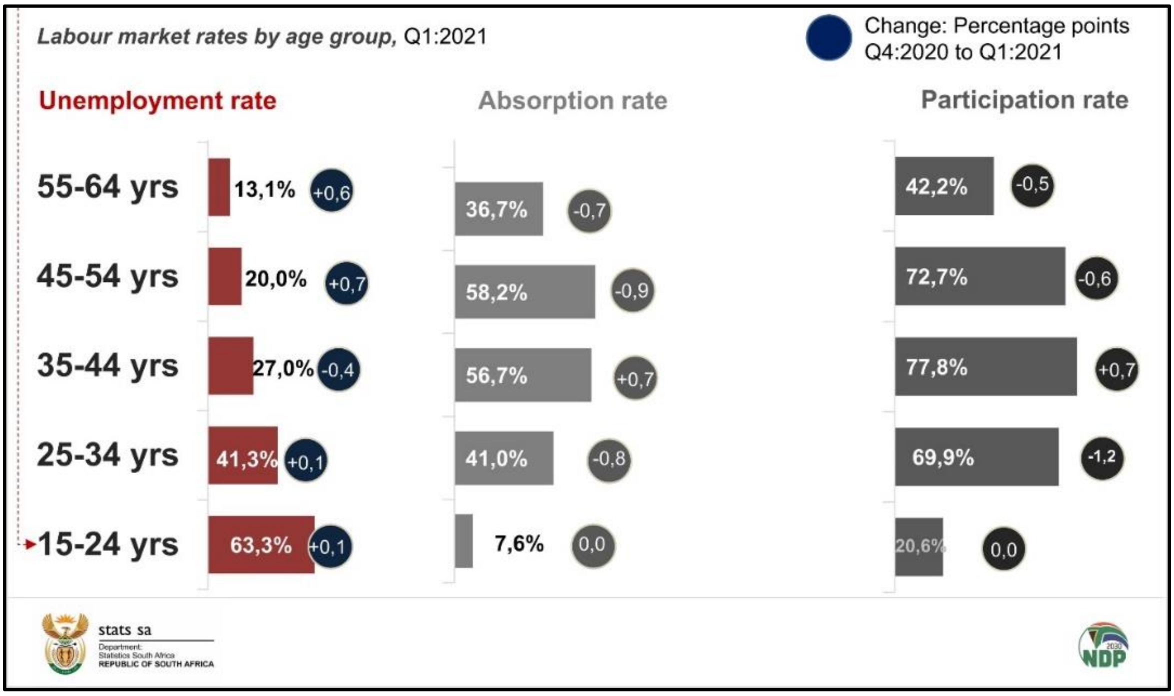


Figure 2. 5: Unemployment rate in South Africa [15]

ii) Unemployment during the 3rd quarter of 2021 in South Africa

Statistics South Africa [15] released the 3rd quarter quarterly labor force survey. It showed a depressing situation of the unemployment rate which increased to 34.9% as indicated in *Figure 2.6*. Also, the official unemployment rate by province is the highest in Eastern Cape

(47,4%) and in the Northern Cape (24,9%). The unofficial unemployment rate among the Blacks in South Africa is well above the national average being 38,6%.

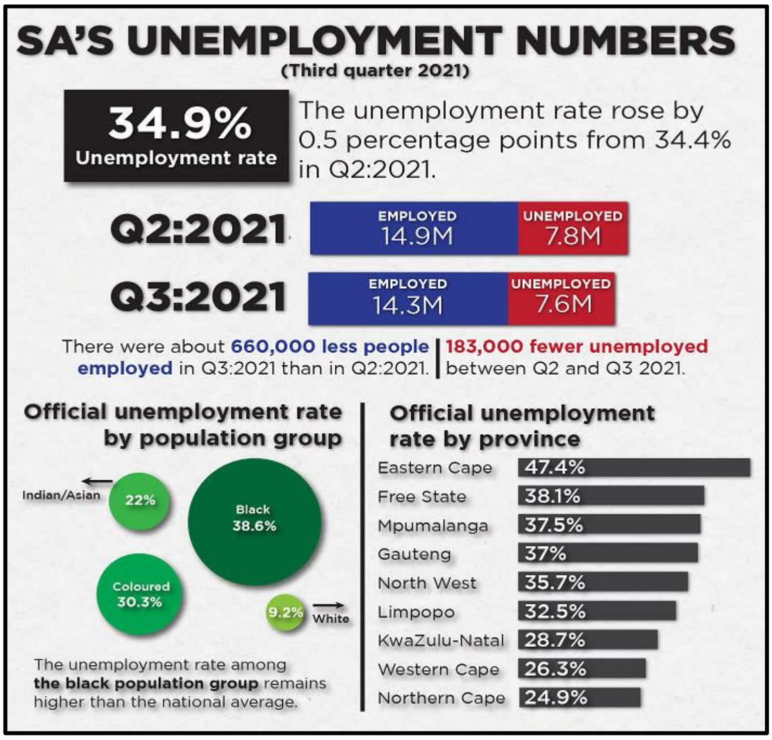


Figure 2. 6: Unemployment numbers in South Africa [77]

The highest unemployment rate has been recorded since the quarterly labor force survey started in 2008. It is sad that the unemployment rate among women was 37,3% in the third quarter of 2021 compared to 32,9% among men. This is indicative of a struggling economy battling with high job retrenchments and stagnation in the economic activities. This scenario was compounded by Covid-19 pandemic lockdown restrictions as well as the July 2021 social unrest in parts of South Africa more especially in Gauteng and KZN leading to businesses being burnt and permanently shut down [15].

iii) Youth unemployment in South Africa

South Africa is still trying to combat its high unemployment rate with the first quarter of 2023 being at 32,9 %, which is very high against the rest of the world. The Quarterly Labour Force Survey (QLFS) revealed that there was an increase of 0,2 % in comparison to the fourth quarter of 2022 [78]. Sever and İğdeli [79] state that unemployment is defined as *"the situation in which persons between 15-24 years of age who are involved in the age of work and make an effort to be employed within a certain period of time and can be employed when a job opportunity is given at the moment (pg. 1)"*

However, the world population review [16] defines unemployment as *"the percentage of unemployed workers in the total labor force. The unemployment rate includes workers who currently do not work, although they can do so. The unemployment rate is a lagging indicator pg. 1."* This means that unemployment is sensitive to the economic conditions and changes in the country.

iv) Unemployment rate of South Africa

Figure 2.7 indicate that the 20 countries have been ranked according to their unemployment rate for 2022. The first 2 countries projected a high rate of unemployment with South Africa being 34,38% and Sudan 27,67%. Unfortunately, South Africa has the highest rate of unemployment in respect of the 20 listed countries. The unemployment rate has a negative impact on the South African economy and on wellness of the citizens [80].

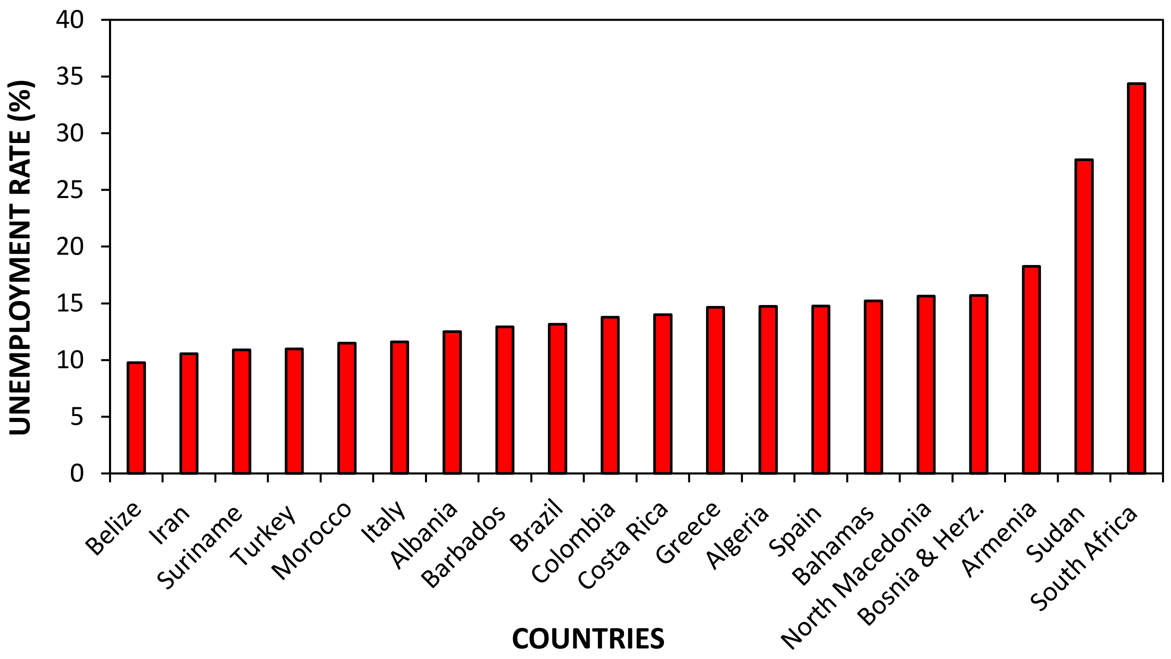


Figure 2. 7: Unemployment rate in South Africa in comparison to other countries [80]

The world population review [16] also warns that the high unemployment in South Africa affects the people's lives in respect of their health and welfare. In addition, it increases general criminal activities, decrease in economic activity, attrition of skills and portrays a bleak picture of the future.

2.2.3 The impact Covid-19 pandemic on unemployment

The onset of Covid-19 pandemic has plunged the unemployment rate in many countries in the world at a much higher level. This has resulted in people being poorer, employers were unable to pay their employees and forced many company shutdowns [81]. It was noticed that during the period from February to April 2020, the unemployment rate in the United states was shocking. It more than trebled from 3.5% to 14.7%, which later decreased in the month of August to an average of 8.4%. However, the study revealed that in Australia, the unemployment rate significantly increased from 5.4% to 11.7%. Canada recorded a substantial increase in the unemployment rate during four months between February to May from 5.6% to 13.7% [82] [83]. The Covid-19 pandemic outbreak had a disastrous effect globally and has been detrimental to members of poorer social groups and in the most vulnerable areas. Hence, the pressure and renewed implementation of the SDGs of 2030 have become much more difficult now as compared to previous years to ensure that the quality of lifestyle of the masses are improved [84].

2.2.4 Solutions to unemployment

The creation of learnership programmes is one of the solutions initiated by the South African government to allow a learner to earn an income and at the same time enhance their skills within their work places. Whilst this policy shift was not totally welcomed by some unions, it served the ultimate goal of job creation in all sectors of the job environment [85]. Gamede [86] promoted the concept of collaboration between the rural based universities and tertiary institutions within local communities to encourage entrepreneurship. In their study, Mkhize et al. [87] found that street vendors lacked an important component of training and education in the area of business skills and management. In a survey, it was revealed that street vendors also played a vital role in promoting job opportunities for others. Approximately 3 in every 10 street vendors exercised their skills of employing another paid assistant to do some of their work.

Another way of reducing the unemployment crises is to think of new business possibilities in the labour market. In this way, more avenues were encouraged for young adults to pursue some type of job [88]. In the study concluded by Jubane [7] it was suggested that special programmes be designed to equip youth with numerous skills which would assist them in the real working environment. A recent study conducted by Rodríguez-Caballero and J. E. Vera-Valdés [89] emphasized that continuous unemployment makes it more difficult for people in this situation to receive employment opportunities in the near future.

2.3 A global housing crisis- A threat to sustainability

The Constitution of the Republic of South Africa, 1996, Section 26 [90] promotes access to housing. It also mandates the government to take steps through legislation and other measures to progressively ensure that the right to access to housing for all South African is realized. The Department of Human Settlements (DHS) [91] also makes provisions through a framework to ensure that national, provincial and local government helps those who are desperate to get housing through the housing development scheme. The DHS also focuses on the provision of sustainable housing developments. Each year, millions of people vacate their homes in the rural areas and migrate towards urban areas to find new opportunities, improve their lives or to find a temporary job. Others are forced to escape their homestead due to conflict or disasters [92].

South Africa's urban migration is increasing at a shocking rate and it is projected that by 2050, about 80% will be living in urban areas. The migration of rural people to urban areas deprives rural areas of skilled, semi-skilled people, critical thinkers, innovative individuals and possible business leaders. The increase of people in urban areas will cause pressure on government resources, services and traffic congestion. Unfortunately, some people migrate into urban areas and fall prey or are part of petty and organized crimes [93]. The study conducted by Ganiyu et al. [94] indicated that the pressure of housing demands made it necessary for government and real estate agents to deliver affordable housing to lower- and medium-income groups.

2.3.1 The global housing challenge

Tibaijuka [95] contends that it is compulsory to address the housing backlog in response to the extraordinary demand. He believes that the discourse and debates on housing and housing demand for more than 100 years has now shifted into a new paradigm from linking it to economic growth and development, to sustainability and sustainable development. Affordable housing is of utmost importance to the security of all citizens and nations. However, access to basic needs and services with regard to health, education and housing still remains as the major national and global challenges.

The Habitat III study [96] demonstrates the housing challenges in urban areas. About 25% of those living in the world's urban areas still live in squalid conditions. From 1990, 213 million people have contributed to an increase in the number of people living in slum conditions globally. It is recorded that over 90% of urban development is noticed in the developing countries. An estimated figure of about 70 million new residents are moving into urban areas in developing countries annually. It is forecasted that by 2035, the urban population growth of South Asia and Sub-Saharan Africa will double thereby resulting in a progressive increase in the informal sector and slum areas. In 2015, approximately 61.7% lived in poor or slum conditions in Africa. It is projected that by 2050, Africa's urban inhabitants would treble from 400 million to 1.2 billion. In Asia, it is recorded that 30% of the urban population is now living in slums. The urban dwellers in some regions of Europe have increased drastically but are unable to pay their monthly rent.

2.3.2 The analysis of housing challenges in South Africa

Two aspects of housing are presented namely, lack of affordable housing and increase in the building construction costs.

2.3.2.1 Lack of housing in South Africa

Phago [97] highlights in his study that housing is one of the benchmarks for a successful and healthy way of life. In a social context, housing plays a major role in the health and welfare of individuals. It was indicated that the construction of houses in South Africa remains at a sub-standard level since 1994. Marutlulle [98] argues that the challenge of inadequate and affordable housing still remains a political, social and economic debate for this problem to be resolved. It is glaring that the lack of suitable and adequate housing grows at an alarming rate annually. It unfortunately impacts negatively on the disadvantaged communities and more particularly those that belong to the disadvantaged, poor and those that live in urban areas with a lower income and are forced to live in a threatening environment.

2.3.2.2 Increasing building construction costs in South Africa

From the study conducted by Windapo and Cattell [99], it was highlighted that there is a high demand for specific kinds of building materials or that there is sometimes an over demand of these materials implying a mismatch between supply and demand. That study also concluded that in order to promote the growth and development of the construction industry in South Africa, it is important to conduct more studies as to why there are increases in the building costs. It is recommended that some action be taken to ease the increases in the building material costs.

In their study, Windapo et al. [100] evaluated the determinants of building construction costs in South Africa. They examined whether there is a link between the cost of construction equipment, labour and building. Their research concluded that there was a gradual increase in construction cost each year, which was not in line with inflation. However, there was a relationship between construction and equipment costs. It was also concluded that just one-unit increase in construction equipment costs resulted in 25% increase in the overall building construction expenditure. Construction equipment was the major determinant of increasing building construction costs in South Africa. It was therefore recommended that contractors and others in the building and construction industry in South Africa make use of construction equipment effectively and efficiently and not leave them standing on building sites.

Alabi and Fapohunda [101] discovered that the cost of construction was not the same at all times. It was greatly affected by the increase in the cost of building materials when they were delivered in Western Cape. Their findings also concluded that one of the reasons for the high maintenance cost stemmed from poor quality of workmanship, ridiculous increase in repair costs which was resultant from low quality of materials used in Western Cape Province of South Africa. It was recommended that contractors have a well-developed plan for the delivery of materials well in advance to escape unnecessary rise in building materials. The purchase of building materials in advance within the building schedule and providing a suitable storage place for them can reduce building costs.

Based on a study conducted by Alabi and Fapohunda [101] in Western Cape province of South Africa, it was concluded that there are other factors contributing to increase in the cost of construction and housing delivery. These include an increase in project abandonment, collapse of building due to less quality materials used, termination of construction workers, and fraudulent practices by developers.

The report of the Department of Minerals Resources in South Africa [102] had indicated that the increased population growth in the urban areas of South Africa has certainly placed much strain on the existing infrastructure. This was due to the need for more resources, services, housing, recreation facility and industrial developments. The South African construction industry has experienced a continuous period of very little growth due to the reduced demand for construction activities.

Dithebe et al. [103] warns that the South African construction industry needs much attention. It was documented that one of the major factors affecting the growth and development of the construction industry in the country was economic instability and also the rise in the prices of building materials. This study indicates that although South Africa manufactures some of its own building materials for the construction industry, it has no option but to import large quantities of building materials from countries abroad. The price of the construction material is said to be the most important factor of the industry. Hence, the pricing of imported goods usually has an impact on the construction price that was initially confirmed with the client many months before the project.

Figure 2.8 depicts a radical increase in the number of houses constructed and provided to disadvantaged people post 1994 to 1999 [104]. The sudden increase from 60 000 to 240 000 by the South African government was due to the extreme pressure for the demand for housing. This was one of the goals of the government to provide housing to the majority of its citizens who had been disadvantaged pre 1994. However, there is a visible decrease in the construction and delivery of housing since 1999. There has been an inconsistent number of housing construction and the delivery of housing units from 1999 to 2018. There has been a decline from 240 000 in 1999 to about 90 000 in 2018. The rate of housing construction and delivery is far behind in respect of the demand. This is attributed to the steady growth of the South African population that surpasses the number of houses required.

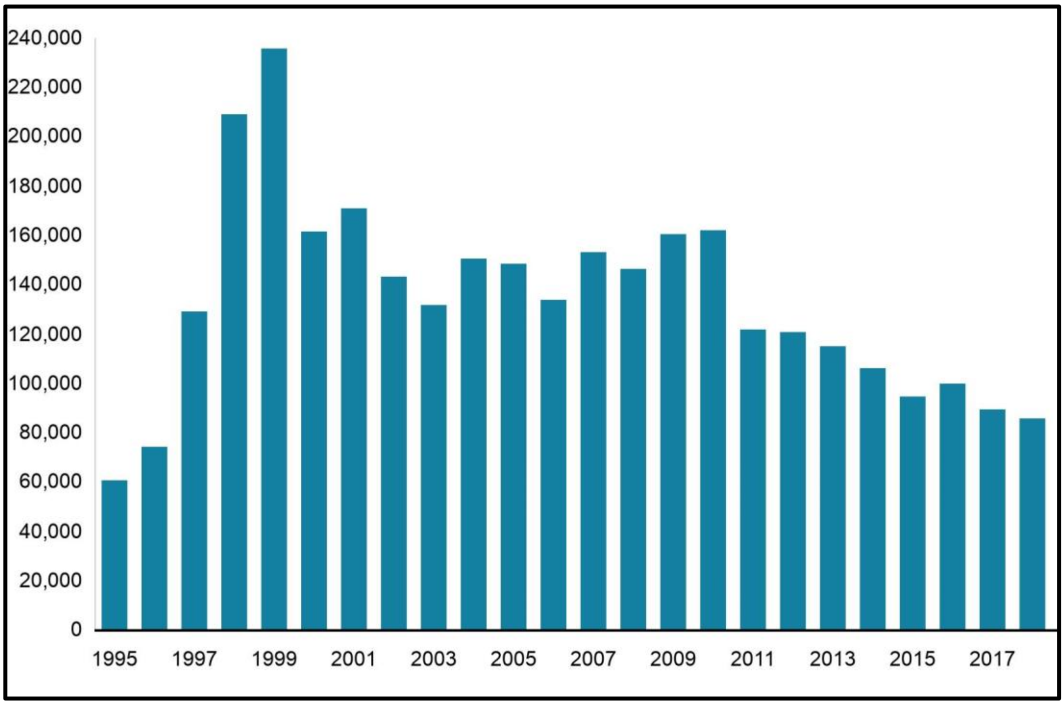


Figure 2. 8: House building in South Africa [104]

In general, the increased cost of building materials in South Africa has negatively affected the building industry. Therefore, the negative outlook of the South African construction industry is no secret since it has been struggling since 2000 [105]. Bowen et al. [105] express a serious concern regarding the scope, depth and kind of corrupt activities that exists in the construction industry in South Africa. They provided evidenced that corruption was real and rife in the country. There were various cases for corruption which were evident ranging from procurement processes, tender evaluation and inspections at different stages. These findings reveal that the standards of ethical behaviour need to be increased at all levels within the construction industry.

2.3.3 The increasing building construction costs in Africa and abroad

Akanni et al. [106] stated that the cost of building materials has played an important role in the construction industry in Nigeria. It has been found that the building materials costs has a direct link on both the quality and cost of housing. The mounting cost of building materials in Nigeria places stress on the construction industry as well as on the citizens who have low salary depriving them the right to own a house. The findings reveal that the main causes for the rise in the building costs are: (i) the high exchange rate of Naira, (ii) increased cost of fuel and power supply, (iii) escalating cost of raw materials, (iv) shortage of raw materials for building, and the (v) increased transportation and labour costs.

Bah et al. [107] stated that the population of Africa is on the rise at an average rate of 2.5% annually. This steady pattern of population growth is most likely projected for the future. The population in Africa during 2015 was approximately 1.18 billion and this is projected to double to 2.44 billion by 2050. Noting that 60% of Africa's people are living mainly in rural villages and that there is a constant rural-urban migration, will eventually result in over-crowding in urban areas and a decrease in rural population leading to challenges in both locations. A high percentage of housing backlog and urbanisation is recorded in many parts of Africa as indicated in *Table 2.1*:

Table 2. 1: Housing backlog and urbanisation in Africa [107], pg. 7

Country	Housing backlog	Urbanization rate, 2000-2015	Urban share 2015 (percent)
Angola	1,900,000	5.34	44
Burkina Faso	100,000	6.33	29.9
Burundi	30,000	5.75	12.1
Democratic Republic of the Congo (DRC	3,000,000	4.05	42.5
Egypt	3,500,000	1.7	43.1
Mali	400,000	5.35	39.9
Nigeria	17,000,000	4.78	47.8
South Africa	2,300,000	2.04	64.8
Tanzania	3,000,000	5.19	31.6

Uganda	1,600,000	5.27	16.1
Africa	50,562,000	3.5	40.4

Table 2.1, shows that the highest housing backlog is in some countries such as, Angola- 1 900 000, DRC- 3 000 000, Egypt- 3 500 000, Nigeria- 17 000 000, South Africa- 2 300 000, and Tanzania- 3 000 000. Africa as a whole has a backlog of 50 562 000 houses. The table also highlights the urbanization rate in Africa. The highest urbanization rate is recorded in Angola- 5.34%, Burkina Faso- 6.33%, Burundi- 5.75%, Mali- 5.35%, Tanzania- 5.19% and Uganda- 5.27%, with Africa as a whole having a 3.5% urban rate. This means that these backlog and urban rate records signals that something has to be drastically done to change the current situation on inadequate housing supply. Failure to finding a suitable solution will lead to an increase in social problems such as poor environmental conditions, continued over-crowding, poor health and sanitation and a high crime rate will constantly prevail.

Ebekozien et al. [108] presented three main causes that resulted in the high development and construction cost in Malaysian low cost housing scheme. The main causes were: (i) the provision of land, (ii) construction of various building being given to some companies by the developing agencies, and (iii) shortage of urban land. The overall construction cost steadily rose over the years.

Quality affordable houses should be constructed to ensure socio-economic stability. There is a desire to improve the delivery of affordable houses that is currently frail in Malaysia. It is vital to reduce the construction costs of housing to ensure that the housing prices are lower and making it possible for private developers to construct low cost housing with few challenges. In their study, Tan et al. [109] argued that there must be a close, positive and transparent communication in the partnership between the state and the potential developer from the start of the building project. It is vital to provide an explanation of the advantages of establishing the requirements for affordable housing.

Participants in the study conducted by Jzen and Chim [110] reported that there were many negative economic impacts of housing shortage, which resulted in people living in slum conditions, people taking advantage of overcrowding rental premises, and sudden increase in rental tariffs. The study also pointed out that the raw material used in various types of construction doubled from 15% to 30%. Also, the limited construction has resulted in the shortage of appropriate housing which eventually led to a drastic increase in housing prices. The study also revealed that the high cost of construction material automatically led to an increase in the total construction costs.

2.3.4 Solutions to the housing challenge

There needs to be urgent interventions and solutions from the state, business and other stakeholders for the construction and delivery of affordable housing. Bah et al. [107] argues that given Africa's housing development problem, it is important to solve the continent's critical affordable housing shortage by focusing on four critical issue. *Firstly*, sustainable solutions can only be achieved through democratic and transparent political leadership. *Secondly*, the factors of housing finance, affordable bank loan facilities and housing microfinance, as well as micro-insurance must be kept in mind. *Thirdly*, sustainable solutions must endeavor to focus on providing increased access to affordable housing for those who are in the category of poor to middle-income families. *Lastly*, it is worthwhile to industrialise the housing construction sector so that the housing backlog of over 50 million units can be realized across the continent. Also, the provision of technological innovations in the building and construction industry, including the use of prefabricated materials in the form of wall, roofs and panels will also assist in the promotion of growth in the housing industry.

According to Ebekozien et al. [108], there needs to be some policy changes such as waiving kinds of taxes for low cost housing to alleviate the high building cost in Malaysia. The study also suggested that: (i) the government should make a contribution in the form of subsidies towards land acquisition, (ii) provide assistance for industrialized building system, and (iii) the ceiling price of houses should be revised.

However, Thompson [111] explains that although the modular construction is not currently suitable for all types of societies, the concept has shown promising results in contributing towards the need of low-income housing. He argues that through the modular method much more housing units can be created when compared to old-fashioned methods**.** The following advantages are documented on housing modularization:

- it increases workplace safety at all times,
- it helps to decrease the risk of unforeseen environmental risks whilst on the project,
- it makes it very easy to assemble the components and its parts,
- it increases labour efficiency by greater than 30%.
- modular houses can be transported very easily from factory to site.

2.4 Global climate change crisis- A threat to sustainability

The effects caused by climate change stems from human activities. When there are more GHG emissions, weather patterns will result in extensive damage across our globe. It must be remembered that the future effects of climate change will depend on the total amount of carbon dioxide (CO_2) that is emitted by household and industry and well as the negative behaviour patterns displayed by citizens. So, if individuals can reduce emissions, we can reduce some of the devastating effects and untold damage on our planet. As indicated by Hoegh-Guldberg et al. [112] there needs to be greater energies to fast-track decarbonisation of the atmosphere and follow a path to net-zero gas emissions. Extensive action must commence earnestly to avoid the negative impact that is driven by humans. This last section covers the severe, pervasive and irreversible impacts of climate change and some solutions to ensure sustainability.

Morales-Méndez and Silva-Rodríguez [23] provides a definition of the ozone layer as "*The ozone layer is a band of natural gas called 'ozone'. It is found between 9.3 and 18.6 miles (15 to 30 kilometers) above the Earth in what is known as the stratosphere, and it functions as a shield against harmful ultraviolet B (UVB) radiation emitted by the sun*, pg. 2.*"* They stress that the major concern of the ozone layer is that it is continuously being affected and destroyed by the release of many pollutants such as Ozone (O_3), Nitrogen dioxide (NO_2), Carbon monoxide (CO), Sulphur dioxide (SO_2), CO_2, water vapor, methane (CH_4), and chlorofluorocarbons (CFCs). The National Geographic team [24] argues that the excess heat that is trapped in the atmosphere eventually contributes to an increase in the average global temperature. When temperatures increase for a long period, it leads to changes in weather patterns and disturbs the natural balance of nature. Humans and all other forms of life face a condition known as global warming.

Short and Farmer [25] focuses on recent research on climate change in cities. Cities have the potential of contributing to climate change through the process of GHG emissions and are unfortunately negatively impacted by climate change. Climate change is increasing at an alarming rate, while structural adjustments to cities are moving at a slower pace. Cities are facing more weather-related catastrophes such as flooding, heat waves and wildfires. Major climate disasters in cities have a bigger impact on the under-privileged and the marginalized communities.

2.4.1 The burning of plastics involves a complex chemical process

The structure of plastic can be categorized into micro-molecular or macro-molecular compounds. During the burning of plastics, several processes such as warming, degradation, flashover and combustion takes place. It is noticed that the low-molecular compounds can be easily vaporized directly into the atmosphere or oxidize in solid form. Plastics of a macro-molecular nature will have to decompose into smaller molecular compounds to start the combustion process. During the combustion of plastic two zones are formed. The first zone is called the pyrolysis zone which involves the evolution of gases and the second zone is called the chark zone which consists of porous solid residues. These gases that are formed and emitted during the decomposition of the waste plastic material is extremely dangerous which poses a serious risk to health of humans and environment. The incineration of PVC plastic polymers presents the greatest challenges to society [113].

2.4.2 Waste incineration in South Africa

The local environmental authorities in South Africa has totally prohibited an application to construct waste incinerators in an underprivileged township near Johannesburg. The main reason was due to well-known dangers of waste incinerators. If constructed, these incinerators would have released dangerous materials such as enormous quantities of dioxins and heavy metals that would have negative effects on the general health of people. Dioxins are highly toxic and can cause cancer, reproductive and developmental problems, damage to the immune system, and other illnesses [114]

Leonard [115] also argues that there have been many hazardous waste incineration suggestions in South Africa. Unfortunately, there has been a national push by many cement industries within the country to get rid of hazardous waste using their cement kilns through a burning process. Some of the waste which was planned to be burnt in these kilns included plastic drums, general plastic, plastic solvents, rubber waste and polluted packaging material. The burning of these hazardous waste material in the cement kilns would discharge persistent organic pollutants (POP's) such as heavy metals, dioxins and furan into the water, land and more especially into the air. These toxic emissions will take a long time to break down when they are in the environment and would result in long term effects on humans and would deplete the ozone layer.

2.4.3 Gas emission in Africa

Figure 2.9, shows an upward trend in Africa's CO_2 emissions between 1990 and 2017 except in 2015. During this period, it is clear that South Africa has released the highest CO_2 emission as compared to the other countries namely Egypt, Algeria and Nigeria. South Africa is identified to be the continent's largest energy consumer and accordingly the leading emitter of greenhouse gases. During the period 1990 and 2017, its energy intensity has been more than 0.2 gigatonnes (Gt) CO_2 per year which reflects the high ratio in comparison to the rest of African countries. The highest increase in CO_2 emissions in the rest of Africa between the same period of 1990 and 2017 occurred in Benin (740%), Mozambique (300%) and Ethiopia (256%) due to an increase in population [116].

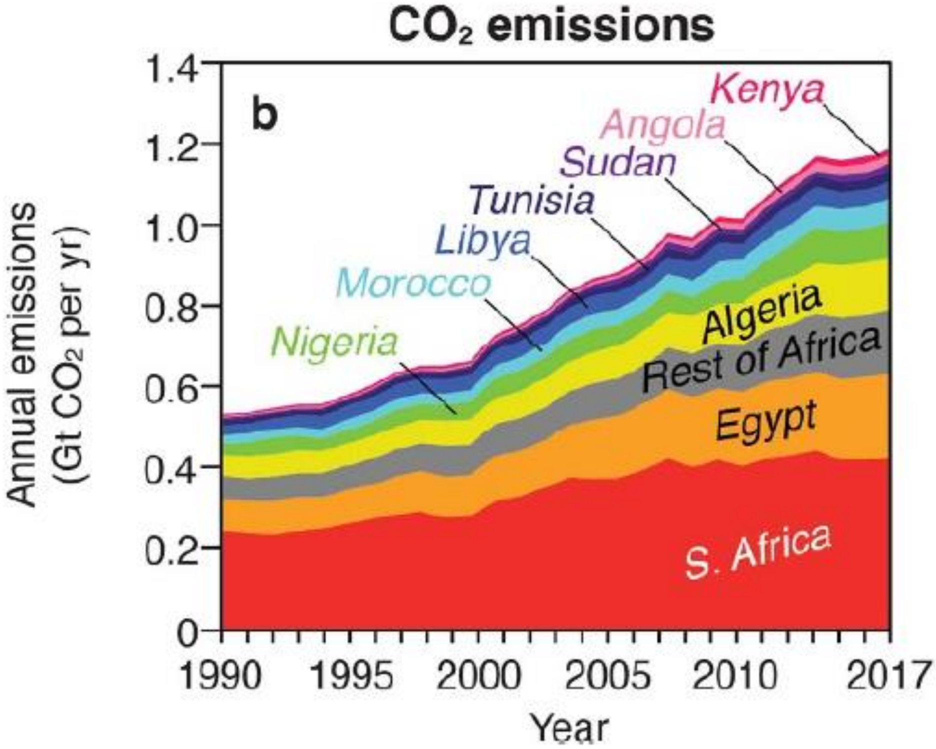


Figure 2. 9: Gas emission in Africa [116]

2.4.4 Global greenhouse gas emission

Figure 2.10, demonstrates the expected outlook of GHG emissions in relation to plastic packaging waste incineration as well the exponential growth of plastic packaging waste. The future looks disturbing regarding the condition of the atmosphere. With 16 million tons of CO_2 produced during 2015, 84 million tons is projected in 2030 and 309 million tons CO_2 e/year in 2050. These figures must be viewed with the accelerated growth of plastic packaging waste produced of 128 million tons in 2015, 219 million tons in 2030 and 435 million tons in 2050. This means that the release of greenhouse gases produced from 2015 to 2030 (within 15 years) is projected at approximately 68 million tons of CO_2 e/year. The projected emission of greenhouse gases from 2030 to 2050 (in the next 20 years) is expected to be approximately 225 million tons of CO_2 e/year. This means that the destruction of the greenhouse gases in the future would be unconceivable [117].

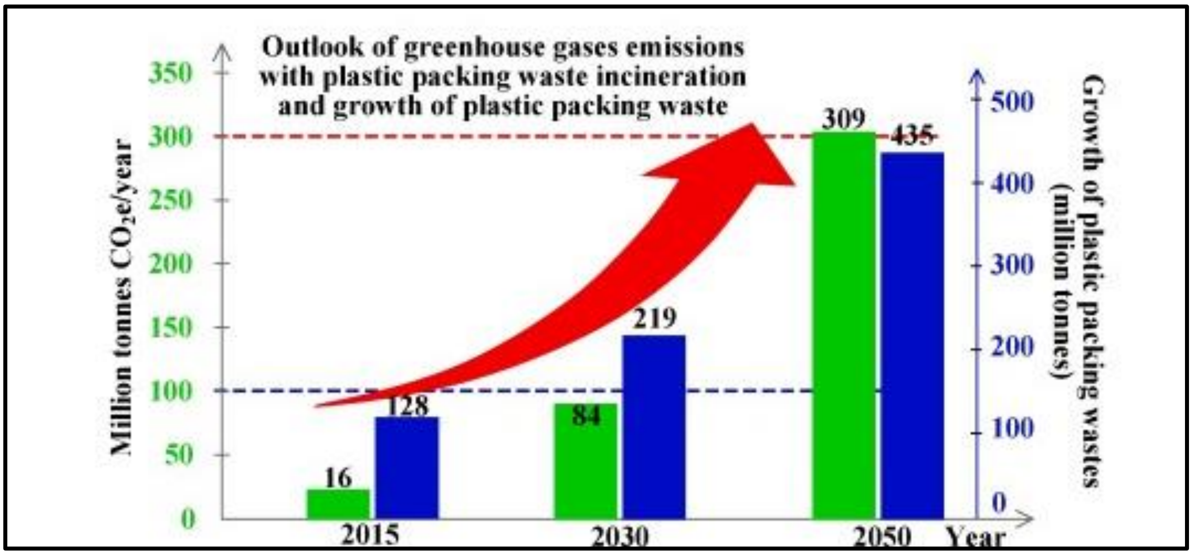


Figure 2. 10: Greenhouse gas emission [117]

In their study, Shen et al. [117] also concluded that there exist ample evidence indicating that plastic contributes a huge risk to both the environment and human health. Taking note of the challenges and uncertainty of plastic production, one needs to consciously record the impact of plastic economy on climate, which is serious matter and a reality. Hence, society as a whole should not neglect the negative impact of plastic waste on global climate change. Plastic industries are becoming one of the fastest growing contributors to GHG emissions.

Figure 2.11 warns that the current GHG emissions from the plastic lifecycle poses a serious threat and limits the ability to meet global climate benchmarks. The following key findings are presented:

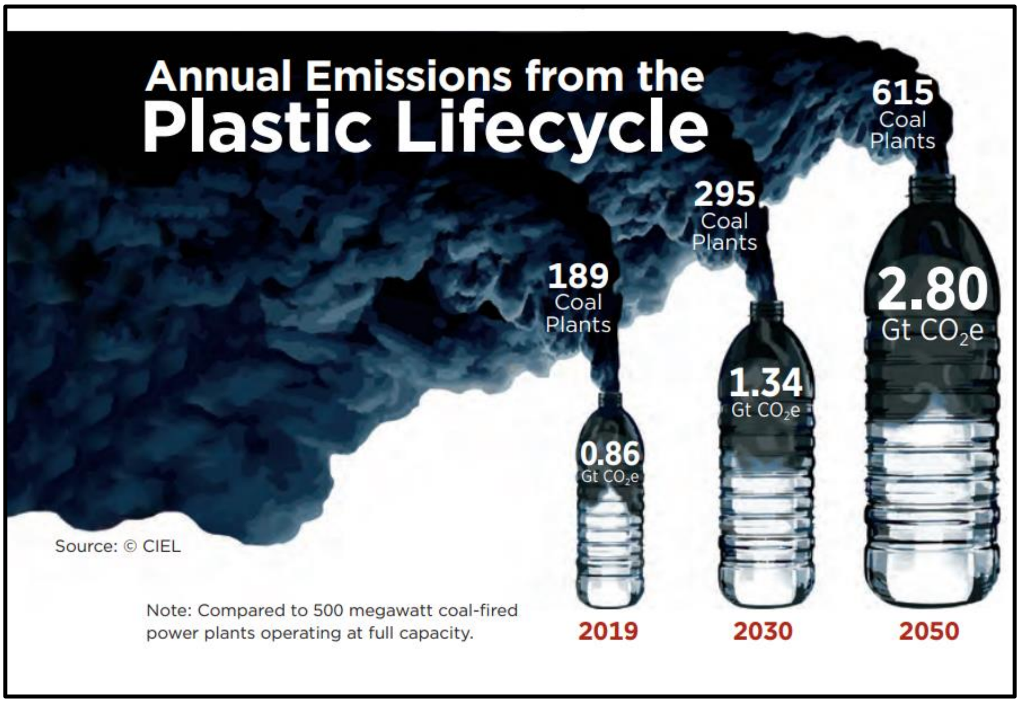


Figure 2. 11: Annual emission from plastic lifecycle [118]

1. In 2019, the production and incineration of plastic was projected at 0.86 Gt of CO_2 per year emission, which is equivalent to 189 coal plants with 500 megawatts (MW) operating at full capacity.
2. As projected in reality, that plastic production and its ever-growing use in 2030 will be 1.3 Gt of CO_2 per year emission, which is equivalent to 295 coal plants with 500 MW operating at full capacity.
3. The most horrific picture is projected in 2050 because the accumulation of greenhouse gases from plastic production will surpass 2.8 Gt per year of CO_2 emission per year, which is equivalent to 615 coal plants with 500 MW operating at full capacity.
4. The above picture predicts that plastic waste incineration is projected to grow uncontrollably due to the increasing use of plastic products. The increase in greenhouse emissions is certainly going to be unmanageable in the near future.
5. The above scenario presents an opportunity for recycling within a sustainable concept that must be taken seriously [118].

Dabaieh et al. [119] argues that there is a very high amount of carbon emission and energy consumption during the manufacturing of fired clay bricks as compared to sun-dried bricks. Sun-dried clay bricks showed very little environmental impacts regarding carbon emission and energy strains. For every 1000 sun-dried bricks produced there is a saving up to 5907 kg CO_2 emission and 5305 MJ of energy.

In another study, Eil et al. [120] highlighted that the brick manufacturing process is causing huge problems to humans. The brick manufacturing process is becoming dangerous as toxins are released into the air. *Table 2.2* shows the approximate total annual emissions of the following pollutants in three countries namely Bangladesh, India, and Nepal during 2016 from Clamps/ Down Draught Kilns (DDKs), Fixed Chimney Kilns (FCKs)/Mobile Chimney Kilns (MCKs), High Draft Kilns (HDKs)/Zigzag Kilns (ZZKs), Vertical Shaft Brick Kilns (VSBKs), Hoffman Kilns (HKs), Tunnel Kilns (TKs): Suspended Particulate Matter (SPM), SO_2, Nitrogen oxides (NOx), Black Carbon (BC), Particulate matter (PM) PM10 and PM2.5. From the Estimated Annual Local Air Pollution Emissions, particularly PM10 (Particulate Matter) and PM2.5, have dangerous impact on human health and welfare of people. These pollutants are detrimental in nature since they cause a variety of respiratory issues such as lung cancer, asthma, chronic bronchitis, and emphysema; cardiovascular and neurological problems.

Table 2. 2: Estimated Annual local air pollution emissions from brick making [120]

Estimated annual local air pollution emissions from brick making (tons/year)						
Country	**SPM**	**SO2**	**NO2**	**BC**	**PM10**	**PM2.5**
Bangladesh	84.327	159.793	5.268	7.148	36.886	22.132
India	1.412.420	2.002.673	50.660	137.044	661.164	396.698
Nepal	24.868	42.839	872	2.044	9.370	5.622

2.4.5 Solutions to climate change

Mailloux et al. [121] argued that humans are guilty of producing gas emissions such as CO_2, CH_4, nitrous oxide, fluorinated gases and BC that are generated from electricity and food production, machinery use in agricultural activities, industry, transportation, building and construction and many other sources. Some of the strategies to mitigate climate change are replacing coal and natural gas with windmills and solar power to generate electricity would reduce gas emissions to a large extent. There is a need to change our current transportation systems and also redesign our urban town planning to reduce the need of fossil-fuel solely from powered vehicles such as busses, cars, trains to cycling and walking, which will reduce gas emission and promote good health. It has been discovered that changes in the food and agriculture sectors could assist in addressing the challenges of climate change such as reducing food waste and a change to more plant-based foods. There is a need to protect our ecosystems, which would result in the reduction of GHG emissions and carbon, thereby reducing emerging infectious disease risk. Moreover, the destruction of forests must be avoided since it helps to remove CO_2 from the air.

Studies conducted by Gattuso et al. [122] and Hoegh-Guldberg et al. [112], give attention to ocean-based actions that may meaningfully reduce the scale and rate of ocean warming, marine acidification, and the rise in sea-levels, including their negative impacts on marine life and ecosystem services. They also explain the promising role of the ocean, with its massive volume of water and efficiency in mitigating CO_2. It is noted that the ocean is playing a leading role in the universal carbon cycle and is responsible for using up 25 to 30 % of anthropogenic CO_2 that is continuously being released into the air.

Hoegh-Guldberg et al. [112], presented a report which assesses the mitigation potential of how the oceans can play a role to reduce climate change. Some of the wide array of potential ocean-based mitigation options are indicated below:

- Increasing the use of offshore wind by means of installing fixed and floating offshore wind turbine.
- Increasing the extraction energy from ocean waves, tides and currents to reduce coal fired power plants operations.
- Increasing the potential of mitigation impact of reducing emissions from domestic and international marine transport and shipping.
- Reducing emissions from fuel used for inland, coastal, and deep-sea fishing trips.
- Promoting CO_2 storage in the seabed.

Implementing ocean-based mitigation options involves various economic implications and financial requirements. The costs associated with these strategies can be significant and depend on factors such as the specific mitigation option, geographic location, scale of implementation, technology advancements, and regulatory frameworks. Some key considerations are highlighted below:

i) Infrastructure Development Costs:

Investing in the restoration of underwater vegetation, known as ocean afforestation, demands substantial commitments to research, development, and the establishment of appropriate infrastructure. Coral reefs and seagrass ecosystems, in particular, stand out as requiring considerable financial resources for restoration efforts. There is a critical need for increased investment aimed at refining restoration techniques and undertaking large-scale restoration initiatives to address the challenges posed by the complexity and cost of rehabilitating these ecosystems [123].

ii) Technology Advancements:

Harnessing renewable energy from ocean resources, such as wave or tidal energy, necessitates technological advancements to render it economically feasible and scalable. The ocean represents an extensive reservoir of renewable energy, and contemporary technology enables the extraction of energy from tides. There is a growing interest in exploring tidal current technologies due to compelling reasons, including the security and diversity of energy supply, predictability despite intermittency, and limited social and environmental impacts. Ocean energy can be harnessed in various forms, encompassing energy derived from waves, kinetic energy sourced from tidal and marine currents, potential energy extracted from tides, and energy generated from salinity and thermal gradient. Tidal energy is predominantly captured during the oscillation of the sea level, specifically during the rise and fall of tides **[124].**

iii) Regulatory Frameworks:

The establishment of regulatory frameworks to oversee ocean-based mitigation initiatives incurs legal and administrative expenses. Governments may find it necessary to formulate and enforce regulations to guarantee environmental sustainability and avert unintended repercussions. However, Röschel and Neumann [125] highlighted the necessity for research not solely focused on the technical feasibility and cost-effectiveness of Ocean-Based Negative Emission Technologies (ONETs), but also on determining the criteria for "good" governance of ONETs. This includes considerations from both an ocean and environmental perspective.

In summary, the economic implications and financial requirements for ocean-based mitigation options are multifaceted and require a comprehensive approach involving governments, the private sector, and international collaboration. Successful implementation will depend on addressing technological challenges, establishing effective regulatory frameworks, and securing sustainable financing models.

2.5 Opportunities of recycling of plastic waste

Several studies [126] [127] [128] concludes that, recycling of plastic waste leads to valued opportunities and commercial ideas for citizens, business and government to transform plastic waste to other valuable items. While it is understood that plastics waste is harmful to human health, it can be potentially used for great opportunities for business and wealth generation [129]. Covenant University, conducted a study in a waste-to-wealth scheme, having taken cognisance of the impact of managing and using plastic materials to produce other recyclable products [127]. In this thesis, recycling of plastic waste to manufactured plastic-sand brick is the solution to reduce the negative impact of the four threats to sustainability.

The process of recycling safeguards the environment in the long term [130] and helps in the protection of the atmosphere since it makes use of the plastic waste that is converted into useful material [13]. The beneficial nature and properties of plastics allows them to be used in several applications. Hence, the recycling of plastic waste is considered as a substitute for alternate construction materials due to its light weight, which could be suitable for fittings, windows, door frames, interior and exterior fixtures [131].

In their study of recycling, Olukanni et al [126] observed that the accumulation of plastic waste has been drastically reduced and has offered many economic benefits in other industries such as construction, architecture, textile, sculpture and art as well as design. While plastic waste disposal was found to be difficult to manage, it was proven to serve many advantages when it was converted into a variety of different fabric which were later produced into beautiful garments [132].

Recycling has demonstrated the potential to reuse plastic waste and convert it into fuel which is another useful source of energy [133]. There is much interest when fuel is extracted from plastic waste. Thus, the enormous amount of plastic which were once waste can now be converted into fossil fuel alternatives [134].

Bajracharya et al. [135] indicated that recycled plastic waste is currently being used in some civil engineering applications. Recent innovative materials such as plastic lumber is now gaining momentum to be used in construction industry. Plastic lumber is also used to make recreational outdoor item such as fencing and park benches since they are weather resistant. Baishya et al. [128] also substantiated that the conversion of plastic waste into plastic lumber is one of the solutions to reducing the challenges of plastic pollution. Plastic lumber is known to be produced from some recycled plastic such as HDPE, PS, polyvinyl chloride (PVC) and polypropylene (PP). There are many advantages of plastic lumber over real wood since it can be used as a substitute to make other products such as plastic coasters, bed side tables, garden furniture, exterior doors, shoe insoles, decking, building structures and plastic hand fans. The expanded polystyrene (EPS) material extracted from plastic waste are eco-friendly and are suggested for use in prefabs or prefabricated building components such as panel walls, floor blocks and fascia boards which are used in factories and construction sites [136].

2.6 Conclusion

The current study is focussed on recycling waste plastic to manufacture plastic-sand brick that would be a solution to reduce the negative impact of the four threats to sustainability. *Firstly*, the development of plastic waste as an alternative binding material for the construction industry towards assisting with the immediate decrease of plastic waste material that causes so much of short as well as long term consequences to sustainability. The study promotes the retrieval of plastic waste from the industries which can be systematically used for recycling purposes before it gets to landfills, natural environments and in the marine oceans causing untold damage to human, plants and animals as well as to the marine life as explained in section 2.1.

Secondly, the study is directly linked to finding a solution for job opportunities such as waste pickers, machine operators and staff for brick manufacturing, since it explores the potential of recycling plastic waste to produce plastic-sand bricks. Waste pickers can now find opportunities to collect household or commercial plastic waste. They may also collect from waste bins along streets or from open dumpsites for recycling.

Thirdly, the study is connected directly with the demand for affordable housing since the recycling of plastics waste to produce plastic-sand bricks will contribute positively towards the building industry. It will definitely assist in the building of eco-friendly houses which will be available at a much lower costs as compared to the conventional clay or cement bricks. The focus of this study is on using plastic waste that accumulates in the environment to build affordable housing is now a reality. People nationally and globally are engaging in research and are developing innovative strategies to collect plastic waste successfully from their environment to be use in the development of greener housing developments. The conversion of waste plastic into construction materials for the construction houses, schools and community buildings is on the rise. The study will contribute to a turn-around strategy and looks at the construction industry with optimism. It investigates the possibility of an alternative building material which will benefit the construction industry tremendously. This study is significant because the waste plastic is used as an alternative material to provide better options of construction of a greener and eco-friendly housing projects.

Fourthly, the high energy intensive processes and the green-house gases which are released from clay brick production makes it incumbent for the transition from clay to plastic-sand brick. The trend of pollutants that are released into the atmosphere cannot continue since they have a detrimental effect on human sustainability currently and in future generations. Nevertheless, it is noted that gradually, the amount of GHG that are emitted into the atmosphere is still increasing significantly. As a result, it causes an increase in the global temperature which leads to climate change. This will have a major negative impact on the needs of the current and future generations [137]. The study is significant because the production of plastic-sand brick requires less energy intensive methods and does not require the burning of non-renewable resources for the baking process in kilns. The same amount of waste plastic that would have been dumped is now recycled and used in the manufacture of plastic-sand eco-friendly bricks as proposed in this study. Therefore, there is much gains from the use of plastic waste as an alternate binder material to be used in for the construction industry.

Lastly, the utilization of plastic-sand bricks as an alternative construction material can have both positive and negative implications for long-term sustainability and the environment when compared to conventional construction materials like clay or cement bricks. The sustainability of plastic-sand bricks depends on various factors, including the composition of the material, production processes, and end-of-life considerations. An overview of the potential impacts is described below:

i) **Energy Consumption:**

The energy consumption during the production of plastic-sand bricks depends on the manufacturing process. If the production involves recycling plastic waste, it might require less energy compared to traditional brick manufacturing processes. Frequently, conventional clay bricks undergo firing in kilns, and the production of cement bricks involves the energy-intensive process of cement production. Both of these procedures contribute substantially to overall energy consumption. Firing remains the prevailing method for brick production, characterized by substantial energy usage and a notable carbon footprint. Although firing is recognized for its reliability and widespread applicability, it is widely acknowledged that the production of fired clay bricks has consistently been an energy- and resource-intensive process **[138]**.

ii) **Carbon Emissions:**

Zhang et al. [138] pointed out that utilizing recycled materials for the plastic content in plastic-sand bricks has the potential to yield a reduced carbon footprint compared to traditional bricks. However, it is imperative to thoughtfully examine emissions from both the plastic recycling process and the overall production process. Traditional brick production, whether for clay bricks involving high-temperature firing or cement bricks requiring cement production, results in notable carbon dioxide emissions. Firing stands out as the predominant method for brick production, and despite its prevalent use, this process involves substantial energy consumption and a significant carbon footprint. Therefore, incorporating plastic in brick manufacturing can have a lasting positive impact over the long term.

According to Kumbhar et al. **[139],** the adoption of plastic-sand bricks can contribute to the reduction of greenhouse gas (GHG) emissions and mitigate global warming. This is achieved by eliminating the incineration of plastic waste and reducing the use of energy-intensive processes, such as high-temperature kilns during the curing of clay bricks. Traditional brick production, especially the incineration of coal in kilns and the burning of diesel during transportation, contributes substantially to gas emissions released into the environment. The largest percentage of gases released into the air is attributed to CO^2 emissions. Therefore, the adoption of plastic-sand bricks offers a promising avenue for reducing overall carbon emissions and addressing environmental concerns associated with conventional brick manufacturing processes.

iii) The ecological footprint of plastic-sand bricks is shaped by elements like sand extraction and the ecological consequences of collecting and recycling plastic waste. According to Tom, transforming plastic waste into plastic-sand bricks not only minimizes reliance on clay and cement for brick production but also enhances cost efficiency **[140].** The ecological footprint of conventional bricks is influenced by factors such as clay extraction (for clay bricks), limestone quarrying (for cement production), and the environmental impact of kiln firing

In conclusion, the sustainability of plastic-sand bricks as an alternative construction material depends on several factors, including the source of plastic, production processes, durability, and end-of-life considerations. While they have the potential to reduce plastic waste and energy consumption, careful evaluation of their entire life cycle and comparison with conventional materials is necessary to determine their overall environmental impact. Local conditions, regulations, and building practices also play a significant role in the sustainability of construction materials.

CHAPTER THREE

LITERATURE REVIEW

3.0 Introduction

Chapter three is divided into two sections. Section A provides an overview of the classification and types of plastics, explores the feasibility of utilizing plastic waste in brick manufacturing, reviews previous research on plastic recycling in the production of plastic-sand bricks, identifies gaps in the existing literature, discusses the use of an extrusion machine in the manufacturing process, and highlights the envisaged impact of plastic-sand bricks.

Section B focuses on the theoretical and conceptual framework that forms the basis of this research. *Firstly*, it commences with the conceptual understanding of the term “Theory of sustainability” and sustainable development by placing the World Sustainable Conferences in context. *Thirdly*, it provides an understanding of the complex nature and various challenges of sustainability. *Lastly*, discusses the South African National Frameworks on Sustainable Development (NFSD) and how it is linked to this study.

SECTION A: DIFFERENT TYPES OF PLASTIC

3.1 Classifications and types of plastics

There are different kinds of plastics available for diverse applications. Some plastics cannot be recycled and are grouped under the category known as thermosetting plastics while the others can be recycled and grouped in the category called thermoplastics, [141] [142]. The advantage of thermoplastics is that they can be broken down and remoulded when heated. Whereas, thermoset plastic can be initially moulded, but cannot be remoulded upon heating. This poses a serious problem for recycling companies and agencies. Therefore, not all types of plastics can be used for the manufacturing of bricks due to their differences in properties and their molecular structure. Since thermoplastics are recyclable, they can be remoulded into different products, also making it possible for brick manufacturing. The feasibility of using specific types of plastic waste for brick manufacturing has been explored in numerous studies. Attention will be given to thermoplastics as indicated in *Figure 3.1*.

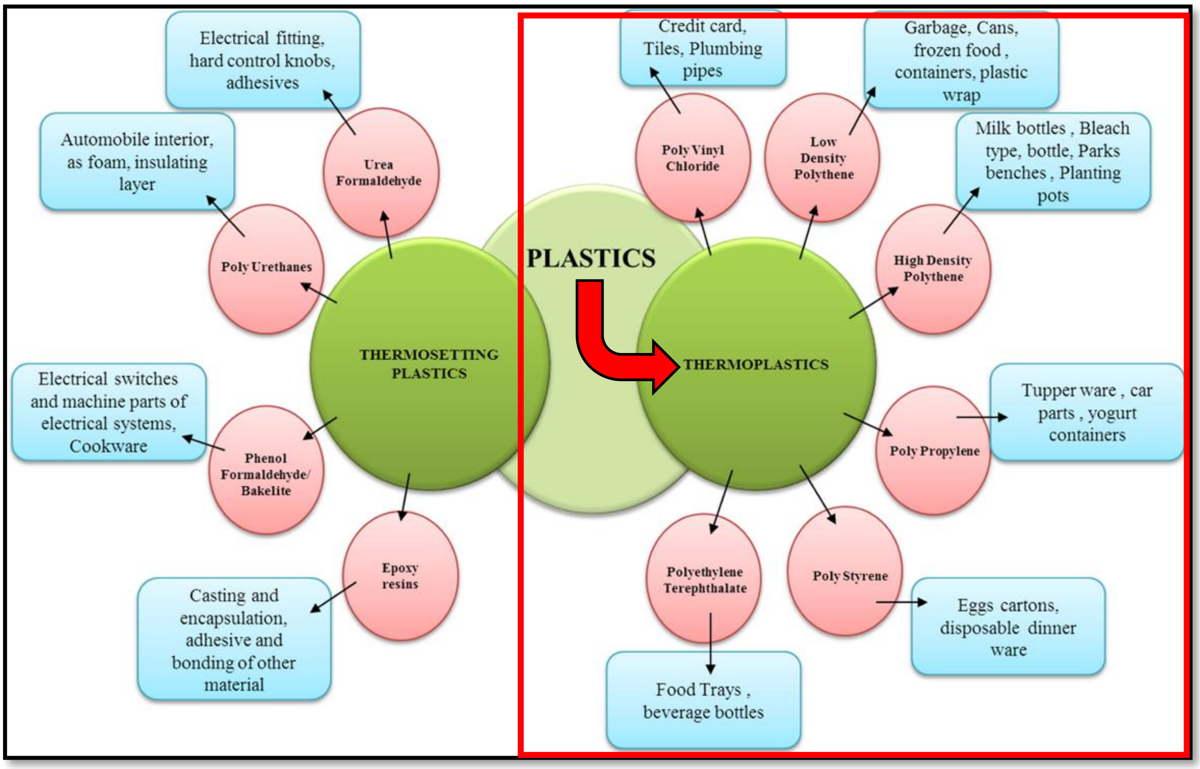
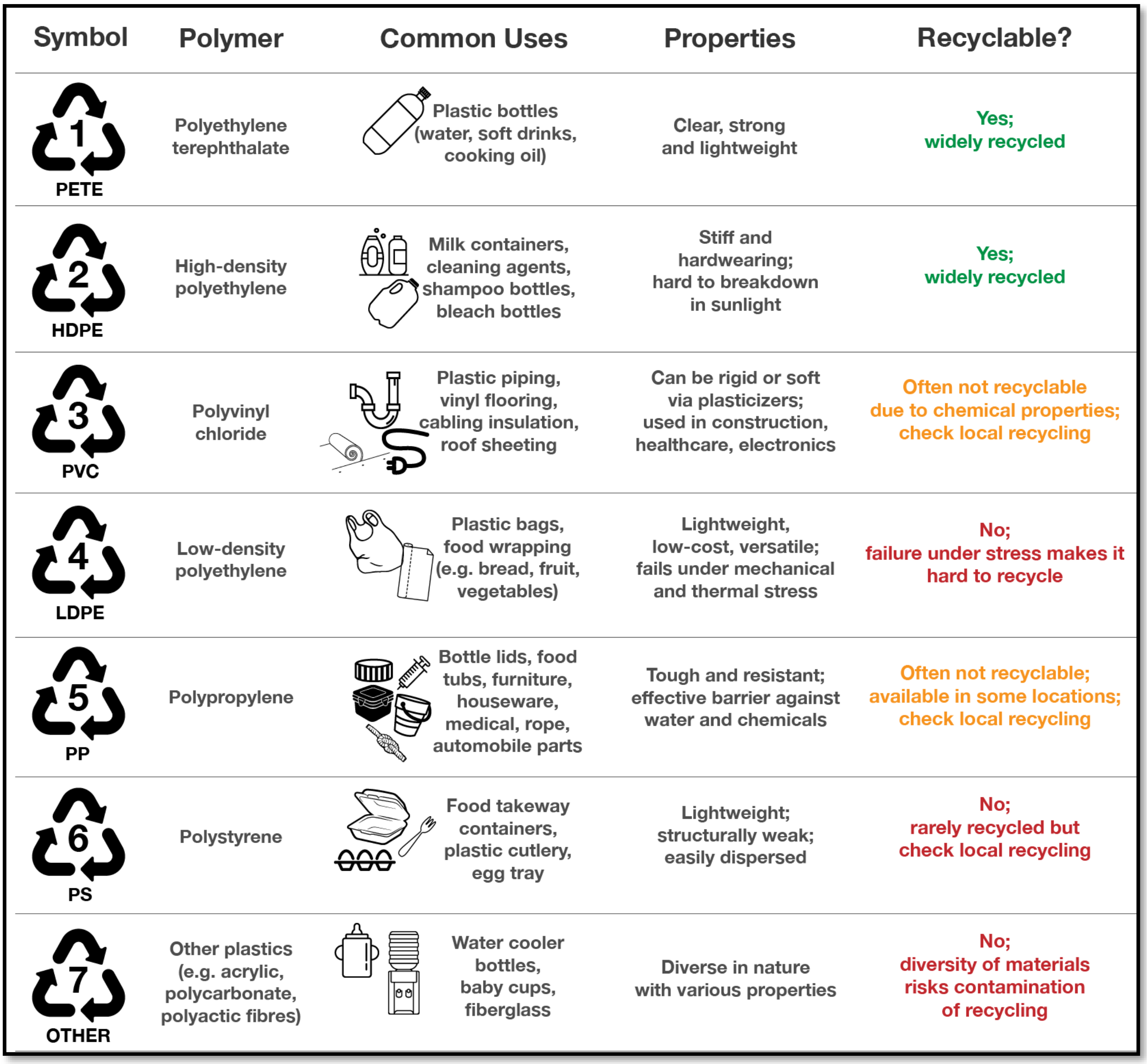


Figure 3. 1: Classification and types of plastic [143]

There are essentially 7 types of plastic classifications namely PET, HDPE, LDPE, PVC, PP, PS and other. The different types of plastics together with their common uses, properties and recyclability are explained in detail in *Figure 3.2:*



Symbol	Polymer	Common Uses	Properties	Recyclable?
1 PETE	Polyethylene terephthalate	Plastic bottles (water, soft drinks, cooking oil)	Clear, strong and lightweight	Yes; widely recycled
2 HDPE	High-density polyethylene	Milk containers, cleaning agents, shampoo bottles, bleach bottles	Stiff and hardwearing; hard to breakdown in sunlight	Yes; widely recycled
3 PVC	Polyvinyl chloride	Plastic piping, vinyl flooring, cabling insulation, roof sheeting	Can be rigid or soft via plasticizers; used in construction, healthcare, electronics	Often not recyclable due to chemical properties; check local recycling
4 LDPE	Low-density polyethylene	Plastic bags, food wrapping (e.g. bread, fruit, vegetables)	Lightweight, low-cost, versatile; fails under mechanical and thermal stress	No; failure under stress makes it hard to recycle
5 PP	Polypropylene	Bottle lids, food tubs, furniture, houseware, medical, rope, automobile parts	Tough and resistant; effective barrier against water and chemicals	Often not recyclable; available in some locations; check local recycling
6 PS	Polystyrene	Food takeway containers, plastic cutlery, egg tray	Lightweight; structurally weak; easily dispersed	No; rarely recycled but check local recycling
7 OTHER	Other plastics (e.g. acrylic, polycarbonate, polyactic fibres)	Water cooler bottles, baby cups, fiberglass	Diverse in nature with various properties	No; diversity of materials risks contamination of recycling

Figure 3. 2: Common uses, properties and recyclability of plastics [144]

i) Polyethylene Terephthalate (PET) [Classification 1]

Jankauskaite [145] explains that PET is known to be a thermoplastic polymer that is used in numerous applications such as bottles, films, textile fabric and many other different moulded products. Over the decades, many different household products are made from PET and are ever increasing. One example is in Lithuania where many companies manufacture 10 000 tons of PET containers each year. Hence, the increasing rate of household plastic products made from PET is causing a detrimental effect on the environment and society. From all the different types of plastics, PET has gained much attention for its post-consumer use since PET bottles are easily available. PET is regarded as one of the top polymers that can be recycled due to its relatively easy recycling process to produce suitable products.

ii) High Density Polyethylene (HDPE) [Classification 2]

Silviyati et al. [146] states that HDPE is one of the polymer materials that is widely used. HDPE products have a very low risk of leaching into foods or liquids. This plastic can be found in bags, milk jugs, yogurt tubs, cleaning product containers, body wash bottles and similar products. There are many toys, beach and park benches, industrial wrappings, garden pots, and pipes that are made from HDPE [147].

iii) Polyvinyl Chloride (PVC) [Classification 3]

One of the greatest disadvantages is that PVC contain harmful chemicals that prevents it from being regularly recycled. It is produced to have rigid and flexible properties**.** PVC plastics are most commonly used for plumbing pipes and it is very toxic when heated up [148].

iv) Low Density Polyethylene (LDPE) [Classification 4]

LDPE has a simple molecular structure compared to other plastic which makes it relatively cheaper and easier to manufacture. LDPE is used to make various types of shopping and plastic bags, transparent food containers and disposable packaging items [149].

v) Polypropylene (PP) [Classification 5]

PP is the world second most widely produced synthetic plastic. It is a thermoplastic polymer that is most flexible on the planet that makes it popular and widespread use [150]. It can also be used for making strong moulding items such as pipes, crates, car batteries, chairs, suitcases and many domestic appliances [147].

vi) Polystyrene (PS) [Classification 6]

PS is a special type of plastic which is used to make beverage cups, packing materials, egg cartons and used as insulation material. PS is relatively cheap and easy to produce and is found almost everywhere since it breaks effortlessly and makes it harmful to the environment [148].

vii) Other [Classification 7]

It is noted that there are several environmental impacts when considering the remaining plastics indicated above. They are too hazardous and toxic to allow them for quick, suitable and easy recycling [151]. Mondal et al. [152] explains that one example is e-waste such as computers which gives off toxic gases when heated. In classification type 7 plastic, Acrylonitrile Butadiene Styrene (ABS) and acrylic that is also part of this category are also challenging to recycle.

3.2 The feasibility of using waste plastic in brick manufacturing

Kognole et al. [153] and Silviyati et al. [146] states that there has been much awareness and debates on the topic of plastic waste as one of the major challenges facing the environment. Hence, the feasibility of making use of plastic waste in the manufacturing of plastic-sand bricks as an alternative building material for the construction industry has been explored. Tiwari [154] explained that since plastic has many good properties and multiple uses, it has been recommended in the manufacturing of plastic-sand bricks. This awareness has risen due to the intense accumulation of waste plastic in landfills, oceans and rivers that is causing shocking effects on the environment, humans and the economic sector. Due to the widespread awareness, much literature was documented on the use of different types of industrial by-products that could be used in concrete such as waste recycled rubber, waste plastic, copper slag, bottom ash, waste foundry sand (FS) and crushed glass aggregate as a substitute for fine aggregate in concrete.

Aiswaria et al. [155] stated that all stakeholders are brainstorming ways to deal with this serious scenario of how to manage general waste, but, more especially plastic waste. Millions of tons of plastic are directed to landfills. The unfortunate situation is that there are insufficient or unsuitable methods to recycle and process the plastic material. The sad part is that tons of plastics are discarded or burnt every day. The increase of the plastic waste in the environment and in the air presents a health risk to plant, animal life and more especially humans. The different types of plastic such as PET, HDPE, PP, LDPE and Polyethylene (PE) and the rest of the types of plastic places pressure on the environmental. Silviyati et al. [146] argues that the accumulated waste material can be reused to produce new products and can be used as an alternative material in the building industry due to the inherent flexibility, adaptability and durability.

Wahid et al. [156] highlights that the recycling of waste plastic material into new products will assist in the reduction of plastic pollution and also avoid the discharging of plastic waste into landfills. They added that the increased consciousness of seeing the value of plastic or plastic waste as an environmentally friendly, cheaper, compact and lightweight resource can be a possible solution in the building and construction industry. The valuable properties of plastic have led to this study probing on how the properties of these materials can be used to assist the environment, humans and at the same time promote sustainability and sustainable development. Hence, the current study is linked to the utilization of waste plastic as a constituent ingredient in the production of bricks for the building and construction industry.

3.3 Research completed on recycling of plastic in the manufacturing of plastic-sand brick

Ponrajkumar [157] concluded in his study that recycling of plastic waste has several advantages such as reducing the use of natural resources and decreasing pollution when compared to the production of conventional burnt bricks. He contended that recycling also lessens the pollution released from kiln during the brick production and drying process. Chauhan et al. [158] also stressed that manufacturing plastic-sand bricks made it possible to lessen the challenge of pollution. The decrease of pollution is a step closer towards accomplishing the sustainable development goals.

The information in several literature sources on the subject of recycling plastic waste has shown the production of plastic-sand bricks to be cost effective. Recycling has contributed positively towards the removal of plastic waste from the environment, decrease of GHGs released into the air and finally, the use of clay and cement to produce traditional bricks have been decreased [153]. Jayaram [159] in his study recommended the use of certain waste alternative such as Ground Granulated Blast-furnace Slag (GGBS), bottom ash and virgin plastic (in the mix ratios) since he found that bricks produced from these alternative material proved to be less costly when compared to other kinds of conventional bricks.

Therefore, this section highlights that recycling is one of the significant activities of collecting and processing of plastic waste as useful materials which would otherwise be simply discarded or dumped into landfills, oceans, rivers and onto land. Recycling would help our society and more especially our environment, converting waste material into new products.

Several investigations conducted on the use of plastic waste for brick manufacturing and other new products has shown promising results. The use of plastic as an alternative building material in the production of plastic-sand brick is presented in four main categories: HDPE, LDPE, PET and PE with its hybrid combinations are indicated in *Figure 3.3*.

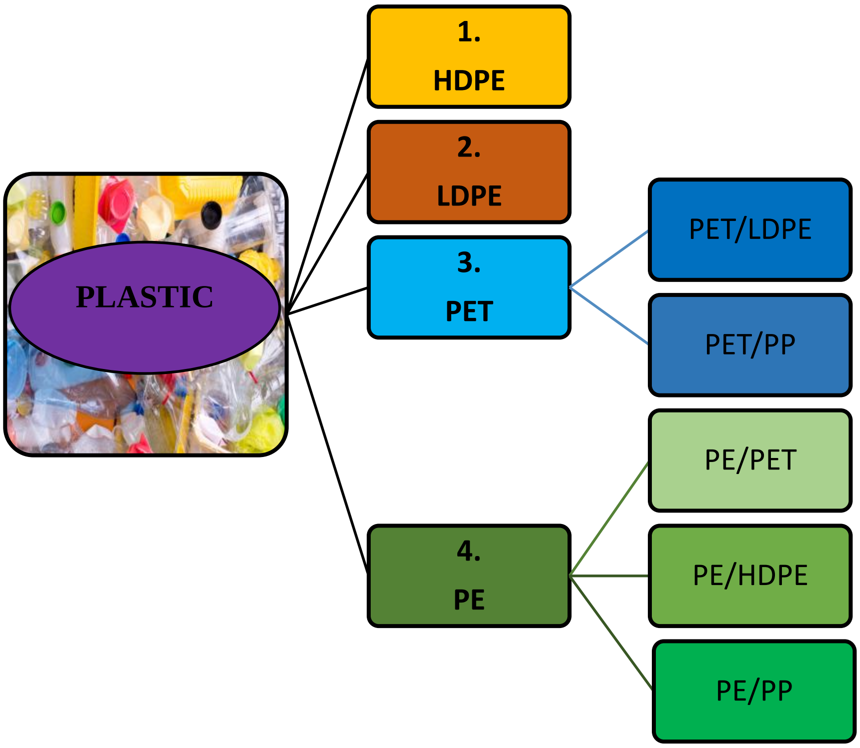


Figure 3. 3: Combinations of plastics used

3.3.1 Utilisation of HDPE in the manufacturing of the plastic-sand brick

Sanchez-Soto [160] explains that the use of talc as a filler material in two blends of HDPE and their matrix properties have been analysed. The first blend is composed of purely granulated injection moulded components (HDPEi) and the second blend was as bimodal blend of 80% weight (wt%) granulated moulded components and 20% wt of recycled HDPE bottles forming the second blend called (HDPEm). Two types of industrial talc, Luzenac 1445 and Mistron MG7C, with a particle size of 2 μm and 10 μm respectively, weighing 10% and 20% were added to both blends. The extrusion machine was controlled at a temperature at 155°C at the hopper section and not exceeding 180°C at the die. The following results have been significant: i) the 20% addition of HDPE from consumer bottles resulted in a reduction in the melt flow index of the HDPEi blend from 6.64 to 2.78g/10 min. ii) the addition of recycled HDPE resulted in no indication of any weak point or early failure at the increased level of strain of the sample. iii) The addition of a reasonable proportion of HDPE from recycled bottles enhanced the toughness of the samples. iv) The mechanical properties improved when very fine talc was added to the blend.

Salahuddin and Zambani [161] in their practical investigation claimed that the main objectives were to establish an effective way to utilize plastic waste, to reduce water and land pollution and to minimize the natural clay resource for the production of bricks. HDPE was utilised with sand to manufacture a plastic-sand brick of ratio 1:4 respectively which is an alternative to the locally available traditional clay bricks. HDPE has a high strength-to-density ratio and has strong intermolecular forces and tensile strength than LDPE. HDPE waste plastic was collected and shredded in a plastic shredding machine into fine flakes and any large pieces were grinded again to ensure small pieces were used for production of the plastic-sand brick samples.

The shredded HDPE plastic was washed in order to remove any contaminants and was air dried to remove any moisture that was present. Natural sand was obtained from the river bed and a sieve analysis was conducted by passing the sand through a 600μm sieve and a 4.75mm sieve for the production of the plastic-sand brick. The two grades of sand were washed and left to dry. An open flame fire was used as the source of thermal energy. The drum was heated to remove any moisture that was present. Thereafter, a single portion of the shredded HDPE plastic required to make the plastic-sand brick was added to the drum. The plastic was heated over the open flame until the shredded plastic turned into a hot molten material.

Four portions of the sand were added to the drum and was mixed manually with a trowel. The hot plastic-sand mix is poured into a wooden mould that was oiled on all its sides for easy removal of the brick. The mixture is compacted using a steel rod and the surface of the brick finished using the trowel. The plastic-sand brick is allowed to cool for a period of 24 hours and thereafter the brick was removed from the mould. After the brick was manufactured various tests were conducted. The plastic-sand brick of the ratio of 1:4 respectively with sand of 600μm displayed an average compressive strength of 7.468 N/mm^2, while the plastic-sand brick with

4.75mm sand had an average compressive strength of 9.141 N/mm² and the traditional clay brick displayed an average compressive strength of 1.685 N/mm².

The brick samples were immersed in water and the water absorption test was conducted. The bricks that had 600µm, 4.75 mm sand and the traditional clay brick had a water absorption rate of 3.060 %, 0.789 % and 23.789 % respectively. The impact test was conducted and the plastic-sand bricks were dropped from a height of 1m. Neither the 600µm, nor the 4.75 mm plastic-sand bricks were broken in the test and was recorded to be of good quality. In the soundness test the 600µm and 4.75 mm plastic-sand bricks were stuck and produced a clear ringing sound which indicated the bricks were of acceptable quality. A rod was indented on the surface of the 600µm and 4.75 mm plastic-sand brick for the hardness test. It was found that there were no scratches on the surface of the bricks which indicated properties of a good brick.

Some of the disadvantages of this study is that the writers used the manual mixing method as opposed to mechanical mixing. They also made use of an open flame which resulted in an uncontrolled temperature and this gave inconsistent results in the properties of the plastic-sand brick. It can be concluded that sand with 4.75mm particles in the plastic-sand ratio of 1:4 resulted the highest compressive strength of 9.141 N/mm², the lowest water absorption of 0.789 % from the 600µm sand particles than the traditional clay brick.

In their research, Wendimu et al. [162] conducted a study in Ethiopia using HDPE waste plastic. They demonstrated that HDPE waste plastic can be used as alternate building material, preventing negative influence on the environment and saving the clay soil as a natural resource that would otherwise be used to manufacture traditional clay fired brick. The collection of HDPE plastic was made from shake zone in a town called Tepi, located in the southern part of Ethiopia. The HDPE waste plastic was washed and cleaned to remove any contaminants that could affect the properties of the brick. The HDPE plastic was dried to remove any moisture that was present and thereafter, the particle size was reduced by crushing the plastic. A temperature of 130°C between a range of 20 minutes to an hour was utilized to melt the HDPE plastic. Thereafter, the plastic mixture was poured into an Ethiopian standard brick mould and compacted with a hammer to reduce porosity of the plastic brick. The 100% plastic bricks were cooled for a period of two days before conducting the various testing stages. Five brick samples were used during the testing process. The compressive test results in the five bricks ranged from 23- 25 MPa. The brick was accepted for the dimensional tolerance test since it satisfied the American Society for Testing and Materials (ASTM) C216 standard limit.

Whilst the brick had an average compressive strength of 24 MPa (Class A, Class SW) and has satisfied the Ethiopian and ASTM standards, it was concluded that HDPE was not recommendable for specific purposes such as the building of kitchen, chimney and walling since it has a low resistance to fire and tends to melt even at a low temperature. One of the disadvantages is that 100% HDPE plastic was used to manufacture bricks for construction. The plastic-sand brick with its poor heat properties, will not be acceptable since plastic is highly susceptible to fire. A potential avenue to increasing the application of this plastic brick would be the addition of sand to the brick since sand would tend to impart insulation against fire.

In another study, Silviyati et al. [146] studied the effects of the addition of HDPE as a binder on Hebel lightweight bricks in Indonesia. In that study, two categories of samples were produced, one (A) without using oil and the other (B) using 250ml of waste oil in all the ratios. The following comparative ratios of the binder: filler was used: 30:70, 40:60, 50:50, 60:40, 70:30 in %wt. The filler was made up of a ratio of 1:1 cement and sand respectively. The binder material is the HDPE plastic waste as mentioned in the binder: filler ratio. The results of this research in respect of the compressive strength showed that the brick sample where the binder: filler of 30:70 was made without oil revealed the highest compressive strength 224.67 kg/cm^2= 22.23 MPa. In the same ratio with oil, the results indicated a compressive strength of 40.45 kg/cm^2= 3.97 MPa.

The water absorption test was completed by submerging the bricks in water for the following consecutive days: 7^{th}, 14^{th}, 21^{th} and 28^{th} day. All the specimens with and without oil on all the days in all the ratios indicated a water absorption rate of below 6%. The most suitable variation obtained from the water absorption test is the ratio of 30:70 in both the specimens with oil and without oil. It has been noticed that all the bricks had closer pores in the result of the scanning electron microscope (SEM) test and the water absorption test indicated that the water absorbed was less than 6% on average.

3.3.2 Utilisation of LDPE in the manufacturing of the plastic-sand brick

In their study, Humzah and Alkhafaj [130] focused on finding a feasible solution in Iraq for the disposal of medical plastic waste in the manufacture of an alternative eco-friendly brick, light in weight and cost effective. In this study, two types of filler materials were used, viz. sand and sawdust. They were tested in the ratios of LDPE: sand and LDPE: sawdust from 100 to 40 and 100 to 50 for sand and sawdust respectively in increments of 10. Waste LDPE syringe piston was collected from a factory, and sand and sawdust were also obtained for the manufacture of the plastic-composite brick. The plastic that was collected was cleaned and separated into batches. A sieve analysis was conducted on the sand and sawdust was obtained through a 600 μm sieve before they were utilized to manufacture the plastic-sand brick. The processing of the LDPE plastic was carried out in a closed vessel between a temperature range of 170- 190°C at around 60-90 minutes to avoid hazardous gases being discharged into the air. The sand and sawdust were added into the melted plastic to obtain the required ratios. The plastic mixture was mixed by hand to ensure that the filler and plastic were properly blended.

The plastic mix was placed into a well-oiled mould to ensure for easy removal of the brick. Pressure was used to compress the brick into the mould. The brick was removed from the mould around 4-6 hours later and left to air dry for a period of 24 hours. Thereafter, various tests were conducted on the cooled plastic brick. The compressive test sample that contained LDPE and sand revealed that, as the plastic content decreased and sand content increased, there was a significant increase in the compressive strength of the brick. The last ratio of LDPE: sand which was 40:60 displayed the highest compressive strength of 61.287 MPa. The high compressive strength could be possibly due to the good adhesion between the LDPE plastic which acted as a binding material between the sand particles. The LDPE: sawdust in the ratio 80:20 displayed the highest compressive strength of 66.89 MPa. A decreasing compressive strength was noticed when there was an increase in sawdust and a decrease in plastic content.

The plastic-sand brick displayed good water absorption properties. The water absorption rate varied between 0%- 0.92% and the lowest ratio of LDPE: sand which was 40:60 displayed a rate of 0.50%. The sand particles filled up the voids within the LDPE plyer structure thus reducing the water absorption rate. The highest absorption rate was observed at a ratio of 50:50. The plastic-sawdust brick was able to absorb water since it was very porous. The density test revealed that as the sand content increased, the density increased as well since the sand was denser than the LDPE polymer. The density for the sawdust plastic brick decreased as the content of the sawdust increased due to both the LDPE and sawdust being light in weight. It was further observed that as the sand content increased, the hardness of the brick increased due to sand having a high content of silicon dioxide that have properties of relatively high hardness. In the sawdust plastic brick, the hardness decreased with an increase in sawdust content. Sawdust is very porous, therefore resulted in weak bonding with the LDPE plastic.

A Fourier transform infrared spectroscopy (FTIR) test was carried out to find out if the bricks underwent any chemical change. The FTIR test revealed that even though no conclusive chemical change in the plastic sawdust brick was noticed, a slight change in the physical properties in the two materials occurred. In the plastic-sand brick, two bonds were broken and subsequently the formation of a new bond. This was possibly due to temperatures beyond melting point in the manufacturing process and in the presence of silica in sand.

In the SEM test, both the lowest and the highest compressive strength from the sand and sawdust filler materials were tested and recorded. When the sand content was increased in the composite material, high mechanical properties were observed and it was noted that the class of fracture changes from plastic deformation to brittle failure. This test also showed good bonding of sawdust with the LDPE plastic because wettability was higher than that of sand. However, the increase in sawdust reduces the mechanical properties drastically since sawdust has a low density and LDPE plastic was not enough in ratio to increase bonding capacity. It has been noticed that these bricks are eco-friendlier and less porous. The compressive strength was increased and water absorption was reduced to a certain acceptable extent.

3.3.3 The utilisation of PET in the manufacturing of the plastic-sand brick

Chauhan et al. [158] stated that the manufacturing of a plastic-sand brick has more advantages such as cost efficiency, durability (less porous), light weight and recorded a higher compressive strength which impacts positively on the sustainable development goals. PET plastic bottles and river sand were used in their study. The manufacturing of plastic-sand bricks was made possible by mixing shredded plastic and river sand in different ratios. River sand was obtained from a local river bed for the manufacture of the plastic-sand brick. A demarcated dustbin point was installed in the canteen for the collection of plastic bottles. Cold drink bottles that were made of PET were collected and sorted into batches. They were washed and dried to remove any moisture content that may be present. A shredding machine made it easier by shredding the plastic into smaller pieces which made it easier to process. Wooden brick moulds were prepared in the workshop. All sides of the moulds were evenly oiled to have a better surface finish on the bricks and for easy removal.

The shredded PET bottles and sand were batched by weight for manufacture of the plastic-sand brick. The river sand obtained was sieved using a 600-micron sieve and this sand was used to produce the plastic-sand brick. A drum was placed over the open flame that was started by the use of firewood. The shredded PET plastic was melted in a drum at around 200°C and the sand was added in the mix proportions of 1:2, 1:3 and 1:4 of a plastic: sand ratio respectively. The mixtures were stirred continuously. The plastic-sand mixture was then placed into the moulds and compressed by a tamping rod. The finished plastic-sand brick was removed from the mould after 24 hours of air cooling.

Average compressive strength for the ratio 1:2 (plastic: sand); 1:3, 1:4 found to be 195.81 kg/cm²; 129.89 kg/cm² and 60,74 kg/cm² respectively. Both the clay on one side and plastic-sand brick on the other were used to construct a wall. A temperature of 500 °C by means of burning coal was applied to one side of the constructed wall. It was noticed that the temperature for the clay brick had increased more rapidly than that of the plastic brick. Whilst the conductivity of the plastic brick was lower than the clay brick, the high exposure of temperature beyond 350°C gave rise to partial melting of the brick which made it unsuitable for fire resistant application. Notably, these researchers' investigation lacked the control of temperature during the melting process since an open fire was used. Furthermore, the mixing process was not constant since it was done manually.

Aiswaria et al. [155] conducted their study on the use of PET in brick manufacturing. Their investigation focused on plastic waste bottles in the form of PET due to it being a huge environmental hazard and non-biodegradable in nature. Their investigation reported that the plastic mixed with mixed manufactured sand (M-sand) had displayed more advantages when compared to the burnt clay bricks and was cost effective. The plastic: M-sand was added in proportions of 1:2, 1:3, 1:4 and 1:5 and 1.6 to plastic after it was heated from the fire below the pan. Various experiments have been conducted to ascertain the new brick properties which revealed the following:

- After examining the compressive strength of the plastic M-sand brick in all the ratios, it was found that 1:4 revealed the maximum compressive strength of 18.13 N/mm².

- The water absorption for the different plastic-sand brick revealed an excellent performance. The water absorption value was the least in the ratio of 1:4 as compared to the burnt clay brick viz. 0.27 and 15.28 % respectively.
- The efflorescence test showed that there was no presence of alkalis in the plastic-sand brick. However, a visible deposit of alkali was present on the surface of the burnt clay brick.
- In the hardness test, it was found that there was no impression on the plastic-sand brick as compared to the burnt clay brick that showed a visible impression on the surface of the brick.
- In the sound test analysis, it was found that both the plastic-sand brick and the burnt clay brick displayed the same clear ringing sound that gave them a good rating.
- Both bricks in the impact test did not break after they were dropped on their corners from a height of 1m. The properties of the bricks indicated that there were good since they did not break or shatter.
- When comparing the thermal resistance of both the bricks after it was baked in the oven for 24 hours at a temperature of 100°C, they showed a reduction of about 9% in compressive strength.
- After cost analysis of the brick, it was noted that the cost of the plastic-sand brick was about 50% of the burnt clay brick, which made it more economical.

Selvamani [163] conducted a study on the use of PET bottles for brick production. In that study, waste PET bottles were washed and mixed with fine sand at plastic: sand ratios of 1:2, 1:3 and 1:4 in hope of obtaining a high strength brick/ block with good sound and thermal properties. A brick mold was manufactured with wood and steel. Five samples of each ratio of 1:2, 1:3 and 1:4 was produced. The fine sand was gathered from the Ponnai River in the Vellore region and the waste PET plastic was collected from hotels, wedding events and plastic collectors. A sieve analysis was conducted in order to obtain the required sand particle size of 4.75mm. An IS sieve of 4.75mm was used in order to avoid the use of larger sand aggregates (particles). The collected river bed sand and plastic were spread over a clean surface and dried in direct sunlight to remove the water content. The drying process was carried out over a period of 3 days.

A pan was used to melt the plastic and was stirred continuously until it started to boil. During the melting process no water or any other cold materials were added. It was noted that the plastic started to produce explosive bursts due to the presence of moisture. The dried sand was added to the plastic in the molten state. Thereafter, the plastic-sand mix was placed in the brick moulds. The plastic-sand mix was compacted in the brick mould with a steel rod. The plastic-sand mix was left to dry for an hour. Thereafter, they were demoulded. Various tests were conducted on the plastic-sand brick to find out its properties and suitability for the construction industry.

- The water absorption test was conducted to find out the amount of water that was retained by the brick without using a standard. The bricks were weighed in dry conditions and thereafter immersed in a bucket of water for 24 hours. The bricks were removed after 24 hours and their surfaces were wiped and weighed immediately to find out the amount of water retention. The normal traditional brick revealed a 12.24 % water absorption rate. The plastic-sand bricks in the ratios of 1:2, 1:3 and 1:4 indicated a water absorption rate of 1.01%, 0.62% and 4.72% respectively.
- The compression strength was found using the compressive testing machine (CTM). The normal traditional brick yielded a compressive strength of 5.58 N/mm². The plastic-sand bricks in the ratios of 1:2, 1:3 and 1:4 indicated a compressive strength of 5.02 N/mm², 8.06 N/mm² and 4.41 N/mm² respectively.
- The hardness test indicated that the bricks have a low impression and is relatively hard.
- In the efflorescence tests, it has been noted that the plastic-sand brick does not show any signs of efflorescence at the surface of the brick when compared to the normal traditional brick.

It was concluded that the plastic-sand brick of the ratio of 1:3 was the most suitable and can be used for construction applications since it displayed the highest compressive strength of 8.06 N/mm² and lowest water absorption of 0.62%. It is recommended to use these plastic-sand bricks for water structures such as septic tanks and underground construction especially below the plinth level to avoid seepage of water.

In their study, Alaloul et al. [164] indicated that the traditional manufacture of bricks that incorporated the use of clay and cement had been replaced with PET waste plastic and polyurethane binder as an alternative material in the production of interlocking bricks for the construction industry. This investigation yielded significant results. A compressive strength of 5.3 N/mm^2 was obtained for a PET/PU in the 60/40 ratio which could be used in the construction of non-load bearing brick wall. This compressive strength surpassed the ASTM standards which required a minimum acceptable strength of 4.14 MPa. Additionally, it could also be used for the construction of internal walls. The highest impact strength recorded was for the PET/PU in the 60/40 ratio with a value of 23.3 J/m. In view of the high impact strength, this interlocking plastic-sand brick is recommended to be used as crash barriers and or column crash barriers. The thermal conductivity test results were acceptable since it was in a range of 0.15 to 0.2 W/mK. This implied that the brick sample was recognized as a good thermal insulating composite material. The thermal conductivity for PET/PU in the 80/20 ratio was the lowest with 0.155 W/mK when it was compared to the other construction materials.

Another study carried out in Malaysia by Deraman et al. [165], aimed at partially replacing a portion of sand with waste PET as an alternative filler material. They also sought to enhance the properties of the cement sand brick and the thermal conductivity. Cement, river sand, 0%, 2.5%, 5% and 7.5% of PET plastic waste was used to manufacture the plastic-sand brick. The sand was obtained from a local river and a sieve analysis was conducted using a 5mm grade sieve. A relatively neutral chemically balanced water with pH of around 6-7 was used for the water-cement ratio of 0.6. A ratio of 1:6 was used for the cement: sand control brick. The PET waste bottles were obtained from the local area in Parit Raja. The bottles were cut into smaller length of around 30mm before they were fed into the granulating machine where their particle size was further reduced to about 5mm making it physically similar to the river sand.

In the production of the brick, the method of mechanical mixing was utilized to achieve a constant mix. The following materials were added to the mechanical mixer in the respective order; sand, cement, shredded PET plastic and lastly water in the proper water-cement ratio. The mixture was poured into a steel mould and compressed with 25 hits of a rod compactor. In the first stage of curing, the bricks were left to cure at room temperature for a day and was thereafter demoulded. The second stage of curing consisted of bricks being covered by a wet cloth for a period of 7 and 28 days respectively and various testing followed. It was noticed that density decreased with an increase in PET plastic waste content. When compared to the control sample, all the plastic bricks displayed a lower density for both 7days and 28 days of curing. The compressive test revealed that the control sample which did not contain any PET waste had the highest compressive strength of 8.6 MPa and 13.40 MPa for 7 and 28 days of curing respectively from all the bricks. With regards to the plastic-sand brick, the compressive strength decreased from 4.20 MPa and 5.10 MPa with an increase in PET plastic waste for 7 and 28 days of curing. The increase in PET plastic content reportedly reduced the bonding capacity between the cement and plastic thus making it very weak.

The water absorption rate for all the bricks increased with an increase in PET plastic waste content and this was noticed as the curing time increased from 7 to 28 days. The control specimen displayed the lowest water absorption rate at 7 and 28 days of 211.64 kg/m3 and 226.62 kg/m3 respectively. Unfortunately, the water absorption test was deemed unfavourable. It was proposed that the brick must be plastered on both sides of the wall to reduce its water absorption. The thermal conductivity indicated that an increase in the PET plastic waste content resulted in a decrease in the K-value. From this study, it was identified that no use of heat was utilized within the production of the plastic-sand brick. The lack of heat could be the possible reason for the decrease in compressive strength and increase in water absorption rate.

3.3.3.1 Applications of PET

PET is recognized to be fully recyclable and can be used for the manufacturing of numerous products such as carpets, fabric, cosmetics, pillow fillings and high quality carpets [145]. A study conducted in Pune by Kognole et al. [153], focused on reducing plastic pollution and incineration of plastics. They were also addressing the high demand for bricks in the construction industry. The following materials were used in the study: Polythene, High density polymer (nylon 66), plastic bottles (PET), plastic wastes, plastic composite with other material, river sand (4.75mm), red soil and cement. Waste plastic was collected within the area and separated into different categories. All the plastic was left to dry after batching them to remove any moisture that may be present. The plastic was crushed into very small particle sizes that was used to manufacture the plastic-sand brick. The shredded plastic waste was heated over an open flame furnace until it turned into a molten mixture. The sand was added to the melted waste plastic and mixed manually.

Elsewhere, Aneke and shabangu [166] outlines in their study on the utilization of PET scrap plastic waste and foundry sand (FS) used in the manufacture of green eco bricks. The mix of FS: PET in the following ratios, 80:20, 70:30 and 60:40 by weight was used. The brick with FS: PET viz, 70%:30% displays the highest compressive strength of 38.14 MPa. However, the compressive strength for FS: PET viz. 80%:20% indicated a compressive strength of 33.25 MPa and 29.45 MPa respectively. It must be noted that all the scrap waste plastic bricks manufactured recorded a higher compressive strength as compared to the fired clay bricks which recorded a compressive strength value of 14.25 MPa. Scrap waste plastic bricks have produced a significantly higher density and compressive strength when compared to fired clay and concrete bricks.

It can be observed in the above study that the utilization of scrap PET plastic focused on the following factors: sustainable construction, energy efficiency and the preservation of materials and resources by the use of recyclables with traditional material in the construction industry. The inclusion of scrap waste plastic with FS in the manufacture of eco-friendly plastic-sand bricks would assist in saving much needed energy that would be otherwise consumed by the normal baking of bricks.

It must be noted that the time used to manufacture the scrap waste plastic brick is 10 minutes as compared to 15 hours in the manufacture of clay bricks [166]. It must be noted that the scrap waste plastic bricks manufactured within the above study is linked directly with the concept of sustainability. The manufacturing of bricks using FS and scrap waste plastic has demonstrated to be cost effective and eco-friendly. The use of scrap plastic in the long term proves to be productive since it reduces pollution on land, air and water and more importantly improves the health and safety of people and the environment. It is promising that the manufacturing of scrap waste plastic bricks will be 25 times cheaper than the conventional clay fired bricks [166]. The study concluded that the use of scrap waste plastic and FS in the production of eco-friendly bricks would make significant strides towards the building of low-cost housing.

3.3.4 Utilisation of PE in the manufacturing of the plastic-sand brick

In their study, Dinesh et al. [167], investigated PE bags which were cleansed and mixed with natural river sand as fine aggregate using different ratios to manufacture a high strength brick having excellent thermal and sound insulation properties. The following ratios of (plastic: river sand) 1:3, 1:4 and 1:5 was investigated. The fly ash brick consisted of 60% fly ash, 10% cement and 30% sand. The findings from the study of the Chennai Central Institution of Technology revealed the following in the manufacture of the plastic-sand brick processes.

- The comparison of the compressive strength of the plastic-sand brick in the ratios of 1:3, 1:4 and 1:5 (plastic: sand) were 4.49 N/mm², 5 N/mm² and 5.56 N/mm² with an average of 5 N/mm² as compared to fly ash brick with a compressive strength of 3.83 N/mm² respectively.

- The water absorption test was conducted after the bricks were submerged for 24 hours. The difference in the weight of the bricks revealed that the water absorption rates for the plastic-sand brick in the ratios of 1:3, 1:4 and 1:5 (plastic: sand) were 0.935%, 0.727% and 1.033 % respectively with an average absorption rate of 1.33%. Corresponding value for the fly ash brick was 8.012%.
- In the efflorescence test analysis, a slight presence of alkali was detected on the fly ash brick, which was within the acceptable range of 10% of the brick surface. On examining the presence of alkali in the plastic-sand bricks in all the ratios of 1:3, 1:4 and 1:5, it was found that there was no alkali on the surface of the plastic-sand brick, which was also within the acceptable alkali range of 10%. Therefore, both the fly-ash brick and plastic-sand brick indicated good properties in the efflorescence test.
- The hardness test revealed that when both the bricks were scratched, it was difficult to indent the surface of the bricks. This showed that the fly ash brick and the plastic-sand brick in the varying ratios of 1:3, 1:4 and 1:5 possessed good hardness qualities.
- In the fire resistance test, the plastic-sand bricks did not show any structural changes up to 180°C.
- The sound test revealed that a clear ringing sound was produced from both the fly ash and the plastic-sand brick respectively. Such a clear ringing sound produced was indicative of a good quality brick.

From the different test analysis mentioned above, it was clear that plastic-sand bricks can be used in the construction industry. However, one disadvantage was that the researchers used an inconsistent hand mixing process to manufacture the plastic-sand brick.

3.3.5 Hybrid combination of plastic

i) Utilisation of PET and LDPE in the manufacturing of the plastic-sand brick

In their study, Bansal and Jain [13], made bricks with various materials, namely clay, sand mixed with PET and LDPE. The sand and clay were mixed in their various proportions i.e. the standard component being clay with a 10%, 20% and 30% of sand with a second set including the aforementioned materials and ingredients with a 5%, 10% and 15% plastic content. The clay sand plastic brick sample was mixed manually. The plastic was heated until a molten state was reached at approximately 200°C. Thereafter, the molten mix was poured into a brick mould with a size of 19 x9 x 9 cm^3. Various testing and analysis of natural soil was done to obtain its index and engineering properties. The results indicated that the pure clay brick revealed a compressive strength of 8.5 N/mm^2. When clay was added with 10%, 20%, 30% of sand, it revealed a compressive strength of 9.5 N/mm^2, 9.6 N/mm^2, 9.8 N/mm^2 respectively. However, when waste plastic material was added in the ratio of 5%, 10%, 15%, the compressive strength was 10 N/mm^2, 10.5 N/mm^2, 11 N/mm^2 respectively. It was clear that when the percentage of plastic waste was increased, the compressive strength also increased. This results were attributed to the plastic binding well with soil resulting in the increased compressive strength.

ii) Utilisation of PET and PP in the manufacturing of the plastic-sand brick

Saiprasad and Nagendra [168] investigated the bonding properties of clay with waste PET and PP. *Firstly,* the proportion of 80% plastic and 20% sand and *secondly,* 50% plastic and 50% sand were manufactured. Four tests were conducted to evaluate the suitability as a brick for the building and construction industry. The compression test revealed the average strength for the brick with 80% plastic and 20% sand was 5.25 N/mm^2 and for the 50% plastic and 50% sand was 8.75 N/mm^2. The water absorption test with 80% plastic and 20% sand indicated an average rate of 2.75% whilst the brick with 50% plastic and 50% sand indicated an average rate of 1.35%. The brick made with 80% plastic was more susceptible to fire ignition as compared to the brick made with 50% plastic due to the increased plastic content. A sieve analysis of IS 4.7mm, 2.36mm, 1.18mm was used. However, the researcher found that the analysis for the different size of sand particles in that study was not disclosed.

As previously observed, one of the main disadvantages of this study was that the researchers used an open flame and an uncontrolled environment which resulted in the polymer bonds also being burnt and possibly lost to oxidation. This drastically reduces the strengths between bonds and the overall strength and absorptivity of the brick.

iii) Utilisation of PE and PET in the manufacturing of the plastic-sand brick

In this paper, Mak et al. [151], contended that the use of plastic waste in brick manufacturing helps in reducing hazardous waste disposal of plastic. The inclusion of waste plastic as an important material in the building and construction industry certainly reduces the economic cost of construction in general. This also creates a sustainable, realistic and affordable practice to reduce the effects of pollution that is caused by incineration of plastic waste materials and the careless dumping of them in landfills. Most of the polymers falls within a lower price range as compared to sand and soil, both of which are prone to natural depletion on an ongoing basis.

During the brick manufacturing process, the different materials were mixed with varying percentage of plastic waste as well as fine aggregate, while 55% of fly ash, 15% of lime and 5% of gypsum remained constant. It is reported that the 25% of fine aggregate with 0% of plastic waste yielded a significantly high compressive strength of 4.5 N/mm^2, while 5% of fine aggregate with 20% of plastic waste yielded 3.25 N/mm^2. It was concluded that an increase with fine aggregate with a decrease in plastic waste resulted in higher compressive strength.

On the contrary, the lowest percentage of fine aggregate (5%) and the highest percentage of waste plastic of (20%) displayed a compressive strength of 2.5 N/mm^2. Therefore, an increase in the percentage of the waste plastic content does affect the quality of the brick. From the five samples of the bricks manufactured, it was noticed that when the constant mix (55% of fly ash, 15% of lime and 5% of gypsum) with 15% of aggregate and 10% of waste plastic resulted in the lowest absorption of 9.1%. The absorption test was completed after 7-28 days, which revealed a high degree of porosity and low thermal conduction. The bricks also had a low rate of efflorescence. Acoustic test was conducted on the brick that had plastic waste and indicated a high absorption of sound levels, which implied the possibility of reducing the noise levels in buildings.

iv) Utilisation of PE and HDPE in the manufacturing of the plastic-sand brick

In a study by Dinesh et al. [169] HDPE and PE (bags) were cleansed and mixed with sand and aggregates at different percentages to obtain a suitable high strength brick that had thermal and sound proof properties. The waste plastic and PE bags were collected and washed to remove any dust and contaminants. Thereafter, the plastic bags were dried to remove any moisture content that was present. An open flame was setup using firewood for the source of heat. The plastic bags were added to the drum and melted until they turned into a molten state. The river sand was added to the plastic in molten form and was mixed manually using a steel rod and trowel. For paver blocks, less than 10% of red oxide by weight of total mixture was added as a colouring agent. The moulds were prepared by oiling them on all their sides for easy removal. The hot mixture was put into the moulds immediately and compacted using a steel rod. Thereafter, the surface was smoothened and finished with a trowel. From the mixed quantities in the ratio of 1:2, 1:3, 1:4, 1:5 and 1:6 of plastic: river sand respectively, the following results were noted:

- The compressive strength of 1:4 was the highest, indicating a strength of 5.12 N/mm². However, when comparing this plastic-sand brick with its counterpart, the following results were noted: The strength of the Fly ash was 4.19 N/mm² and burnt clay was 3.15 N/mm². Evidently, the plastic-sand brick showed a higher compressive strength than the other bricks.
- The sample bricks were placed in water for 24 hours. The water absorption for the fly ash, burnt brick and plastic-sand brick were 8.012%, 9.086% and 1.01% respectively. The plastic-sand brick indicated the lowest water absorption rate making it the most suitable brick for the building and construction industry.
- The brick samples were submerged in water for 24 hours. The efflorescence test analysis was completed. The plastic-sand brick indicated a low alkali content displaying very little white alkali patches on the surface of the brick.
- Although plastic was prone to fire, the presence of the proportion of sand acts as an insulator in the plastic-sand brick. The fire resistance test indicated that the structure of the brick was not altered up to a temperature of 180°C. However, beyond this temperature, cracks were noticeable with the increase in temperature.
- A steel rod was used to conduct the hardness test. It showed that the plastic-sand brick was of a high quality since it was difficult to scratch the surface of the brick.

Similarly, a noticeable disadvantage in the above study was that the plastic was burnt using an open fire process.

v) Utilisation of PE and PP in the manufacturing of the plastic-sand brick

In the experimental study [140], PE shopping bags and PP pipes were collected from a local industry in Oman. The plastics that were obtained were washed to take out any contaminants and thereafter dried for 1 day to remove moisture content that was present in the plastic. PP and PE plastic was heated to a temperature of 180°C into a molten state and 5 grams of red oxide was added to the mixture. Thereafter, the sand was added to the mixture to obtain the desired varied ratios of plastic-sand brick. Six different plastic: sand samples were produced in the defined ratio of 1:2, 2:1, 2:2, 2:3, 2:4 and 2:5 respectively. The plastic-sand mixture was mixed manually with a steel rod and poured into moulds that were oiled on all their sides for easy removal of the plastic-sand brick. The plastic-sand brick was air cooled for a period of 24 hours before removing them from the mould. The plastic-sand bricks were left to cure for 14 days. Thereafter, various tests were conducted on the different ratios of plastic-sand brick and the results were indicated below:

- The efflorescence test indicated that there were no noticeable deposits of efflorescence on the brick.
- The water absorption rate, in all six ratios varied from 0% to 2.82%. However, the ratio of 1:2, 2:1 and 2:5 (plastic: sand) indicated a 0% rate of water absorption. This was not a good indication because in the building and construction industry, a small amount of water must be absorbed to prevent possible cracks or any defects at a later stage.
- Of the six samples of bricks, the sample ratio of 2:1 (plastic: sand) showed the highest compressive strength of 12.43 N/mm^2. For the ratio of 2:2, 2:3, 2:4 and 2:5, the compression strength was 3.76, 4.41 and 6.25 N/mm^2 respectively, reflecting an increase with sand content. However, in the last sample with the ratio of 2:5 (plastic: sand) the compressive strength decreased drastically to 3.84 N/mm^2, which could be the results of certain defects within the brick.

3.3.6 The use of the extrusion machine in the production of plastic-sand bricks

Kumar et al. [170] stated that the use of plastic waste material is useful for construction material. The extrusion machine plays a vital role in the conversion of waste plastic into a molten form which has a possibility to be used in the construction industry. The extruder machine is also not hazardous and does not pose any threats to the environment. The machine does not release toxic emissions in the form of air pollution as compared to the pollution generated by the kiln during the brick production process. The final summary indicates the waste plastic bricks has a higher strength as compared to traditional bricks.

In their study, Shah et el. [58] made a plastic brick from 100% waste plastic dust from PVC pipes. They used the extruder machine that helped in the systematic and timeous mixing of the brick components unlike in the previous research studies where the uncontrolled flame was used to melt the plastic and manual stirring methods implemented. The extruder machine played a vital role to ensure that the temperature was controlled to produce the plastic brick. The plastic dust brick had a compressive strength of 6.66 N/mm^2 which was higher than the traditional burnt brick which had a strength between 3-5 N/mm^2. Thus, in this study, the extruder has been employed to address the following challenges: i) transforming waste plastic into its molten state, ii) controlling temperature effectively, iii) achieving systematic mixing of the plastic-sand material, iv) reducing the excessive utilization of sand (a natural resource) from river beds traditionally used in burnt clay brick manufacturing, and v) mitigating the high pollution levels generated from kilns during the conventional brick manufacturing process [58].

Table 3.1 shows a summary of experimental work and findings discussed in the aforegoing section in pursuit of eco-friendly materials.

Table 3. 1: Materials experimented with and results in pursuit of eco-friendly materials

MAIN PLASTIC TYPE	RESEARCH STUDY	MATERIAL USED			MOST SUITABLE RATIO FOR:								
						TESTS CONDUCTED							
		BINDER	SOIL TYPE	SIEVE ANALYSIS	RATIO	COMPRESSION	WATER ABSORPTION	EFFLORESCENCE	FIRE RESISTENCE	SOUNDNESS	HARDNESS	IMPACT	AUTHORS
HDPE	1	HDPE	River sand	4.75mm	1:4	9.141	0.79%	-	-	Clear ringing sound	Good-No scratches on the surface	No bricks broken	Salahuddin, S (35)
	2	HDPE	-	-	-	23-25 MPa	-	-	-	-	-	-	Wendimu,T (36)
	3	HDPE, Portland cement	Silica Sand		30:70	22.23 MPa	<6% ave.	-	-	-	-	-	Silviyati,I et. al. (37)
LDPE	1	LDPE LDPE	Sand Sawdust	600micron	40:60 80:20	61.287 MPa 66.89 MPa	0.5% 1.8%	-	-	-	Good Moderate	-	Hamzah, A (51)
PET	1	PET	Sand	4.7mm	1:3	8.06 N/mm^2 (MPa)	0.62%	No salts was present	-	Higher ringing sound than clay brick	Good-Relatively hard	-	Selvamani, C (11)
	2	PET	River Sand	-	1:2	195.81 kg/cm^2 (19.2 MPa)	1.16%	-	Hold s well up to 180◦ C	-	-	-	Chauhan et.al. (12)
	3	PET	M/sand	-	1:4	18.13 N/mm^2 (MPa)	0.27%	Excellent	-	Clear ringing sound	Good-No impression	No bricks broken	Aiswaria, K (15)

	4	PET, cement	River sand	5mm	2.5% (PET) 97.5%	5.1 MPa (28days of curing)	234.12kg /m3	-	-	-	-	-	Deraman, R (49)
	5	PET, LDPE	Clay, sand		Clay+30% sand+15% plastic	11 N/mm² (MPa)	6.25%	-	-	-	-	-	Bansal, N (7)
	6	PET PP	Sand Sand		50:50 50:50	8.5 N/mm²(MPa) 9 N/mm² (MPa)	1.5% 1.2%		Fire resistance decreased with increase with plastic	-	-	-	Saiprasad, MK (8)
	1	PE, fly ash, cement	River sand		1:5 1:4	5.56 N/mm²	0.73%	No salt was present	No change until 180◦ C	Clear ringing sound	Good hardness quality	-	Thirugnanasambantham, N… (17)
PE	2	PE, PET, fly ash: lime: gypsum	Sand		Fly ash: 55% Lime: 15% Gypsum: 5% Sand: 20% PET: 5%	4.5 N/mm²	9.2%	Low rate of salts was present	-	-	-	-	Shu-Lun Mak et. al (31)
	3	HDPE, PE, red oxide	River sand		1:4	5.12 N/mm²	1.1%	Low alkaline content	No change until 180◦ C	-	High quality	-	(21)
	4	PE, PP, red oxide	Soft refined sand		2:1	12.43 N/mm²	0%	No alkaline deposit on surface		-	-	-	(24)

In the research study of Salahuddin and Zambani [161]; Wendimu et al. [162] and Silviyati et. al. [146] it was observed that HDPE was used in the ratio between 20% and 30%. Their results for the compression tests ranged from 9.141 MPa to 25 MPa. The water absorption rate ranged from 0.79% to less than 6% on average.

In using LDPE, Hamzah and Alkhafaj [130] found that in using the 600micro sieve with a ratio of plastic: sand (40:60), the compression test was 61.287 MPa and the water absorption was 0.5%. On the other hand, with a ratio of plastic: sawdust (80:20), the compression test was 66.89 MPa and the water absorption was 1.8%.

Selvamani et al. [163]; Chauhan et.al. [158] and Aiswaria et al. [155] made use of PET and sand. They used ratios of PET: sand between 1:2 to 1:4 and produced a compressive strength that varied from 8.06 MPa to 19.2 MPa. The study by Deraman et al. [165] found that by using 2.5% (PET):97.5% (cement and river sand) and by making use of the 5mm sieve, a compression strength of 5.1 MPa was obtained and the water absorption rate was 234.12kg/m^3. Bansal and Jain [13] on the other hand, found that by using Clay + 30% sand + 15% plastic (PET, LDPE) the compression strength was 11 MPa and the water absorption was 6.25%. Saiprasad and Nagendra [168] used both PET: sand and PP:sand separately in their study with the ratio of 50:50. It was found that PP had a higher compressive strength of 9 N/mm^2 (MPa) as compared to PET which had a corresponding value of 8.5 MPa. PP had a lower water absorption rate of 1.2%, while PET had 1.5%.

There were various studies conducted using PE, fly ash, cement, PET, lime, gypsum, HDPE, PP, red oxide with sand. Only in the study conducted by Patil et al. [140] with the combination of PE, PP, red oxide: soft refined sand and the ratio of 2:1 yielded the highest compressive strength of 12.43 MPa with water absorption rate of 0% and no alkaline deposit on surface.

3.4 Gaps in the literature

There is currently insufficient literature on the subject of how plastic waste can be used creatively in manufacturing of other products. The investigations and the use of plastic-sand bricks and its widespread use in the building and construction industry need to be explored. Notably, the researchers' investigation on plastic-sand bricks and other related products lacked the control of temperature during the melting process since an open fire was used. Furthermore, the mixing process was not constant since it was done manually. Using an open flame could have several effects on the plastic type that is used. Different types of plastic have different melting points. Therefore, the use of open flame is an area of concern. [158] [153] [155] [169] [167].

The danger of manual mixing methods during the manufacture of the plastic-sand bricks could result in incorrect or inconsistent mixing of the materials used. There would be huge differences during the testing of the brick samples if these samples were manually or machine mixed. The consistency of the mortar does matter in plastic-sand brick making due to the nature of plastic itself. Some plastic do not mix well with other materials due to its composition [158] [153] [169] [167].

One of the disadvantages of the study conducted by Aiswaria et al. [155] on PET was that it was conducted with uncontrolled temperature and open flame. Another drawback was that manual mixing method was also used in the process of manufacturing this plastic-sand brick which may be unfavorable for ensuring a homogenous distribution of the plastic and sand particles. No brick standard was not followed when both bricks were dropped on their corners from a height of 1m during the impact test. Although the properties of the bricks indicated that there were good since they did not break or shatter, the results must be in line with a particular standard.

Notably, in their study using PET and LDPE, Bansal and Jain [13] also did not conducted their investigations with controlled temperature and this would affect the physical and chemical properties of the plastic. Some of the polymers may have been lost to oxidation as well as the bonds being burnt due to increased temperature above the workable heat zone of the PET plastic.

Selvamani [163] in his study on the use of PET bottles for brick production concluded without using a proper brick standard that a clear ringing sound was observed when the bricks were struck together and they did not crack on their surfaces. This showed that the bricks were of a good quality. This is not quantitatively reported and the results of this “ringing sound” must be discredited. A number of other weaknesses can be linked to this study such as i) molding of the brick were done manually and these could give rise to other problems due to hand mixing and/or compacting, ii) an open pan was also used in this experiment with uncontrolled temperature and iii) the plastic was allowed to boil and this was incorrect since all plastics have a workable heat zone and any temperature above the heat zone will cause the polymers to burn and be lost to oxidation.

It was discovered that most of the experimental papers which were read and analysed have been completed on a small scale. It will be difficult at this stage to fully understand the mechanical and environmental properties with limited studies carried out on a small scale using a specific type of plastic. Currently, there are very few studies conducted that measures the feasibility of commercialising the production of plastic-sand brick [158] [153] [146] [156] [169] [167]. There is still restriction on using the plastic brick for certain applications such as for internal use only [171], for underwater construction, underground construction, building of septic tanks and building below the plinth area [163].

There are inadequate industrial regulations for recycling of plastic waste and converting them into new products such as plastic-sand bricks. Some countries are still developing their regulations on the use of alternate building materials for example the use of plastic-sand bricks for general construction works. Although there is a paradigm shift in the use of alternate building materials in South Africa, there still needs to be a clear regulatory framework for alternate building materials [21]. Furthermore, there are no clear building standards that needs to be observed. This leads to incorrect testing procedures and differences in the results [142]. In the study conducted by Al-Sinan and Bubshait [142], the absence of standards and uniformity in performing the experiments, may have led to major discrepancy in the results.

The risk of the use of plastic-sand brick in the open markets is still prevalent. This is due to some properties of plastic-sand brick needs further testing and development. Information on practical aspects such as thermal conductivity and fire resistance regarding plastic-sand bricks is either very limited or unavailable [142].

The widespread commercialization and utilization of plastic-sand bricks could have both positive and negative long-term environmental impacts, and these impacts depend on various factors. The considerations related to durability, resistance to weathering, potential chemical leaching, and overall contribution to sustainable waste management and environmental conservation are indicated below:

i) Durability and Resistance to Weathering:

Karthick et al. [172] highlighted that HDPE is a robust and durable material with versatile performance properties suitable for a wide range of applications. Plastic-sand bricks are intricately designed and meticulously manufactured to not only meet but surpass expectations when it comes to durability and weather resistance. The materials carefully chosen for these bricks are characterized by a remarkable level of endurance, ensuring that they withstand the test of time and environmental challenges. Additionally, their inherent weatherproof properties make them highly resilient to the effects of varying climatic conditions. The thoughtful selection of materials, known for their robust nature, contributes to the overall longevity and structural integrity of plastic-sand bricks. These bricks are engineered to endure external stressors, such as harsh weather conditions, without compromising their performance or aesthetic qualities. Whether facing intense sunlight, heavy rainfall, or fluctuating temperatures, plastic-sand bricks are designed to maintain their form and functionality over an extended period. In essence, the commitment to durability and weather resistance in the design and manufacturing of plastic-sand bricks underscores their suitability for diverse applications in construction, providing not just strength and stability, but also a lasting solution that stands up well to the elements [173].

ii) Potential Leaching of Chemicals:

Plastic-sand bricks undergo careful design and testing to guarantee that they do not release harmful chemicals into the surrounding environment. These bricks are recognized for their environmentally friendly characteristics. By formulating them properly and adhering to safety standards, the risk of chemical leaching is minimized. The use of moisture-resistant and impact-resistant HDPE plastic materials further contributes to safety, as they are known for lower risks of leaching and are considered safe in the long term [174].

iii) Contribution to Sustainable Waste Management:

Plastic-sand bricks contribute to sustainable waste management by utilizing plastic waste as a resource in construction materials. The production process involves recycling and reusing plastic, it helps reduce the amount of plastic entering landfills or ending up in the oceans. Reusing plastic waste in construction material has proven to be an alternative method instead of recycling or landfilling to tackle plastic waste pollution [175].

iv) Environmental Conservation:

The utilization of plastic-sand bricks holds the potential to contribute significantly to environmental conservation by alleviating the demand for traditional construction materials like clay or cement, which may carry higher environmental footprints. Moreover, the integration of recycled plastic aligns with the principles of a circular economy. In contrast to the linear "take, make, use, dispose" system, a circular economy strives to prolong the utilization of resources, maximize their value during use, and recover and regenerate products at the end of their useful lives. The production and application of plastic sand bricks and blocks serve as a noteworthy example of the innovation needed to establish a circular economy [142].

Understandably, the long-term environmental impacts of plastic-sand bricks depend on factors such as their durability, resistance to weathering, potential leaching of chemicals, and overall contribution to sustainable waste management. Therefore, rigorous testing, adherence to environmental standards, and responsible manufacturing practices are crucial for maximizing the positive environmental contributions of this innovative construction material.

3.5 Envisaged impact of plastic-sand bricks

A pragmatic model was developed within the South African context highlights the economic implications of recycling plastic waste and its potential to address plastic pollution. Their analysis, depicted in *Figure 3.4*, demonstrates that recycling not only reduces the volume of plastic waste but also creates employment opportunities. These findings support the use of recycled plastic in constructing eco-friendly houses, reducing gas emissions, and promoting sustainability.

THE POTENTIAL IMPACT OF CONVERTING 2 TONS OF PLASTIC WASTE INTO PLASTIC-SAND BRICKS IN SOUTH AFRICA	
2 tons of plastic	**Plastic pollution** When 2 tons of plastic waste is recycled is equivalent to 2000 kilograms of plastic waste being collected from the environment and eventually decreases the plastic waste in land, rivers, seas and oceans. This recovered plastic waste offers several breakthroughs when they are washed, chemically cleaned, shredded, flaked and produced into totally new useful products such as plastic-sand bricks, pavers, outdoor furniture, toys, plastic lumber, clothing, shoes, shampoo bottles, biofuels, pallets, crates, pails, frames foldable boxes and other outdoor moulded components [13] [126] [128] [176]
Creation of 40 jobs	**Unemployment** From current waste picker experiences, it is recorded that they can gather approximately 50 kilograms of recyclable waste plastic in one day (8 hours) [177]. In trying to meet the collection demand of 2 tons of plastic waste from the environment could actually create employment for 40 unemployed people per day. This means that 40 waste pickers per day or 1 waste picker can be employed for 40 days, which is approximately 2 months, to ensure that collect 2 tons of plastic waste is collected. This opportunity: ● creates jobs in the informal sectors for many unemployed people such as waste pickers and sorters. ● creates avenues for entrepreneurial activities in developing countries such as opening a small business. ● creates employment in the sorting, batching and conversion process of plastic waste. ● presents different job opportunities in the formal sector such as skilled artisans, technicians, machine operators and other related skilled jobs ● promotes the civil and construction industry since individuals can employ more different jobs.
1 small house	**Affordable eco-friendly housing** Particularly, the conversion of 2 tons of plastic waste into plastic-sand bricks will result in providing jobs for the poor and under-privileged. 1 waste picker who works for approximately 2 months or 40 waste pickers working for 1 day would potentially manufacture approximately 2222 bricks to construct one small eco-friendly affordable house (see calculation below). 2 tons (2000 kg) = 2 000 000 grams of plastic waste. Note that 1 plastic-sand brick= 3000g. This is based on the ratio of 70% sand (2100 grams): 30% plastic (900 grams). 2 000 000 grams of plastic can be transformed into approximately 2222.22 plastic-sand bricks. The reality of converting plastic waste from land, seas, rivers, lakes and oceans into plastic-sand bricks (as explained above) also extends this opportunity of creating work for brick layers, civil and construction related jobs [126]. Therefore, converting 2 tons of plastic waste into 2222 plastic-sand bricks is a reality in South Africa. This could also be used to construct eco-friendly houses, windows, stairways, boundary fencing, light and heavy-duty paving and walk ways.
Reduction in approx. 23067 MJ	**Climate change** Approximately 10.38 mega joules (MJ) of fossil energy is necessary to manufacture a single 3kg clay brick. Coal is a nonrenewable fossil fuel that is burnt and used to produce electricity. It is the most used fossil fuel in comparison to oil and gas [178]. The advantages of using an extrusion machine must be noted when converting plastic waste into numerous products. Studies showed that using an extrusion machine does not have serious negative impact on the environment. Due to its minimal negative impact, it eradicates the need for non-renewable materials for brick curing. Notably, the amount of air pollution that is generated from brick curing kilns in the conventional production of burnt clay brick is now evaded [170].

Figure 3. 4: The potential of converting 2 tons of plastic waste into plastic-sand bricks in South Africa

The impact of converting 2 tons of plastic waste through the recycling process will result in 40 jobs per day, and potentially 2222 bricks could be manufactured to construct a single affordable house. Finally, about 23 067 mega joules (MJ) of fossil energy can be avoided if plastic-sand brick were produced for the building and construction industry.

Therefore, there is need for an engineering strategy to reduce plastic pollution, provide an alternate way of constructing eco-friendly houses, a way of creating job opportunities and prevent the depletion of the ozone layer for the benefit of all citizens. An attempt has been made for this strategy to be accomplished in this study, therefore in effect supporting, enhancing and promoting sustainability. An engineering solution viz. plastic brick manufacturing as an alternate binder material to be used in the construction industry has been advanced using recycled HDPE plastic waste.

SECTION B: UNDERPINING THEORETICAL AND CONCEPTUAL FRAMEWORK

3.6 Theoretical and Conceptual framework

Figure 3.5, highlights the theoretical and conceptual framework that is used to explain this study. It commences briefly with understanding the Theory of Sustainability and proceeds to how the concept has emerged over 50 years from 1972 to 2022 and its associated links to the three pillars of sustainability viz. environmental, social and economic at a global level. The greatest challenges in understanding the concept of sustainability and its complex nature is discussed. Further, there is no singular definition in the body of knowledge. However, South Africa has shifted from the Venn diagram approach to a systems approach that led to the National Framework of Sustainable Development to promote sustainability. This framework serves the purpose of articulating the country's vision for sustainable development on both national and global levels. It aims to provide strategies that will guide and structure South Africa's path towards developmental growth in a more comprehensive and directed manner. Hence, The South African framework for sustainable development represents a clearer understanding of the concept of sustainability for this study. This understanding is crucial and provides a better focus on sustainability that forms the lens through which the RQ *"How can sustainability be encouraged and promoted by introducing an alternative eco-friendly building* *material in the construction industry?"* will be examined, magnified and understood for possible solutions.

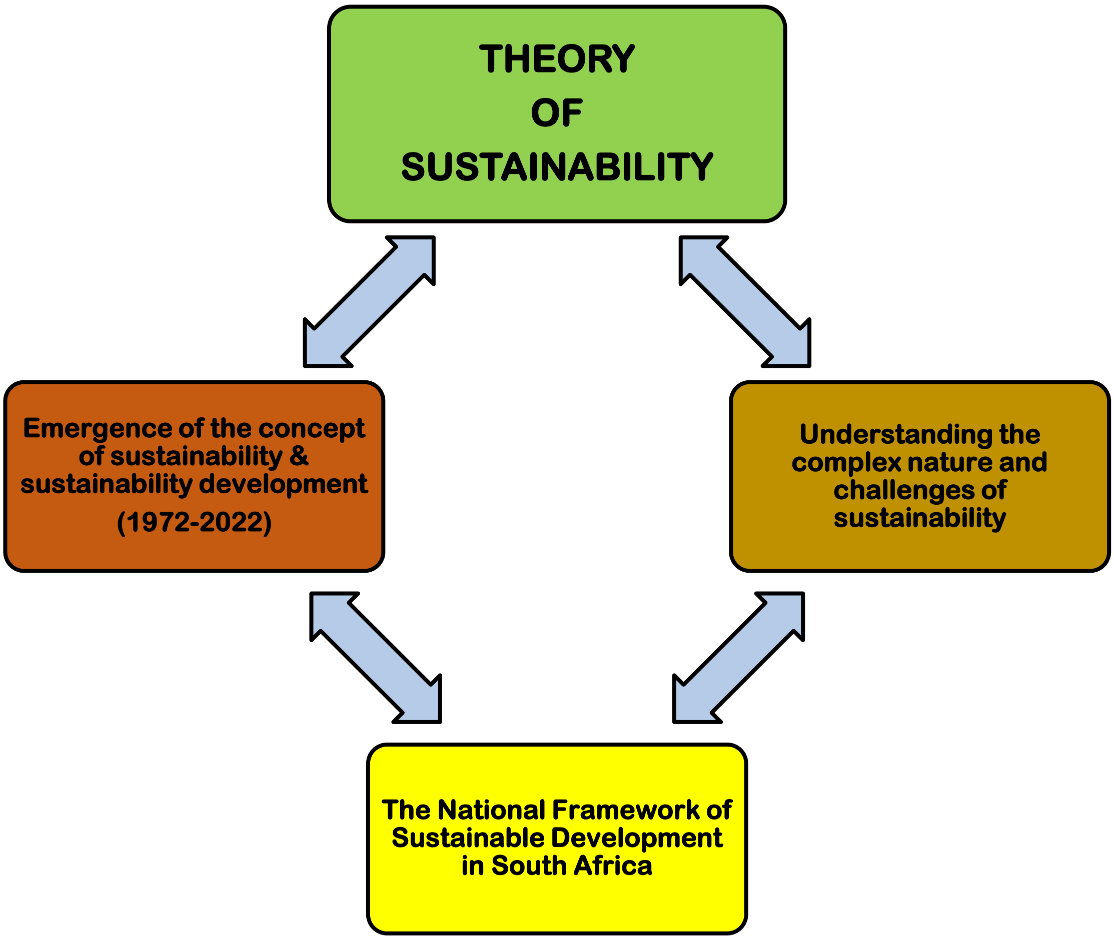


Figure 3. 5: Understanding sustainability and sustainable development

Kivunja [179] stated that a theoretical framework comprises all the voices of leaders around the world that contributed towards the RQ and it also provides a structure on the phenomena that is being investigated. More importantly, it provides a special lens on how to examine and conduct the data analysis, interpret results, how to engage with the findings, make possible recommendations on how to resolve the research problem and provide conclusions.

3.7 Theory of sustainability

The concept of sustainability was initially understood as saving our natural resources and how they should be distributed and used to sustain future generation. However, many scientists, theorists and environmentalists believe that natural resources will not be able to support the world's growing population knowing that the demand outweighs the supply. There are those who claim that the threats to sustainability come mainly from overpopulation and consumption, while the others argue that the threats to sustainability come from bad planning and poor policies implementation [180].

The theory of Sustainable Development (SD) surfaced during the 1980s, concentrating on the coordinated efforts to support the economy, society, and environment which has radically made its way into the political terrain. Presently, SD theory is the responsibility of governments and leaders at a national and global level. Hence, the concept of SD has slowly advanced from one that was confusing or misunderstood to a thrust of global action that is needed to sustain future generations [181]. Therefore, it is important to commence with how the concept has emerged of many years.

3.8 Emergence of the concept of sustainability

The concept of sustainability has gained prominence through various United Nations conferences and initiatives. These conferences have served as platforms to address global environmental challenges and promote sustainable development. The concept of sustainability has been significantly influenced by various United Nations conferences, as well as the work of the Brundtland Commission and the establishment of the Sustainable Development Goals (SDGs).

The Brundtland Commission, formally known as the World Commission on Environment and Development, was created by the United Nations in 1983. The commission's landmark report, "Our Common Future," released in 1987, introduced the concept of sustainable development. It defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This report played a crucial role in shaping the understanding and promotion of sustainability worldwide.

Several significant sustainable development conferences have taken place between 1972 and 2022 (Refer to *Appendix A*). These conferences, among others, have played a crucial role in shaping the global sustainable development agenda, raising awareness about environmental issues, and fostering international cooperation to achieve a more sustainable and equitable world. It emphasized the need to protect and preserve natural resources while promoting sustainable economic growth and social development. Through all these conference initiatives, the UN has highlighted the importance of sustainability in all aspects of human activity, including environmental protection, economic development, and social equity. They have played a crucial role in shaping the global agenda for sustainable development and promoting the transition towards a more sustainable future [182] [183] [184] [185] [186] [187] [188] [189] [190] [191] [192] [193] [194] [195] [196].

The United Nations Sustainable Development Goals (SDGs) were adopted by UN member states in 2015 as a universal call to action to end poverty, protect the planet, and ensure prosperity for all. The SDGs consist of 17 goals and 169 targets that cover a broad range of social, economic, and environmental issues. They provide a comprehensive framework for sustainable development, addressing key challenges such as poverty, hunger, education, gender equality, clean energy, climate change, and sustainable consumption and production [194].

Collectively, the emergence of the concept of sustainability through the UN conferences, the work of the Brundtland Commission, and the establishment of the SDGs have played a vital role in promoting sustainable development worldwide. They have provided a framework for addressing global challenges, fostering collaboration between nations, and working towards a more sustainable and equitable future for all.

3.9 Understanding the concept of Sustainability

3.9.1 The complex nature of sustainability

The biggest challenge in understanding sustainability is that there are no singular definitions in the literature reviews. Trying to understand the concept of sustainable development is not so straightforward. Both these concepts are sometimes confusing but they are subtle differences between them. Authors as discussed later in this section define these concepts in so many ways and by placing emphasis on different aspects of sustainability. After reading from the plethora of literature on sustainability and sustainable development, it was revealed that both these concepts are used interchangeably, confusingly at times and is time bound. However, there has been a proliferation of literature on sustainability over the last few years.

Goni et al. [197] confirmed that there has been a steady increase in the number of research undertaken in the sustainability development due to its constant awareness, importance, debates and discourse on sustainability. The analysis of the research conducted for the timeframe between 1987 to 2010 (over a 24-year period) in respect of the number of sustainable articles published in five international journals totalled 29616 survey articles as seen in *Figure 3.6*. The articles spanned on the subject on waste minimisation, green engineering, manufacture, pollution control and prevention, sustainable energy and energy management and water research. These subjects highlighted predominantly environmental aspects during this early period. There have been further accelerated research efforts from the year 2000 after the adoption of the MDG at the three-day conference which was held in NY, USA on 6-8 September 2000 [187].

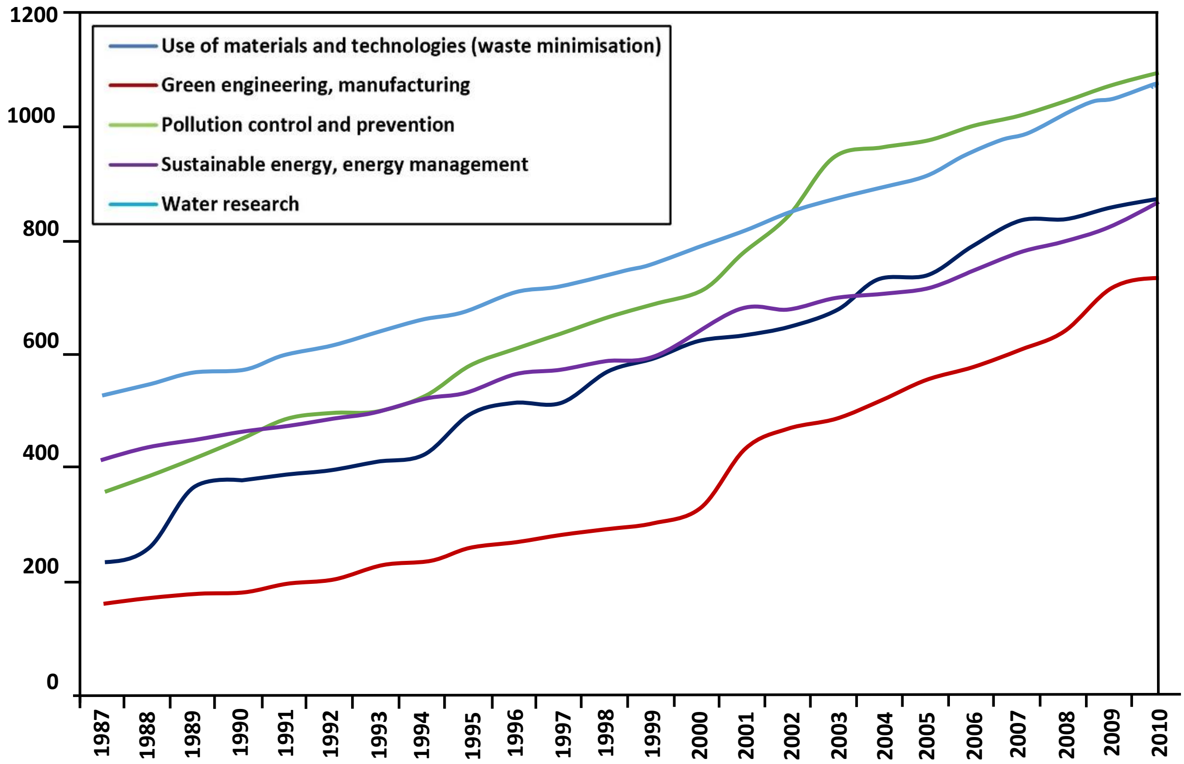


Figure 3. 6: Total number of sustainability articles by five primary research focuses over the years (Adapted from [197])

Initially, sustainability was linked to environmental aspects such as increased rate of pollution, global warming, depletion of non-renewable resources. As the concept unfolded, it was looked beyond the boundaries of the environment. Other social aspects such as unemployment, poverty, health and safety of citizens were included in the discussions and debates of sustainability. Further, economical aspects such as profits, manufacturing and industries have also become topics of interest. Thus, sustainability looked at environmental, social and economic aspects as key components that must meet the needs of current generation without compromising the ability of the future generation to meet their own needs. Goepel [198] argues that although sustainable development has gained dominance in most policy debates the concept itself still presents a degree of ambiguity. It is further argued that sustainable development lacks conceptual clarity and at times since it portrays vague and conflicting interpretations of how it should manifest itself in practice. Carter and Rogers [29] is of the same opinion that after reviewing the available literature on sustainability, the concept is still inconsistently defined.

Hence, sustainability is a broad concept that can be understood as knowing what resources we have and whether we will be able to manage these to an extent of making use of them without depleting them or compromising the needs of future generation. The concept of sustainability can also be used in the retail, health and medical, construction, financial, telecommunications, manufacturing, agriculture, mining, aerospace, automotive industry and in education.

As Kotob [199] contends that the term sustainability is too general in its approach. He highlights that it lacks some kind of measurement that can serve as an indicator of sustainability. This could be one of the reasons why sustainability is struggling to be implemented and achieved in the world. Hence, sustainability should be looked at in measurable terms which means the amount of progress which is achieved must be quantified. Therefore, in trying to understand the complexity of sustainability, it means that there must be a contrived action which is deliberately created that needs to be formally implemented to produce a resultant outcome in the environment, social contexts and the economy. For example, government, NGOs and private providers must take action in creating incentives and initiatives to create jobs. Then this outcome is quantifiable in terms of social and economic sustainability.

Heilig [200] argued that there is no universally accepted methodology that is available to measure and rank sustainability. He explains that merely using qualitative approach to describe or explain whether a condition is more or less sustainable is also still inadequate and subjective in nature. He contended that there is a dire need to locate sustainability within a quantitative approach. He further acknowledged that the UN division for sustainable development together with other leading organisations such as the World Bank, the World Resource Institute and various other global research institutes on sustainability made an ambitious attempt to develop indicators for sustainable development. The author stated that the UN initiative to develop indicators for sustainable development merely compiled a shopping list of existing statistical indicators and completely lacked the scientific backing, proof or measure on the concept of sustainability. He indicated that sustainable development could be developed into a scientific concept but the various indicators of sustainability must be based on empirical data.

Hák et al. [201] argues for the importance of indicators that is required from different sources. Indicators have various characteristics since they can be descriptive in nature, show performance, indicate efficiency and demonstrate policy effectiveness. The greatest challenge facing our current generation is the question of choosing the most appropriate indicator to assist us to make correct decision to resolve problems at the appropriate time. It is recommended that there be an indicator framework to accurately monitor and understand the situations and conditions within the context so that one can decide how to act and be able to understand the impact of policies and where they are driving society to.

Kotob [199] explains that the Brundtland report has been quoted and simplified by several writers. He argued that the term sustainability in the last few decades has looked into the integration of 3 aspects of sustainability namely environmental, economic and social. Most of the sustainability reports covered these 3 aspects. However, some reports prioritise on environmental only. However, a common understood definition is taken from Brundtland Commission Report (1987) which describes the concept of sustainability as *"development that meets the needs of the present without compromising the ability of the future generations to meet their own needs"*. The report indicated that the increase in population and their varied activities has finally had major unintended consequences on the planet and everything in it such as atmosphere, soil, water, fauna and flora as well as the different relationships that they shared and coexisted in. The accelerated change is making it difficult for human kind to implement recovery strategies. However, it is urged that the call for desperate collaborative action must be immediate amongst the national and international communities. The report actually forms a basis for an action plan in respect of the following areas: our threatened future, moving towards sustainable development, the imperative role of the international community, population and human resources, food security, species and ecosystems, energy, industry, the urban challenge, managing the commons (oceans, space, Antarctica), peace, security, development and the environment as well as a common call for action [1].

Elliott [202], drawing on the works of Ger Asheim defines sustainability as a pre-requisite to our current generation to carefully control the utilization of natural resources in such a way that our current average lifestyle can be successfully shared by future generations in the same manner. By implication, it means that the current generation have a co-responsibility to take care of the future and are not living in isolation. This will ensure that the future generations will be sustained in this manner of consideration. Simply, it means that our current actions have a bearing on the future.

When evaluating both the definitions provided by Brundtland and Elliott it is seen that two concepts "fairness and equity" plays a pivotal role in sustainability. At the heart of both definitions, is the idea of fairness and equity. We need to take cognisance of how resource is allocated and at the same time we need to take note of how resources are distributed over time (future generations). We need to be concerned about fairness in resource allocation across time. An example is that it would be totally unfair for our current generation to consume all the fish from the ocean which will lead to a shortage and no regard for future generations. The idea of knowing the value of intergenerational equity is key in any definition of sustainability [202].

As indicated in the South African National Environmental Management Act (NEMA), 1998, [203] sustainable development can be understood as the integration three factors namely social, economic and environmental. These factors must be taken into consideration when planning, during the implementation process and when decisions are made to the best interest of our present and future generations. Ultimately, sustainability requires a harmonious integration of these three aspects to create a better world for all.

3.9.2 Challenges of the concept of sustainability and sustainable development

Karvonen et al. [204] argues that the main challenge in evaluating or assessing sustainability is the lack of empirical data. The limiting factors are lack of empirical data, its practical application, poor understanding of how the three pillars namely economic, social and environmental aspects are integrated. They recommend that there should be a strong and powerful science-based evidence on sustainability thresholds regarding planetary boundaries.

The three pillars of sustainability can be understood as a Venn diagram showing three spheres represented in a form of a circles as indicated in *Figure 3.7*. The intersections of the circles share a common centre called the area of sustainability. This way of understanding sustainability is only made possible and can be achieved when all three pillars (societal [28] , environmental [30] and economic [29]) are integrated and equally engaged [27]. The three spheres can also be represented as people, planet and profit. However, these concepts will be briefly explained separately in order to obtain a more simplified and easier understanding of each concept. It must also be noted that these three concepts should work in synergy. They cannot be separated and must been seen as integrated, interlocked and embedded into each other to create a sustainable future.

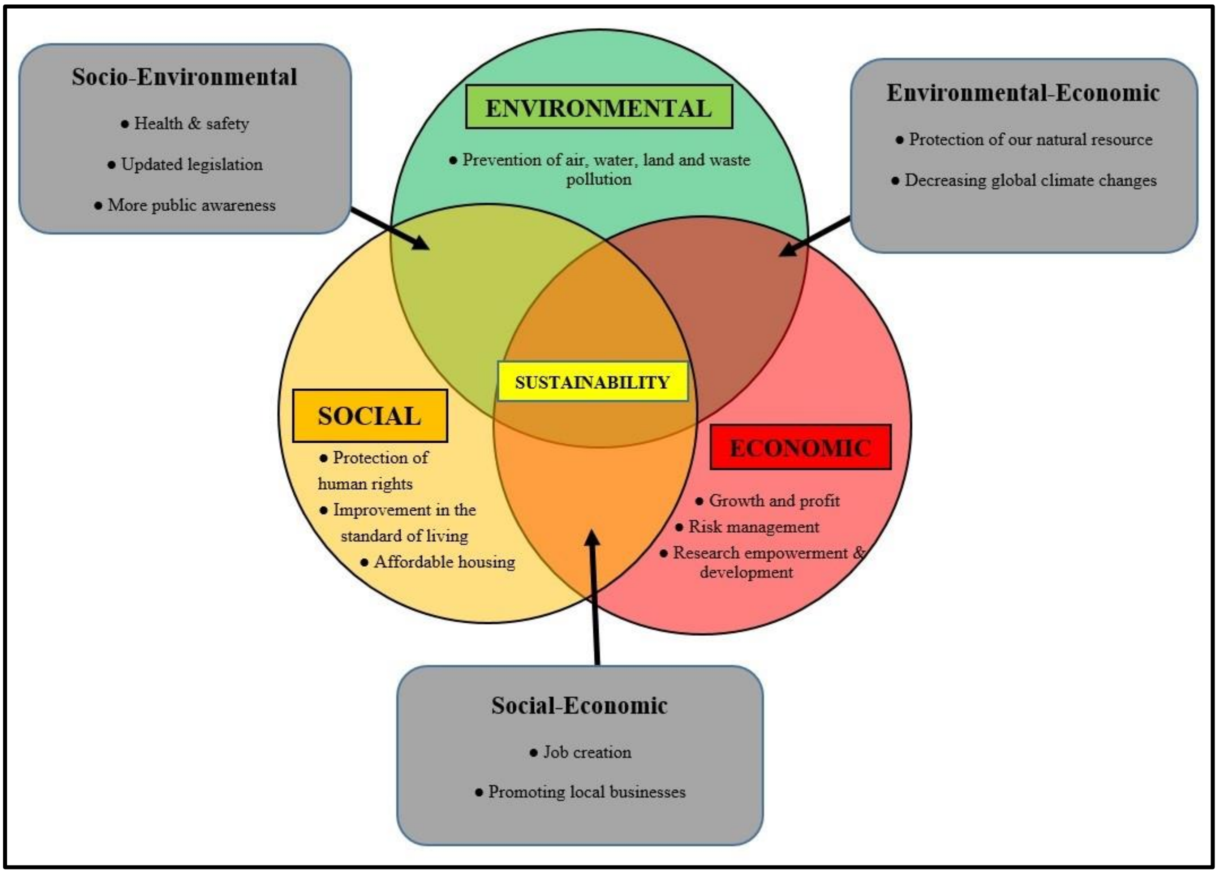


Figure 3. 7: The Three spheres of sustainability (Adapted from [205])

i) Environmental sustainability

Arora [206] warns that environmental sustainability is a prerequisite for survival. Currently, environmental sustainability is one of the greatest challenges facing mankind. The ever-increasing population, coupled with the careless activities of mankind poses a serious question whether we are able to sustain our natural resources on our planet. It is a given that the earth is affected by all human activities and their negative impacts on the environment. Human actions have far-reaching negative impacts on the environment, from pollution to overexploitation of resources. Slum conditions, migration from rural to urban cities, industrialisation and modern chemical agricultural practices have seriously caused sea, air and land pollution nationally and globally. The supply of natural resources is over exploited, depleted and contaminated with harmful chemicals making it difficult for the current and future generation to sustain itself. Hence, environmental sustainability calls for effective and prudent use of resources without compromising the ability of the future generation to meet their needs. Key practices of environmental sustainability are reducing pollution, recycling, utilising non-renewable resources efficiently, preserving fauna, flora and marine life [180].

ii) Social sustainability

Social sustainability means that the social aspects of a country, organisation or a community can or will be able to continue itself in the long term without compromising the ability of the future generation to meet their needs. Some examples of social sustainability are eradicating poverty, upholding human rights, providing housing for citizens, maintaining health and safety, improving living conditions and creating opportunities for employment [180].

iii) Economic sustainability

Economic sustainability means that a country, organisation or business is able to make use of all its resources in an effective and responsible way to produce a profit in the long term without compromising the ability of the future generation to meet their needs. It is also the ability of a people to create revenue to sustain themselves in a market economy. Key elements of economic sustainability include maintaining investments, good governance and risk management [180] [202]

iv) Integration of the environmental and economic system

Figure 3.8 illustrates the integrated relationship between the environment and the economy. The environment, social and economic pillars of sustainability must be view as an integrated, interconnected, embedded and interlocked system operating within each other. Similarly, each dimension should operate in tandem to promote and achieve overall sustainability.

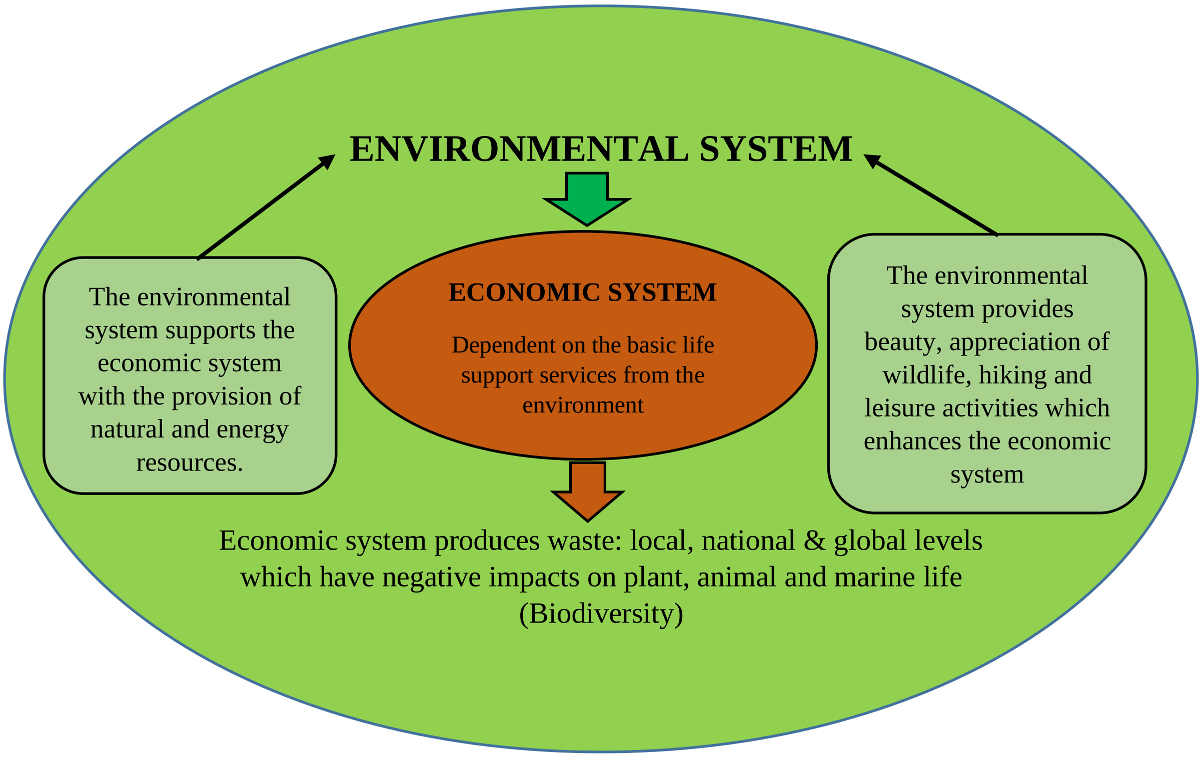


Figure 3. 8: Integration in environmental and economic systems (Adapted from [207])

Hanley et al. [207] explains how the environment and the economy are interlinked. The economy is located and developed within the environmental system. Some examples of an economy are a sum total of all the firms that forms the industry, governments, people who are consumers and are part of the labour force. Some examples of the environment are natural resources, forests, wetlands, deserts as well as the fauna and flora found within these environments. *Firstly*, the environment provides resource inputs which supports the economic system with the provision of natural and energy resources. These natural resources can be renewable such as wind, solar and hydro energy or non-renewable such as coal and crude oil. These resources are then converted into useful outputs which is then demanded by consumers such as petroleum into plastic.

Secondly, the economic activity also generates waste, resulting in negative impacts on biodiversity and the environment. These wastes result in unwanted remains from production lines and end processes such as CO_2 emissions emitted from the combustion of coal or bagasse from sugar production. Pollution results in a negative and detrimental impact on the environment and economy.

Thirdly, the environment directly contributes to people's well-being through amenities like environmental beauty, appreciation of wildlife, hiking and leisure activities such as fishing in the environment (amenity values).

Fourthly, the economic activity can have a negative effect on biodiversity, the wildlife population and plant growth by encroaching on their habitats, as seen when a natural forest is cut down due to the possibility of a quarry or mining activity.

Lastly, the economic system is dependent on the basic life support services that is provided by the environmental system.

3.10 The National Framework for Sustainable Development in South Africa

The South African National framework for sustainable development [208] adopts a systems approach to four interconnected objectives: economic development (including the eradication of extreme poverty), social inclusion, environmental sustainability, and good governance (including security) as depicted in *Figure 3.9*. Each of these four dimensions of sustainable development contributes to the other three, and all four are therefore necessary for individual and societal wellbeing. Sustainable development is often described by the first three dimensions: economic, social, and environmental. Good governance and personal security have been added as a fourth dimension to highlight several enabling conditions for sustainable development. Good governance encompasses factors like transparency, effective institutions, the rule of law, participation, accountability, and adequate financing for public goods. These principles of good governance apply not only to the public sector but also to the private sector and civil society. By including good governance and personal security as integral components of sustainable development, the framework highlights the need for an inclusive and comprehensive approach to achieving long-term well-being and progress.

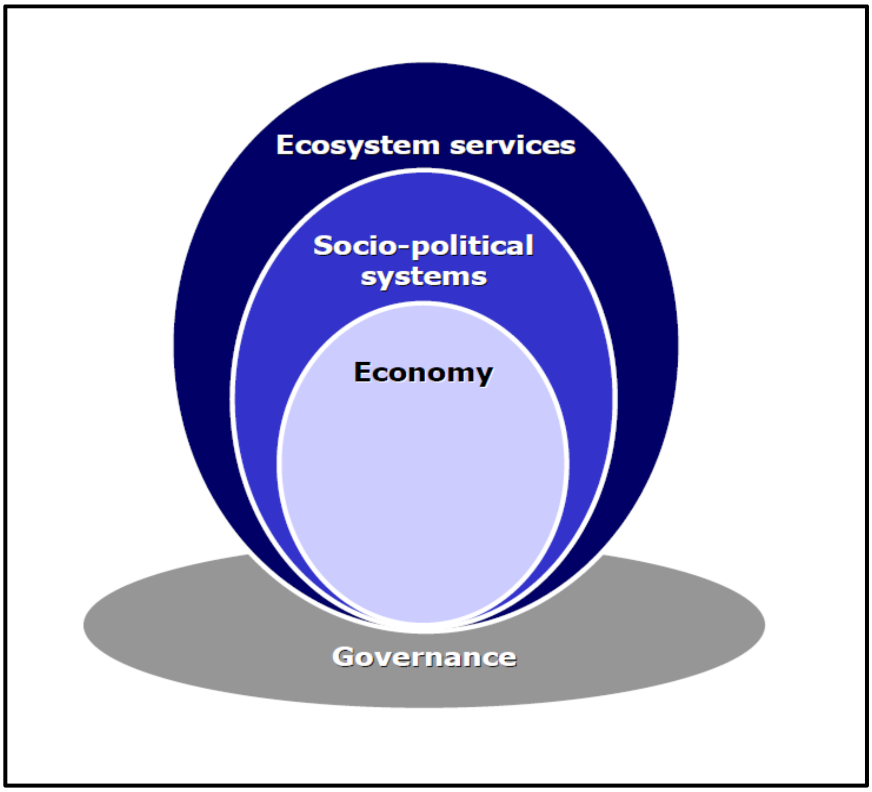


Figure 3. 9: National Framework for sustainable Development in South Africa 2008 [209]

Over the past 50 years, the United Nations' sustainable development agenda has influenced South Africa to adopt its own National Framework for Sustainable Development (NFSD) [209]. This framework aims to present a clear national vision for sustainable development and outline strategies to realign the country's growth and development path with a stronger focus on sustainability. The NFSD is intended to guide and facilitate a long-term plan for resource and impact decoupling, seeking to promote economic growth while minimizing negative impacts on the environment.

i) A national vision for sustainable development in South Africa

The national vision for sustainable development is guided by the government's principles. The Department of Environmental Affairs (DEA) adopted the vision for a sustainable society in

2008, envisioning South Africa as a self-reliant nation that ensures economic prosperity while safeguarding democracy. This includes meeting the fundamental human needs of the people, responsible management of ecological resources for current and future generations, and fostering integrated planning and governance through collaboration at national, regional, and global levels [210].

ii) Principles

The fundamental principles which are underpinned in the National Framework for Sustainable Development promotes the democratic values of: Human dignity and social equity, justice and fairness as well as democratic governance. The substantive principles also underpin the National Framework for Sustainable Development which spells out clearly what content and the appropriate conditions that is required in order to have a sustainable society. These principles are: effective and sustainable use of natural resources, socio political and economy are embedded and dependent on the ecosystem as well as basic needs must be met [209].

iii) A shift from the Venn diagram approach

The South African system's approach has shifted away from the Venn diagram approach which places emphasis on the inclusion of the role of governance. Instead, the South African national framework is modelled in such a way where the economic system, socio-political systems and ecosystems services are embedded within each other as seen above in *Figure 3.9*. These three systems are integrated and facilitated through the governance system, maintaining an approved regulatory framework to ensure they work harmoniously together. Sustainability in this context means these systems collaborate in an integrated manner over time to promote a sustainable society. Sustainable development then means that the framework has to align these systems by working together in harmony guided by specific actions and interventions. Achieving sustainability implies that there is a positive move towards eradicate poverty and rooting out inequalities [209].

iv) The purpose of the strategic framework for sustainable development

It presents an overview of all the governmental activities as well as how its social partners will intensify their workings together, to relook and re-orientate in a step by step manner to achieve integrated sustainable development in respect of the economy, society and the environment. This also includes how the different departments within the governance systems will be empowered to ensure sustainability will be achieved [209]. The framework with its vision subscribes to the principles as developed in the various international meetings, summits, conferences and assembly special events.

3.11 Conclusion

This chapter categorically concludes that plastic could be a viable binder in the construction industry based on numerous studies exploring different types of plastic and hybrid combinations for brick manufacturing. However, there are certain gaps in the literature such as lack of proper temperature control during brick manufacturing, inconsistent mixing methods employed and the lack of exploration of Kaolin Clay DSF as a reinforcement agent, still exist, and limited knowledge on the use of the extruder to manufacture bricks. Despite these gaps, the envisaged impacts of utilizing 2 tons of plastic waste are promising and can contribute to addressing global, African, and South African crises.

This chapter also concludes that the concept of sustainability is not understood by all stakeholders as a single definition. This research study advocates for government initiatives that integrate waste pickers, updated laws and recycling into the formal economy as part of sustainability efforts. Dernbach and Mintz [211] also advocate for laws to address crucial issues such as poverty, environmental degradation, social inequities, unemployment, housing backlogs, and slow economic growth rates (*Appendix B*). This initiative targets a greater solution by decreasing the pollution that takes place on land, sea and rivers (Environmental sustainability), seeking ways to produce greener housing, better health, welfare and living conditions (Social sustainability) and creating jobs for the formal section where by business enterprise can recycle waste plastic into other products such as benches, chairs and tables as well as promoting the growing informal sector (Economic sustainability).

Thus, it is with great optimism for the building industry, since the investigations carried out in all of the above studies using plastics of different types revealed that there is a great potential for the use of plastic as a constituent in the production of plastic bricks and this will assist in reducing the impact of the four emerging global crises (as explained in great detail in chapter two):

- The inclusion of plastic waste in the manufacturing of plastic-sand bricks will certainly help in the reduction of plastic waste from land, air and water pollution.
- It will successfully contribute to the removal of waste plastic in all areas of the environment, rivers, oceans and landfills by "waste pickers." This will undoubtedly create jobs for machine operators and general workers in the plastic-sand brick plants and reduce unemployment which is extremely high in South Africa.
- The potential of using waste plastic into plastic-sand brick production will increase the demand for "greener material" in the building of houses.
- It will certainly assist in the reduction of GHG emissions and reduce global warming since waste plastic no longer has to be incinerated and the use of high energy intensive processes in kilns during the curing of clay bricks.

Therefore, finding a solution for plastic waste, advancing knowledge in plastic-sand brick manufacturing, addressing the global crises, and transitioning to a greener economy in the building industry are crucial. For these reasons, this study of converting HDPE waste plastic into a useful material has been conducted. This study is supported by Silviyati et al. [146] that plastic can be used as a binder in brick manufacturing. It is now becoming eminent and evident that the eco-friendly plastic-sand bricks have the potential to be used in the construction industry, thereby promoting sustainability and sustainable development within the country and at a global level. Tawab et al. [212], concludes that the concept of sustainability is gradually becoming key in the construction industry locally and globally.

CHAPTER FOUR

METHODOLOGY

4.0. Introduction

Figure 4.1 outlines the graphical format of the research methods used in this study. This section covers essentially seven aspects of methodology.

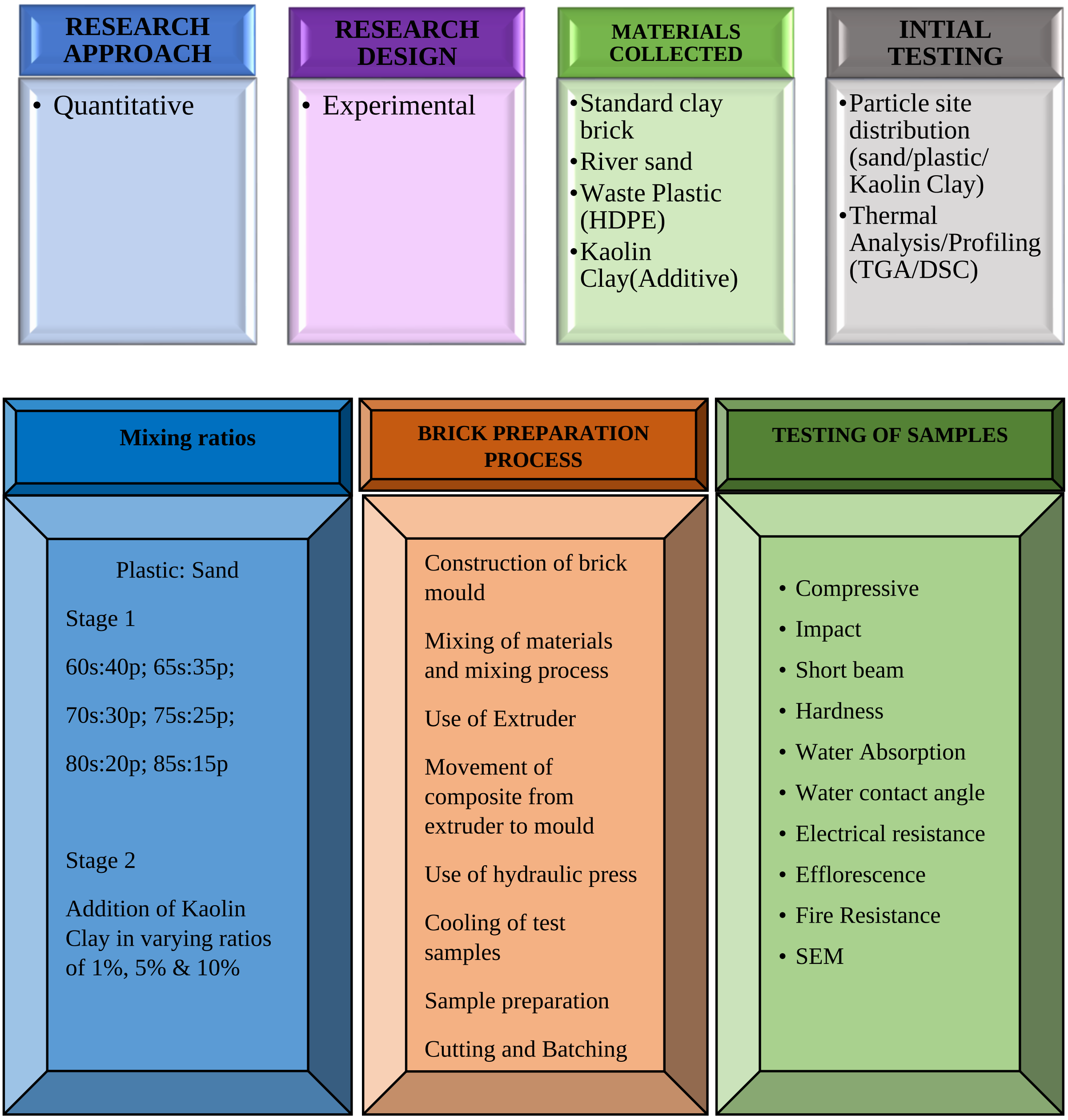


Figure 4. 1: Graphical format of the research methodology

4.1 Research approach

This research study is based on the quantitative research approach as supported by Apuke [213] and Ahmad et al. [214] using an experimental design.

4.2 Experimental design

In their study, Imai et al. [215] indicated that experimentation strictly adheres to scientific (or engineering) methods. They also acknowledge that experimentation is one of the most powerful methodology. Through experimentation, scientists and researchers will be able to establish causal claims empirically. Apuke [213] concludes that in an experimental research, numerical data is collected, the variables are manipulated by the researcher, measured, calculated, analysed using statistical methods and compared to each other.

On the other hand, Montgomery [216] provided a full description on experimental research. According to him, observing a process or the entire system while it is ongoing constitutes a crucial aspect of learning and comprehending its functioning and dynamics. The author contends that comprehending the impact of altering specific factors on an outcome during a process requires more than mere observation. Researchers must delve deeper into the intricacies of the process to achieve a comprehensive understanding. In other words, for a researcher to understand the cause-and-effect relationships, one has to physically change the input variables of the process or system. Thereafter, one has to observe what and how the different variables cause changes in the output. This explains that most challenges in Science and Engineering initially require the process of observation of the system in progress followed by a series of experimentation to elicit data about why and how it works in a certain way. The author cautions that there needs to be a well-designed experiment with good data collection methods in place. The results and conclusions from the experiment is largely dependent on how the data sets were collected.

4.3 Materials

4.3.1 Standard clay brick

SANS 227 (burnt clay masonry units) [217] was used in this study as a benchmark against which to compare the experimental plastic-sand brick samples. These clay bricks are traditionally fired in a kiln at very high temperatures of about 1000°C. Clay brick possesses unique properties and is illustrated in *Figure 4.2*. Their strength, durability, dimensional stability, longevity, fire- and weather-resistance makes them popular throughout the world. There has been much discussion on different platforms to address the firing process, but currently there is great awareness on the huge gas emissions that is causing huge damage to the ozone layer.

Figure 4. 2: Clay brick

4.3.2 River sand

The river sand was purchased from Malik Brick and Block which is illustrated in *Figure 4.3*. The river sand is regarded as the most suitable material used in the construction industry for brick production by Kulu Crete in Port Shepstone which is one of the largest cement brick factories in the lower South Coast. Generally, this sand consists of rounded particles, and it may or may not contain clay or other impurities.

Figure 4. 3: River sand

Sand can also be described as a granular material produced out of finely separated shale and mineral particles through a mining process. It is constituted by its particle size. Aggregate less than 5mm in diameter is categorised as sand. Currently, sand is high in demand and is also regarded as a scarce natural resource nationally and internationally.

For this study, the river sand is used in different ratios to form part of the plastic-sand brick. The river sand was clean and free of large components since it was dredged directly from the river bed. It is also important to mention that this research study is conducted by striking a balance between the increasing demand of river sand in Port Shepstone and the current environmental concerns to save river beds from deep excavations. Hence, these excavations will have a negative impact on the environment, pose a threat in achieving sustainability in the future in local areas and will increase the need to produce alternate construction materials.

4.3.3 HDPE plastic

One of the main aspects of this research study is to ensure that there is an efficient way to utilize the waste plastic which is posing a great threat to human, plant and animal life thus causing an ecological imbalance. There are different ways of collecting waste plastic. *Firstly*, to actually locate them from other sources i.e. rivers, landfills, oceans or at any business disposal outlets such hotels, shops and restaurants [163]. However, according to Chauhan et al. [158], some of the challenges of collecting plastic waste are that they are irregular in shape and size. Hence, they need to be physically processed or cut into smaller pieces of same size using a shredding or granulating machine. Waste plastic must be cleaned to remove any impurities or contaminants and dried to remove moisture. *Secondly*, obtaining plastic waste material would be in its granular or shredded form from a commercial factory that deals with this type of business enterprise. *Lastly*, collecting waste plastic is through a middle agent called “waste pickers.” The following three out of the seven different types of plastic as indicated in *Table 4.1* had the most promising properties for alternate binding material for the construction industry.

Table 4. 1: Properties of PET, HDPE and LDPE

TYPE OF PLASTIC	01 PET	2 HDPE	4 LDPE
Melting point (MP)	250 °C	120-140°C	105°C to 115°C
Density	> 1,38 g/cm³	0.93 to 0.97 g/cm	0.910 - 0.940 g/cm³
Formula	$(C_{10}H_8O_4)n$	(C_2H_4) n	(C_2H_4) n
Recyclable	Yes	Yes	Yes

Mak et al. [151] supports the recycling of LDPE, HDPE, PET and PP since they are safe due to its low toxic content. HDPE and LDPE are accepted at most recycling centers, as it is one of the easiest plastic polymers to recycle. Many recycling companies collect these types of plastic and send them to large facilities to be processed. Currently, the most widely recycled plastic in the world is PET and it is a relatively easy plastic to recycle. PP can be recycled, but, most of these are diverted towards landfills. However, PP recycling is found to be difficult and most expensive. It is also difficult to get rid of the smell of PP. Unfortunately, the so-called PVC and PS that belong to the other category are not recyclable. Based on the above information and discussion, it was decided to use shredded HDPE based on the individual properties, availability and collection challenges.

Choosing between High-Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) for outdoor furniture, decking, and children's jungle gyms involves considering the specific properties and requirements of each material. Here are some factors that might influence the choice of HDPE over PET for these applications:

i) Cost and Durability

High-Density Polyethylene (HDPE) stands out for its superior durability and impact resistance when compared to Polyethylene Terephthalate (PET). This inherent toughness has led to its widespread use in various watercraft, such as kayaks, surf skis, and small sailing boats across different regions globally. The robust nature of HDPE makes it particularly well-suited for these applications, where resilience to impact and wear is crucial [218]. One of the most valuable properties of kaolin, particularly significant in the ceramic industry, is its moldability. Kaolin can be easily molded into any desired shape, and through the application of heat, the water content can be driven away, transforming it into durable products. This characteristic not only contributes to the versatility of kaolin but also plays a crucial role in cost reduction during the fabrication step, especially when utilizing extrusion techniques. This underscores that kaolin is not only cost-effective as a raw material but also holds the potential to streamline and economize the manufacturing process, making it a valuable resource in the building industry [219] .

ii) Weather Resistance

HDPE exhibits better resistance to environmental factors, such as UV radiation and temperature fluctuations, compared to PET. Outdoor items need to withstand prolonged exposure to sunlight and varying weather conditions, making HDPE more suitable for these applications [172].

iii) Water Resistance

HDPE is inherently water-resistant and does not absorb water [220], whereas PET may absorb water over time. For outdoor furniture and jungle gyms, resistance to water absorption is crucial to prevent issues like warping, rotting, and mold growth. This resistance to water absorption significantly contributes to the longevity and durability of these outdoor items, providing users with a reliable and low-maintenance solution.

iv) Recyclability

In the realm of recycling, both High-Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) exhibit recyclability. However, when it comes to recycling practices, HDPE tends to be more commonly recycled, making it a preferred choice in various sustainability initiatives [220].

v) Chemical Resistance

High-Density Polyethylene (HDPE) exhibits superior chemical resistance when compared to Polyethylene Terephthalate (PET). This distinction becomes particularly evident when considering the reaction of these materials to various chemical substances. HDPE, being a thermoplastic polymer, is known for its robust chemical resistance across a broad spectrum of chemicals. It is highly resistant to acids, bases, and a variety of solvents. This inherent chemical inertness makes HDPE an excellent choice for applications where exposure to different chemicals is anticipated. On the other hand, Polyethylene Terephthalate (PET), while a widely used and versatile polymer, has comparatively lower resistance to alkali and strong bases. PET may be susceptible to degradation or weakening when exposed to alkaline substances over an extended period [172].

vi) Safety Considerations

HDPE is generally considered safe for contact with food and beverages, making it a safe choice for children's products. HDPE is used in chemical containers such as oil containers, cleaning products, laundry products due to their resistant to their resistance to chemicals [172]. Silviyati et al. [146] affirm that High-Density Polyethylene (HDPE) stands out as one of the extensively utilized polymer materials. HDPE products, as per their research, demonstrate a very low risk of leaching into foods or liquids. This particular plastic finds widespread application in a variety of everyday items such as shampoo bottles, toys, common groceries bags, recycling bins, yogurt tubs, cleaning detergent containers and similar products. The low leaching risk of HDPE makes it a preferred choice for packaging and storage solutions where contact with food and beverages is a critical consideration, emphasizing its safety and suitability for everyday use. PET is also considered safe but may not be as commonly used for direct contact with food or in children's products.

The recycled shredded plastic was purchased in the form of pellets or granular form from a reputable company in Durban is illustrated in *Figure 4.4*. This was based on the following considerations: time constraints, collection challenges, cleanliness of the plastic, presence of chemicals and the uniformity of particles to be used in the extruder machine for consistent and optimum results. Recycled HDPE plastic type is classified as resin type 2. This recycled HDPE plastic originates from Jojo tanks which were granulated into flakes and thereafter pelletised into smaller particle sizes. Therefore, this is not virgin plastic but is regarded as 1st generation recycled plastic.

Figure 4. 4: Recycled HDPE pellets

4.3.4 Kaolin Clay as brick additive

From the literature review, the investigations conducted on the feasibility of using plastic in the manufacturing of plastic-sand bricks, were limited to components such as fly ash, river and quarry sand and the additives used were bitumen, talc and plastic itself. Kaolin Clay DSF was not used as an additive for brick production. In order to fill this existing knowledge gap and to make a valuable contribution towards understanding the use of plastic as an alternative binding material, varying percentages of Kaolin Clay DSF has been used. Kaolin Clay DSF is described as a dry-separated, raw form of Kaolin Clay powder which is illustrated in *Figure 4.5*. This has been micronized to a mean particle size of 2 microns. Refer to *Appendix C* for the material data sheet for the chemical and physical properties of Kaolin Clay DSF. For this study, it is used in its raw form as an additive to improve the mechanical and environmental properties of the plastic-sand polymer composite material. Kaolin is also known to be a material that is environmentally safe since it has not presented any health challenges [221]. The reason for using Kaolin Clay is also due to its hydrophobic nature i.e. it repels water [222].

Figure 4. 5: Kaolin Clay DSF

Undoubtedly, Kaolin Clay has gained recognition as a valuable material in concrete blends in the construction industry. Due to its silicate mineral, it gives concrete its improved durability and strength of cement materials. Kaolin Clay functions as an exceptional super-filler, efficiently occupying spaces within the cement matrix. This augments the density of the mixture, leading to expedited drying period. Additionally, it serves as a natural filler and an additive in polymers, increasing their flexibility and enhancing crucial mechanical attributes like strength, durability, rigidity, and resistance to impact [223]. It's noteworthy that Kaolin Clay has been proven to enhance mechanical properties in HDPE polymer blends [224]. Extensive research showcases its positive impact on cement mixtures, resulting in improved properties and increased compressive strength [225] [226].

4.4 Sample preparation

Table 4.2 indicates the ratios of sand: plastic used for this study. Literature reviews [13] [163] [156] [157] revealed that the ratios ranging from 10-40% of plastic composition by weight posted promising results. Hence, the ratios of plastic used for this study ranged from 15-40%.

Table 4. 2: Mixing ratios

SAMPLE DESIGNATION	MIXING RATIO	WEIGHT OF MATERIAL (g)	
		SAND	HDPE
Mix 1	60:40	1800	1200
Mix 2	65:35	1950	1050
Mix 3	70:30	2100	900
Mix 4	75:25	2250	750
Mix 5	80:20	2400	600
Mix 6	85:15	2550	450

The plastic-sand brick samples prepared using these ratios were cut into test samples for experimental testing and evaluation. The samples were subjected to a series of tests to determine the optimum ratio of sand: plastic mix.

4.4.1 Ratios of Kaolin Clay

The percentage of 1%, 5% and 10% additive were added to the sand and plastic categories in pursuit of improving the mechanical and environmental properties. The rationale for using Kaolin clay as additives in the manufacturing of HDPE plastic sand bricks involves considering various factors, including the desired properties of the bricks, the intended application, and the manufacturing process. Some reasons why it was chosen over the other clays are indicated below:

i) **Cost-Effectiveness, size, shape and increased properties:**

Kaolin clay is generally more budget-friendly compared to other types of clays. Since clays are natural products, their cost-effectiveness tends to remain lower than that of synthetic alternatives. In this study the cost was taken into consideration. Kaolin Clay plays a crucial role in the manufacturing process of plastic sand bricks. Therefore, opting for Kaolin clay at a reduced cost is the economical decision taken [227]. Kaolin Clay is a commonly utilized filler in the plastic industry due to its several advantageous characteristics. These include its smooth finish, lightweight nature, affordability, ability to minimize cracking and shrinkage, and enhancement of thermal, mechanical, and electrical properties. Additionally, Kaolin Clay exhibits resistance to acid attacks, making it a versatile and valuable component in the formulation of plastic materials [228].

ii) **Availability:**

Kaolin clay stands out as a readily available and extensively used clay mineral. Its abundance is notable in many countries across diverse climates and temperatures. The widespread availability of kaolin makes it a convenient and accessible choice for manufacturers who can easily source this raw material. This wide distribution and accessibility contribute to its global commercialization, as kaolin is utilized and recognized in various industries around the world [219].

iii) **Reinforcement:**

The incorporation of Kaolin into High-Density Polyethylene (HDPE) plastic can yield notable enhancements, particularly in terms of reinforcing and improving specific properties. Studies have demonstrated that kaolin clay serves as a cost-effective and efficient reinforcing agent in polymer blends, contributing to increased stiffness and strength. Kaolin Clay, acting as a reinforcing agent, plays a crucial role in stress transfer within the polymer matrix. This results in improved resistance to breakage, especially under bending stresses. The ability of Kaolin to act as a stress transfer agent enhances the overall mechanical properties of the polymer blend. Notably, this reinforcement contributes to better flexural strengths in composite materials. The cost-effectiveness of Kaolin further adds to its appeal as a reinforcing agent. By enhancing the stiffness and strength of HDPE plastic, Kaolin proves to be a valuable addition in polymer blends, offering manufacturers an economical means to improve the performance characteristics of their products. The versatility of Kaolin in acting as a reinforcement underscores its potential to enhance the overall quality and durability of HDPE plastic, making it an attractive choice for various applications [229].

4.4.2 Construction of brick mould

The choice of specimen dimensions for brick sampling was methodically determined based on the specific characteristics of the testing and cutting machines employed in the experimental process. Instead of strictly adhering to a predetermined standard, the dimensions of 190mm x 90mm x 50mm were strategically selected to align with the capabilities and requirements of the equipment utilized.

This pragmatic approach ensured that the specimen dimensions were not arbitrary but rather tailored to optimize the efficiency of the testing and cutting procedures. The selected dimensions, specifically 190mm x 90mm x 50mm, were chosen to streamline the cutting and preparation of samples, aligning with the specifications outlined in various testing standards. This method allowed for consistency in sample preparation, ensuring that the specimens met the criteria set forth by different testing protocols.

In essence, the decision to determine specimen dimensions based on the characteristics of the machinery involved not only underscored a practical consideration but also aimed at harmonizing the sampling process with established testing standards. By doing so, the research maintained a methodologically sound approach, promoting precision and reproducibility in the analysis of brick samples.

The construction of the brick moulds was outsourced. A carpenter constructed all the brick moulds from plywood so that the samples had a neat finish in terms of shape as shown in *Figure*

4.6. These dimension of 190mm x 90mm x 50mm made it easier for the cutting and preparation of samples as required by the different testing standards.

Figure 4. 6: Construction of brick mould

4.4.3 Mixing of materials and the mixing process

The first step was batching in which sand and HDPE plastic was weighed using specified proportions as indicated in *Table 4.2*. The approved proportions of Kaolin Clay DSF, plastic and sand were mixed before feeding the mixture into the extrusion machine.

As explained by Thirugnanasambantham et al. [169] and Bhushaiah et al. [230], there are two types of mixing performed by hand using a steel rod and mechanical mixing. They caution on the use of these types of mixing processes since they have an impact on the uniformity and the strength of the resultant bricks. They argued that the mixing process must be thorough and consistent so that the mixture becomes homogeneous and uniform in colour. In this study, further mixing of materials was done in a controlled manner since it was fed into and mixed uniformly by the extruder.

4.4.4 Use of extruder

The extruder machine specifications include a single screw equipped with a 3-speed drive and four heating clamps. Following the standard operating procedure at DUT, the temperature range in the melting zone for HDPE is between 150 and 180 degrees Celsius. The dry blend was extruded at a temperature of 250°C [231]. Similarly, in the study conducted by Shiri et al. [232] the temperature of the extruder was preset to 250°C. This temperature was also used specifically to improve the workability of the composite material in its heated state. Omnexus [231] provided guidelines on the use of extruding HDPE at a melt temperature between 200 °C – 300 °C. Shah et al. [58] in their study stated that the extruder played a vital role in converting plastic waste into useful building materials and did not pose a threat to the natural environment. The extrusion machine was used from the Mechanical Engineering Department at the Durban University of Technology as indicated in *Figure 4.7*.

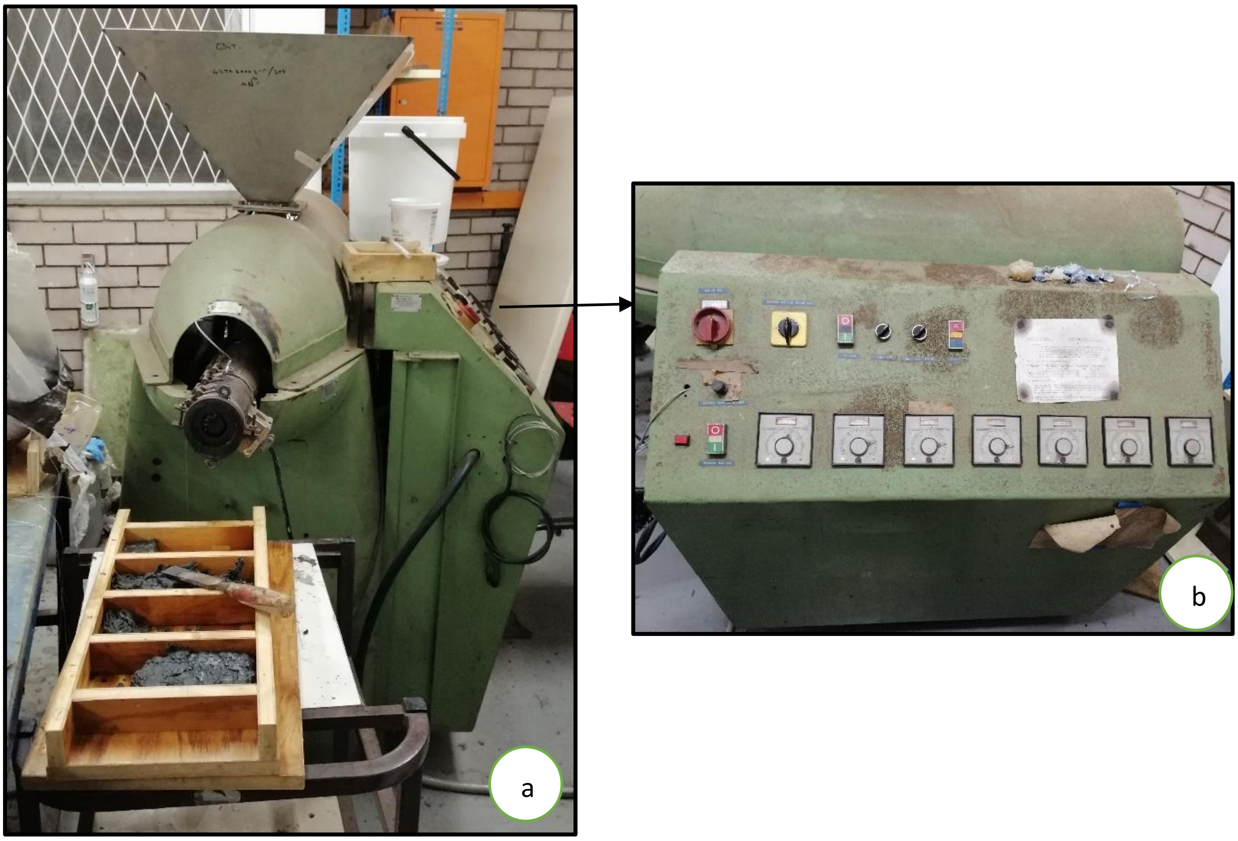


Figure 4. 7: (a) Extrusion machine and fabrication setup. (b) Extrusion machine control panel

4.4.5 Movement of composite from extruder into the moulds

It is important to note that before the homogenous mixture was placed into the brick mould, the mould was oiled.

The application of used car oil on the inner surfaces of the mould was compulsory since the solidification of the brick could pose a challenge. The utilization of car oil in the brick mould serves as a crucial step in the brick manufacturing process, and this practice is grounded in several solid reasons that contribute to the overall efficiency and quality of the production. These are some compelling reasons for using car oil in the brick mould:

Facilitates Easy Release and prevention of deformation

Car oil acts as a reliable releasing agent, creating a thin and uniform layer on the inner surfaces of the mould. This layer reduces friction and adhesion between the mould and the solidified brick, ensuring a smooth and effortless release of the finished product. This is particularly important in preventing the brick from sticking to the mould, which could otherwise result in damage during demolding. This is substantiated by Salahuddin and Zambani, who stated that before placing the mixture into the mould, make sure that, sides of brick mould are oild for easy removal of the bricks. This ensures a smooth and trouble-free demolding process. By oiling the sides of the mould, a crucial preparatory step is taken to facilitate the easy removal of the plastic-sand bricks [161]. The application of oil acts as a releasing agent, creating a lubricated surface on the inner walls of the mould. This lubrication minimizes friction between the plastic-sand mixture and the mould, preventing the mixture from sticking to the sides during the compaction process. As a result, the subsequent removal of the bricks becomes more efficient, reducing the risk of deformation or damage [233].

Cost-Effective Solution:

Car oil is a cost-effective releasing agent compared to some alternative solutions. Its availability and affordability make it a practical choice for manufacturers looking to optimize production costs without compromising on the quality of the final product. Therefore, the use of car oil in the brick mould is a strategic and practical choice driven by its effectiveness in ensuring easy release, preventing sticking and deformation, enhancing mould durability, cost-effectiveness, and compatibility with diverse mould materials. These reasons collectively contribute to a smoother and more efficient brick manufacturing process [158] [169].

The mixture was then placed into the brick mould as indicated in *Figure 4.8*. The molten mixture was levelled with a trowel into the brick moulds. All necessary safety precautions were adhered to during the entire experiment, more especially at the stage when receiving the molten mixture.

Figure 4. 8: Movement of composite to brick mould

4.4.6 Use of the hydraulic press

The hydraulic press was used at the Mechanical Engineering Projects Laboratory as shown in *Figure 4.9*. Once, the mixture was placed into the wooden mould, the hydraulic press was used to compact the mixture into the mould.

The manufacturing process of plastic-sand bricks involves a precise and controlled procedure where four full hand strokes of the ram are applied to the mold. This step is fundamental in shaping and compacting the plastic-sand mixture within the mold to achieve the desired form and structural integrity of the final product. Each hand stroke of the ram is a deliberate and calculated action, exerting pressure on the plastic-sand mixture within the mold cavity. This mechanical force serves to compress the materials, eliminating voids and ensuring a densely packed composition. The consistent application of four full hand strokes is essential for achieving uniformity and homogeneity throughout the entire brick. This controlled compression process is critical for the interlocking of sand particles with the plastic matrix, forming a cohesive and robust structure. The four strokes of the ram contribute to the compaction of the mixture, optimizing its density and overall strength. The precision in the number of strokes is a key factor in maintaining the integrity of the plastic-sand brick and meeting quality standards.

Furthermore, the sequential application of hand strokes facilitates the proper distribution of the plastic binder, ensuring that it effectively encapsulates the sand particles. This uniform distribution is vital for enhancing the overall durability, weather resistance, and structural stability of the plastic-sand bricks. Hence, the application of four complete hand strokes of the ram is a pivotal stage in the production of plastic-sand bricks. It is a controlled and deliberate process designed to compact the mixture, eliminate voids, and create a well-structured brick that meets the desired specifications and quality standards. After this process, the bricks were left in the laboratory for drying.

Figure 4. 9: Hydraulic press machine

4.4.7 Cooling of brick specimens

The plastic-sand brick samples were demoulded and were air cooled at room temperature for a period of 21 days before conducting the various testing. The duration of 21 days for drying bricks is a common practice in the construction industry and is often associated with the curing process rather than simply drying. Curing is a crucial step in the development of the mechanical and physical properties of concrete and certain types of bricks and blocks. It's worth noting that the specific curing duration can also be over 28 days based on factors such as the type of construction material, mix design, environmental conditions, and project requirements [142]. In some cases, accelerated curing techniques or alternative curing durations may be acceptable, depending on the specific characteristics of the bricks and the construction project. It's recommended to follow industry standards, specifications, and guidelines provided by relevant authorities or engineering organizations to ensure that the curing process aligns with best practices for the specific type of bricks being used.

4.5 Cutting process

A jig was made using a piece of timber which helped the plastic brick sample to slide against it while an angle grinder was used to cut it in dry form in *Figure 4.10 a)*. Plastic-sand brick samples were cut for each of the tests as indicated in *Table 4.3*. The samples were chosen from left, middle and the right at random as seen in *Figure 4.10 b)*. Each of the samples were examined for accuracy in size using the Vernier Caliper in *Figure 4.10 c)*.

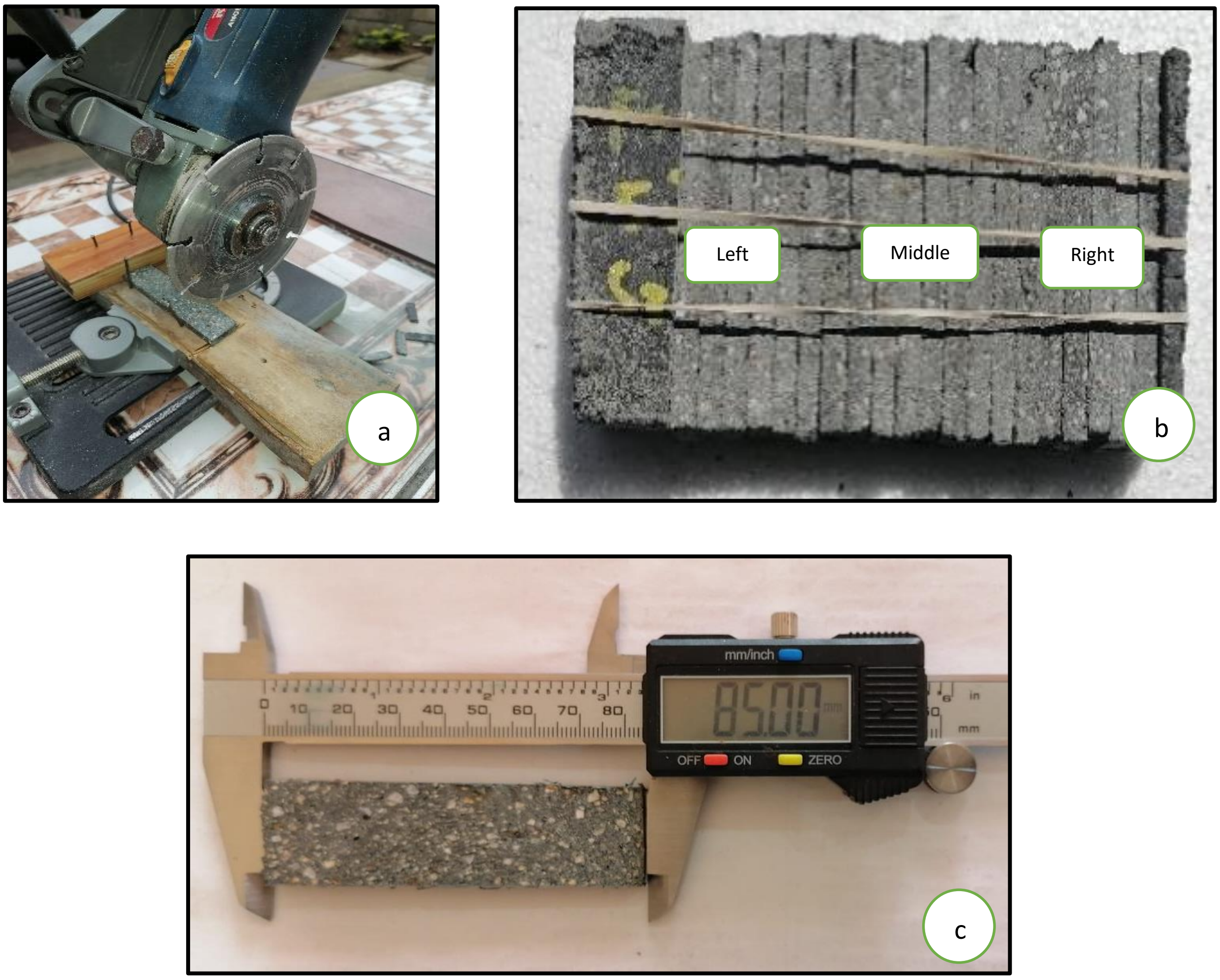


Figure 4. 10: Cutting and brick preparation of specimens: (a) cutting (b) batching (c) measuring of samples with a Vernier Caliper

Table 4. 3: Number of samples prepared for the different tests

Ratios	No of samples prepared for each of the tests: compression, impact, short beam tests, electrical resistance, water absorption , water contact angle, efflorescence test and fire resistance tests				
	O% Kaolin Clay DSF	1% Kaolin Clay DSF	5% Kaolin Clay DSF	10% Kaolin Clay DSF	
60s:40p	5	5	5	5	
65s:35p	5	5	5	5	
70s:30p	5	5	5	5	
75s:25p	5	5	5	5	
80s:20p	5	5	5	0	
85s:15p	5	5	5	0	
Total of samples prepared for each test	**30**	**30**	**30**	**20**	**110**

Sample dimensions

Figures 4.11- 4.14 indicate the sample dimensions that were machined for the nine tests.

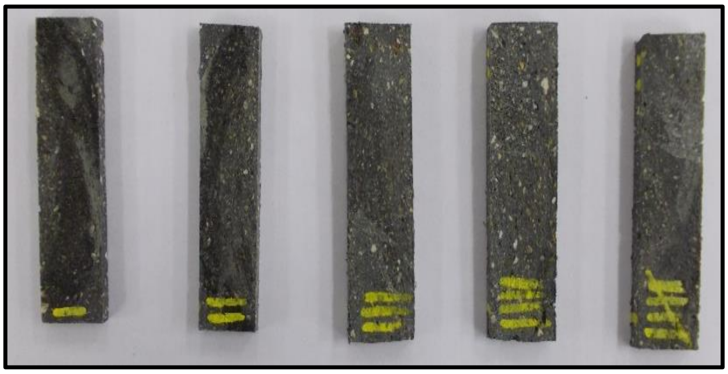


Figure 4. 11: Compression samples- 85x23x6mm

Figure 4. 12: Impact samples- 85mm (L) x 12.7mm (W) x 6mm (T) with a notch of 2mm depth was machined on all the specimens.

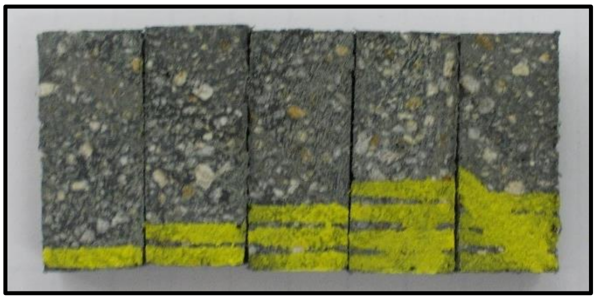


Figure 4. 13: Short beam samples- 36x12.7x6mm

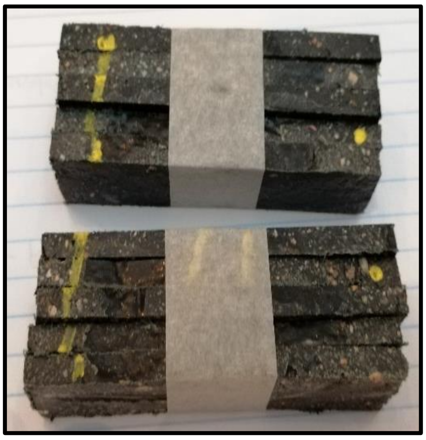


Figure 4. 14: Sample sizes for Hardness, Electrical resistance, Water absorption, Water contact angle, Efflorescence test, and Fire resistance- 85mm x 23mm x 6mm

4.6 Testing of prepared plastic-sand brick samples

Construction Materials Testing (CMT) [234] is also a regulatory requirement. The materials to be used in any building structure, such as a house, plays an important role in every project. Therefore, constructing a robust structure with high-quality approved materials is required. The construction material testing process assesses the quality, safety, efficacy, and endurance of the materials to be used for all construction purposes. Contractors are unaware of the quality of construction materials used. The testing processes within the supply chain are necessary to ensure the safety and integrity of the construction materials.

Various tests were undertaken to determine the properties of the plastic-sand brick samples. All the testing procedures were repeated for samples with 1%; 5% and 10% of the Kaolin Clay The outcome of the different tests on the plastic-sand bricks were benchmarked against the SANS 227 to confirm whether they are suitable as alternate building material for the construction industry. The prepared samples were tested in the Strengths of Materials Laboratory at DUT.

4.6.1 Mechanical properties

The reason for the choice of these tests and its relevance to this study

Despite the potential benefits of using plastic-sand bricks, it remains limited in the building industry. Therefore, there is a critical need to ensure that these bricks possess the required mechanical and environmental properties that adhere to specific alternative building standards within the construction sector [153]. Various authors have conducted comparative studies, testing plastic-sand brick samples using methods such as water absorption and efflorescence tests, which are relevant to this investigation, [233].

In their study, Athithan and Natarajan [235] emphasised that despite numerous studies conducted on the inclusion of plastic in building and construction materials, there is currently still a lack of sanctioned regulations and standards for upcycling plastic into building materials. The absence of established guidelines, particularly concerning procedures like disinfecting and processing plastic waste, highlights the need to carefully consider the ratio and nature of plastic waste obtained from various sources. Additionally, the study pointed out that there was a lack or limited confirmed ratios of polymer that can be utilized as a partial replacement for traditional building material ingredients. This further highlights the importance of developing accepted standards and guidelines to promote the responsible and effective upcycling of plastic waste in the construction industry.

The lack of adequate standards and regulations is hindering the large-scale production and widespread adoption of innovative bricks made from recycled waste materials. Additionally, the slow acceptance of these materials by the public and industry is also impeding their widespread application [156].

To address this gap, this study focuses on conducting nine relevant tests to assess the properties of these innovative plastic-sand bricks and to ensure their compliance with alternative building regulations. Among the tests, compressive strength and water absorption are particularly significant mechanical characteristics for construction materials. While the measurement of compressive strength has sparked debates, both compression and water absorption tests still remain important in various research endeavours [236]. These parameters are considered crucial by researchers, aligning with different standards [156]. Compressive strength, in particular, is a key indicator of a brick's suitability for construction purposes and is routinely assessed in the brick industry before using them in construction activities [237]. The subsequent sections explain the aims and procedures of each of these tests in detail.

4.6.1.1 Compressive test

The aim of this test is to measure the compressive strength of a brick, also known as its crushing strength [156] [238] [239]. This is a crucial test which is conducted to determine the brick's suitability for construction work [141] [230] [240]. The compression testing method is employed to understand how the brick behaves when subjected to a compressive load, measuring fundamental parameters that govern its behaviour under compression, squashing, crushing, or flattening [241]. Ultimately, this test serves as the primary means to evaluate whether the brick meets the required standards for use in construction projects.

It is a compulsory requirement that bricks must have a certain approved standard of a specified minimum compressive strength. If a brick satisfies a certain acceptable standard, then it is possible for such bricks to be used for different purposes in the construction industry. The minimum compressive strength of the clay brick that is acceptable according to the SANS 227 [217] is 7 MPa for non-facing plastered bricks, which is suitable for general building works. Any compression reading below 7 MPa, will be rendered unsuitable for any general building works or would be deemed rejected for the construction industry.

After the curing period of 21 days, the brick specimens were cut and prepared for compression testing at the Strength of Materials Laboratory in DUT. The average width, length and thickness of the test specimens were measured to the nearest 0.01mm with a Vernier Caliper and recorded on the software. The specimen was then placed into the compression tool, making sure that it was aligned to the centre of loading head as depicted in *Figure 4.15*. The parameters were inserted into the software with a testing speed of 1.3 mm/min as indicated in the ASTM Standard for compressive strength of plastics [242].

The bolts were hand tightened to ensure the specimen was held in place during testing. The crosshead of the testing machine was adjusted until the loading head made contact with the specimen. The prepared samples were tested using a calibrated machine to determine the compressive strength of the samples [243]. A load was applied without shock at a uniform rate on the full surface area of the specimen at a constant rate until it displayed physical signs of failure. The maximum load supported by the specimen was recorded. After the testing was conducted, the relevant values were obtained from the software. The procedure was repeated for the rest of the specimens.

The recordings were systematically captured for each of the specimens until failure. Compressive strength was calculated using the formula,

Stress = Maximum load divided by the area of the specimen = P/A

where, P -Maximum load (N) A - Area of the specimen (mm^2).

Five samples were tested one at a time for each category, with the average force being recorded as the compressive strength of the bricks. The MTS Criterion Model 43 30KN machine was used to conduct the compressive test for all samples in the different ratios in *Figure 4.15*.

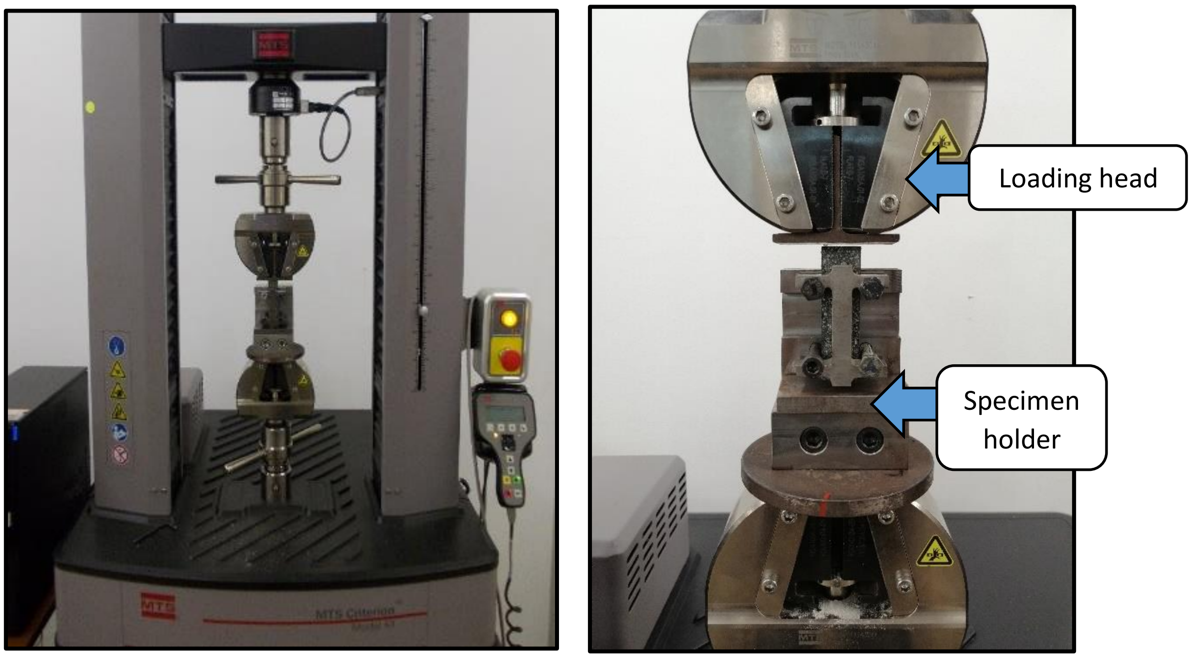


Figure 4. 15: a) MTS testing machine. b) compression test setup

4.6.1.2 Impact test

Naveen et al. [241] and Greene [244] explains that the aim of the impact test is to analyse the behaviour of a material when subjected to sudden and intense loading, leading to immediate deformation, fracture, or measures the material's resistance to impact loading before breaking,

This test helps determine the material's ability to withstand and dissipate energy under impact conditions [164]. Hence, the aim of the impact test is to assess the material toughness and its ability to absorb energy [245].

Illustrating the toughness of the specimen could be completed in many ways. Essentially, there are two main types of impact testing methods that can be carried out namely: The Izod and Charpy tests. Both these tests involve striking a standard specimen with a controlled weight in the pendulum (*Figure 4.16*) which is released or dropped at a set speed. The Charpy impact test was used for this study. The impact testing method on the specimen was generated as per the ASTM standard D6110-04, Standard Test methods for determining the Charpy impact resistance of notched specimens of plastic [245].

Figure 4. 16: Impact testing machine

The plastic-sand brick specimen was placed into the specimen holder of the machine and was supported at the two ends of the anvil. At the bottom most point of the circular path, the hammer was set to strike the opposite notch-facing side of the specimen [246]. The sample was fractured by the striker and also absorbed a measure of the kinetic energy of the hammer itself. With the remaining energy, the hammer continued to swing out onto its path. The amount of energy absorbed in fracturing the specimen was measured and this gave an indication of the toughness of the test specimen.

The notch impact energy indicates the energy required to fracture a specimen and therefore a measure of the toughness of the specimen. Five specimens in each of the categories were tested, the results averaged and recorded. The Charpy test was conducted in the DUT's Strength of Materials Laboratory at room temperature (between 22°C - 25°C), 24 hours after the notching procedure was completed.

4.6.1.3 Short beam shear test

The main aim of the short beam shear test is to understand the shear properties of the plastic-sand brick sample. As implied in its name, the short beam shear test subjects a beam to bending strain. However, the beam itself is very short in comparison to its thickness. The short beam test was used due to its simplicity and the convenient size of the test specimen. The "short beam shear" test is relatively fast, simple, and an inexpensive test to complete. Shear strength results are important to this study due to plastic-sand mixture being used [244].

Samples were placed one at a time in the calibrated MTS Testing Machine. Each of the samples were tested according to ASTM Standard D 2344, Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and their Laminates [247]. The average width, length and thickness of the test specimens were measured to the nearest 0.01mm with a Vernier Caliper and recorded on the software. The span was adjusted such that the span-to measured thickness ratio was 4.0. The supports were adjusted to a span length of 24mm. The jig was positioned such that the loading nose was located equidistant between the supports. The centre of the specimen was marked. The specimen was then inserted onto the short beam jig such that it rested on the supports as depicted in *Figure 4.17*, making sure that the marked centre was aligned to the centre of loading head. It was ensured that there was at least an overhang of the specimen of 2mm on both sides of the fixed supports. The parameters were inserted into the software with a standard testing speed of the cross head at 1.0 mm/min. The test was conducted at room temperature between 22 – 25°C.

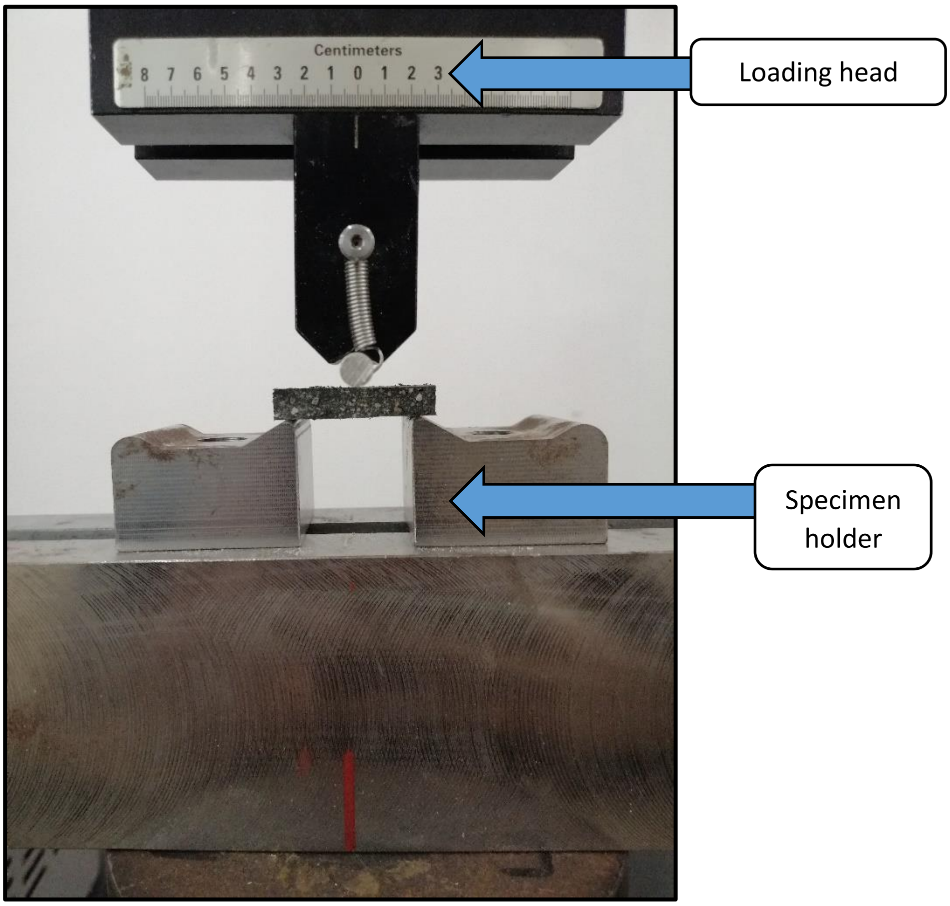


Figure 4. 17: Short beam testing setup

The maximum load supported by the specimen was recorded. The test was conducted and the relevant values were obtained from the software. The procedure was repeated for the rest of the specimens. The recordings were accurately captured for each of the specimens until failure. Five samples were tested one at a time for each category, with the average force being recorded as the short beam strength of the samples.

4.6.1.4 Hardness test

Hardness in bricks is commonly measured through various indentation methods. The nail indentation method is a simple way to estimate the hardness of bricks, but it doesn't follow a specific standard like some more precise laboratory methods. Instead, it is a field test that provides a quick assessment of the hardness of the material. Therefore, the nail indentation method has been used in this study as a quick field test by examining the type of impression which is seen on the plastic sand brick. If the nail makes little [248] or no indentation [155] [249] [250], the brick is considered relatively hard.

The main aim of the hardness test is to assess the brick's resistance to scratching [249]. It effectively measures the hardness of the brick, providing valuable information about this property [142] [250]. The primary aim of this test is to determine the brick's ability to withstand plastic deformation, penetration, indentation, and scratching, which collectively define the material's hardness [130]. Hence, the hardness test was completed to check the hardness property of the plastic-sand brick sample.

A nail was used as the tool to make an impression on the sample from left to right as illustrated in *Figure 4.18*. A hardness test was performed by pressing a nail into the surface of the plastic-sand brick sample. An impression was made from left to right on the surface of the sample. The hardness was determined by examining the depth of the indentation caused by the penetration of the nail. If there was a deep or surface indentation of the samples, the sample can be regarded as poor quality or good quality respectively [155] [163] [167] [169].

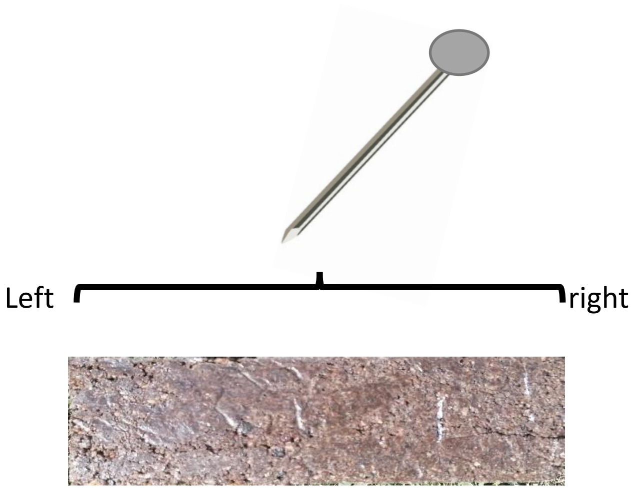


Figure 4. 18: Hardness testing

4.6.2 Environmental properties

4.6.2.1 Water absorption

The aim of this test is to determine the water absorption capacity of the brick [141] [237]. It involves measuring the amount of water absorbed by the brick when subjected to dampness. This test provides crucial insights into how effectively the brick resists moisture when exposed to damp conditions [249].

The water absorption samples were tested according to ASTM D570, Standard Test Method for Water Absorption of Plastics [251]. The first step entailed weighing and recording the 5 samples in each of the six categories in total dry conditions. Thereafter, the samples were immersed in distilled water for a period of 24 hours, 7 days, and 21 days to assess the water content absorbed by the sample under wet conditions as shown in *Figure 4.19*. The samples were taken out of the water after 24 hours, 7 days, 21 days and were wiped with a cloth. The wet samples were weighed again and recorded. In order to calculate the water absorption rate, the difference between wet and dry sample was noted. In essence, the difference is the actual amount of water absorbed by the brick after it was immersed into water.

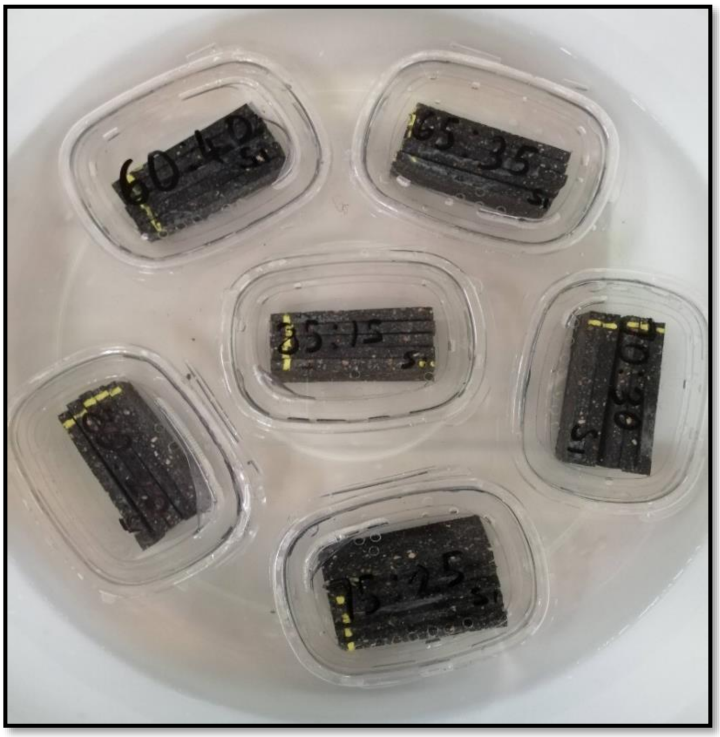


Figure 4. 19: Water absorption testing

The percentage of water absorption was calculated using the formula:

$$\text{Water absorption rate, } \% = \frac{\text{wet weight} - \text{conditioned weight}}{\text{conditioned weight}} \times 100$$

The water absorption reflects the bonding of all the bricks components. A good quality brick is known to absorb less amount of water. Hence, to rate a brick of good quality means that the water absorption needs to be less than 20% of its own weight [252]. A zero rate of absorption is not advised since a small amount of water absorption will prevent any possible cracks or defect in future [140]. The water absorption for all the samples after 24 hours, 7 days, 21 days were recorded using the template shown in *Table 4.4*.

Table 4. 4: Water absorption template for recording data

Ratio	Sample	Water absorption														
		Dry weight	Wet weight (24hrs)	Difference (24 hrs)	% (24hrs)	Average (24hrs)	Wet weight (7 days)	Difference (7 days)	% (7 days)	Average (7 days)	Difference	Wet weight (21 days)	Difference (21 days)	% (21 days)	Average (21 days)	Difference
60s: 40p	1															
	2															
	3															
	4															
	5															
65s: 35p	1															
	2															
	3															
	4															
	5															
70s: 30p	1															
	2															
	3															
	4															
	5															
75s: 25p	1															
	2															
	3															
	4															
	5															
80s: 20p	1															
	2															
	3															
	4															
	5															
85s: 15p	1															
	2															
	3															
	4															
	5															

4.6.2.2 Water contact angle

The aim of using the water contact angle test is to quantify the hydrophobic property and adhesiveness of the surface in respect of the plastic-sand brick sample [253].

The Ossila Contact Angle Goniometer as seen in *Figure 4.20*, was used to conduct, record and analyse the angle of one droplet of water on the surface of the plastic-sand brick sample. This testing method is regarded as a useful, indirect measurement of surface wetting. Wettability is the ability of the droplet of water to spread over the surface of the plastic-sand brick sample. It can be measured by the contact angle between the water and the sample surface.

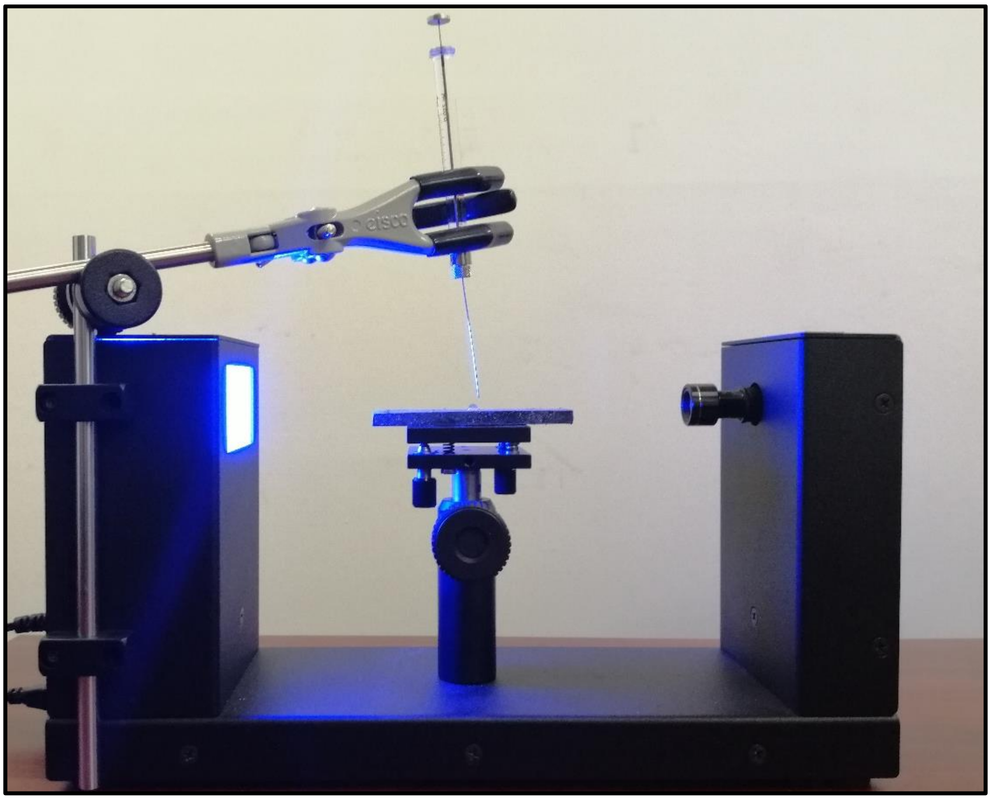


Figure 4. 20: The Ossila Contact Angle Goniometer

Using the water dropping tool, 25 μL of water was dropped on the surface of the plastic-sand brick sample that was placed on the stand of the Ossila Contact Angle Goniometer. The image of the water droplet was captured by the system. The spread on the surface was subjected to the intermolecular interactions between the sample and the water. The water contact angle was measured using the Ossila Contact Angle Goniometer. This instrument provided an indication of the wettability of the plastic-sand brick sample for each of the six categories including 1%, 5% and 10% of Kaolin Clay DSF were recorded using the template shown in *Table 4.5*.

Table 4. 5: Water contact angle recording template

Category	**Water contact angle**					
S:P	**Left Angle**	**Right Angle**	**Average left & right Angles**	**Average contact angle**	**Hydrophobic**	**Hydrophilic**
60s : 40P						
65s : 35P						
70s : 30P						
75s : 25P						
80s : 20P						
85S : 5P						
1% Kaolin						
60S : 40P						

65S : 35P						
70S : 30P						
75S : 25P						
80S : 20P						
85S : 5P						
5% Kaolin						
60S : 40P						
65S : 35P						
70S : 30P						
75S : 25P						

80S : 20P						
85S : 5P						
10% Kaolin						
60S : 40P						
65S : 35P						
70S : 30P						
75S : 25P						

According to ASTM D7334-08, Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement [254], if the recorded contact angle is above 45°C, the plastic-sand brick sample will have poor wetting characteristics i.e. it will resist water. This is called “hydrophobic” as indicated in *Figure 4.21*. On the other hand, if the contact angle is below 45°C, a term hydrophilic is used since the plastic-sand brick sample will actually absorb water as indicated in *Figure 4.21*.

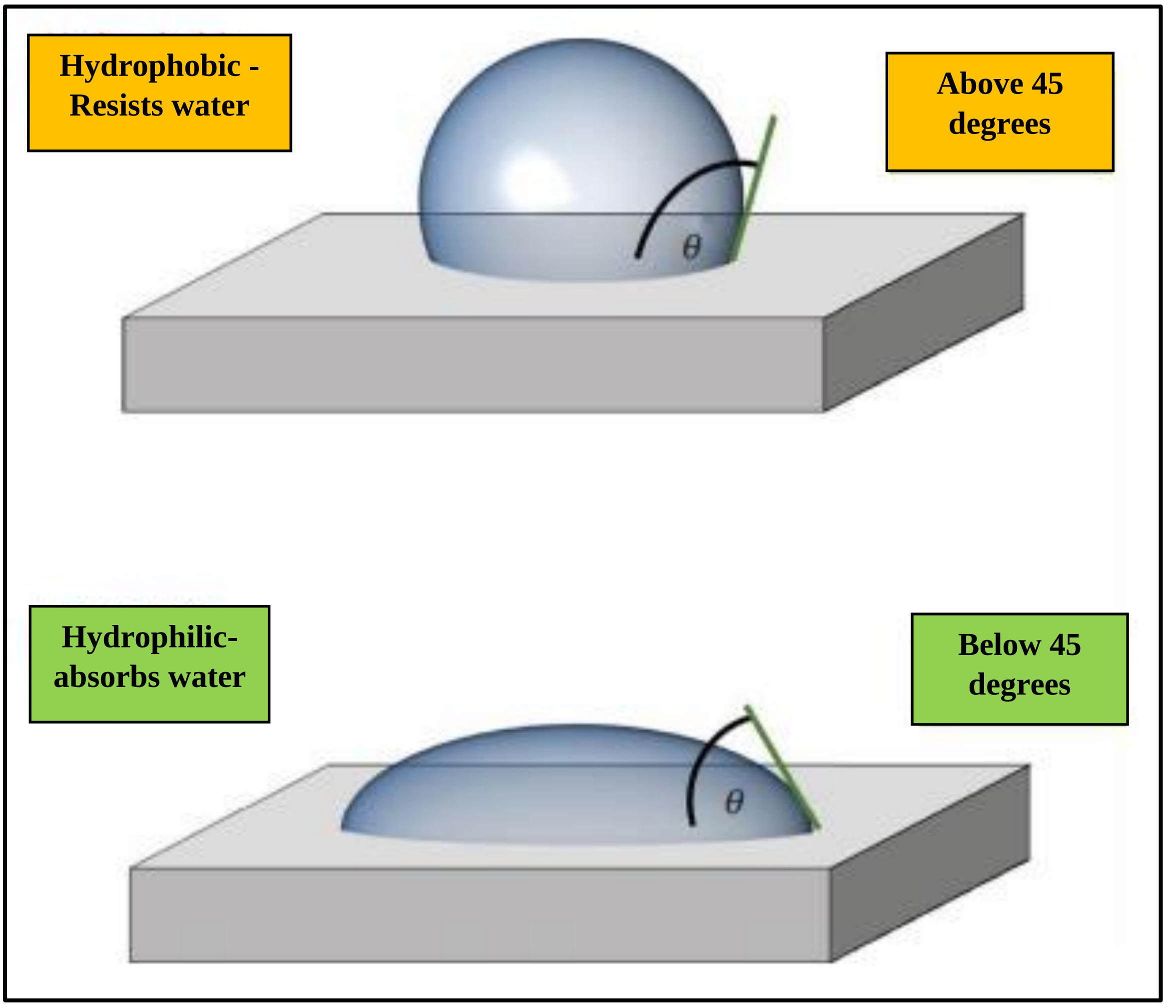


Figure 4. 21: Contact angle interpretation (Adapted from [255])

4.6.2.3 Efflorescence test

The aim of the efflorescence test is to detect the presence of alkalis on the plastic-sand brick sample [249]. Alkalis in bricks can be detrimental, leading to the formation of a grey or white layer on the brick surface due to moisture absorption. This test helps identify the presence of alkalis in bricks [156].

The efflorescence test was conducted according to SANS 227 [217]. This test determines the presence or amount of alkalis on the bricks. The presence of alkali is harmful since they form a grey or white layer on the surface of the brick caused by absorbing moisture. In order to check the presence of alkalis in bricks an efflorescence test is conducted.

Efflorescence is a crystalline, salty deposit that can be visibly seen on the surfaces of bricks. It is generally seen to be white with a powdery appearance. Each of the test samples were immersed in a tub containing 300 ml of distilled water and situated in a well-ventilated room at the laboratory of Durban University of Technology. The brick samples were immersed between 25 mm and 40 mm of distilled water. The water was then allowed to evaporate. When the samples appeared to be dry, a further 300 ml of distilled water was filled in the tub. The samples were left immersed in the tub in a well-ventilated room of temperatures between 20-30°C until all the water evaporated. When the distilled water evaporated and the samples had dried out, visual examination of the degree of efflorescence of each sample was evaluated using the rubric shown in *Table 4.6*.

Table 4. 6: Criteria to determine amount of efflorescence [156] [169]

Nil	0% on the surface of brick	When there is no visible deposit of efflorescence present
Slight	➢ 10% on the surface of brick	If there is alkali (whitish layer) on 10% of brick surface.
Moderate	➢ Around 50% on the surface of brick	If the whitish layer covers around half of the brick, then a moderate alkali is presence.
Heavy	➢ 50% on the surface of brick	There is an absence of powdering or flacking on the brick surface
Serious	➢ More than 50% on the surface of brick	There is visible, heavy deposit of alkali with the presence of powdering and/or flacking on the surface of the brick.

4.6.2.4 Electrical resistance

The aim of the electrical resistance test is to measure the intrinsic property of the plastic-sand brick sample that quantifies the degree to which the material opposes the flow of electric current. It measures the material's resistance to the passage of electric current through it [256].

Table 4.7 indicates the plastic-sand brick samples which were tested for electrical resistance in the six ratios.

Table 4. 7: Test samples for electrical resistance

Ratio	Sand: Plastic + 1% Kaolin	Sand: Plastic + 5% Kaolin	Sand: Plastic + 10% Kaolin	Clay brick (Control sample)
60:40	60:40	60:40	60:40	A clay brick was purchased from the hardware store as a control sample.
65:35	65:35	65:35	65:35	
70:30	70:30	70:30	70:30	
75:25	75:25	75:25	75:25	
80:20	80:20	80:20	-	
85:15	85:15	85:15	-	

Two methods of verification for electrical resistance was used. *Firstly*, the test specimens were connected in series to a matrix direct current (DC) power supply unit and a Fluke 177 True RMS ammeter to measure if the material specimen conducted electrical current. Each of the categories were tested as indicated in the *Table 4.7*. It was ensured that these specimens were cleaned and free from any impurities. Each specimen was connected in series to the power supply and ammeter with the electrodes to measure if there was any flow of current as illustrated in *Figure 4.22*. To ensure the efficiency of the procedure and confirm the ammeter's accurate reading of current flow, the electrodes were disconnected from the specimen after each test. They were then connected to a resistor on a breadboard, allowing the ammeter to verify the current flow from the power supply, as shown in *Figure 4.23*. This process was repeated for all ratios in each category.

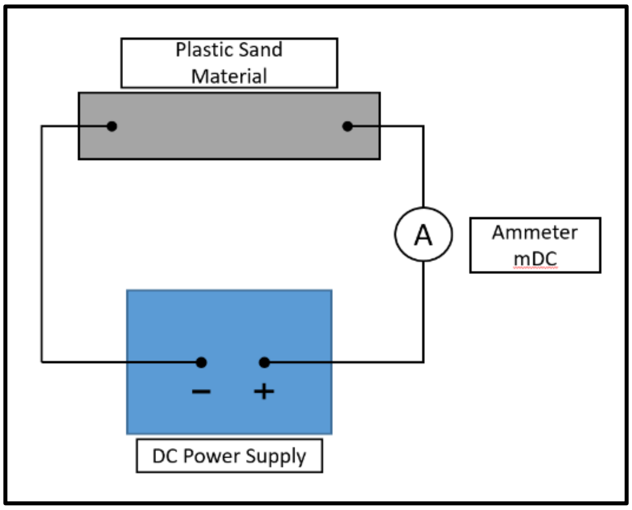


Figure 4. 22: Specimen connected in series with power supply and ammeter

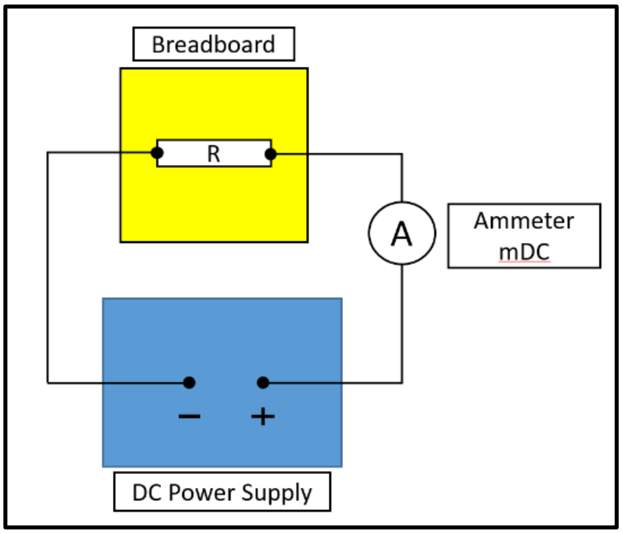


Figure 4. 23: Resistor connected in series with power supply and ammeter

The second method of verification was to test for electrical circuit continuity. This is to check for the existence of a path for electrical current to flow through. Continuity is when there is no break in the circuit and when the switch is closed for electrical current to flow. A UNI-T clamp meter was connected in series with the test specimens to check for continuity in the electrical circuit.

Each specimen was connected in series to the clamp meter to test for continuity as illustrated in *Figure 4.24*. The electrodes from the clamp meter were placed on either ends of the specimen for this test. To verify this procedure, after each test specimen, the electrodes were removed and placed on either ends of the resistor on the breadboard as illustrated in *Figure 4.25* and a ringing sound should be observed. This would mean that there is continuity in the resistor and that it is a conductor. Both of the above tests were conducted on the clay brick as the control sample.

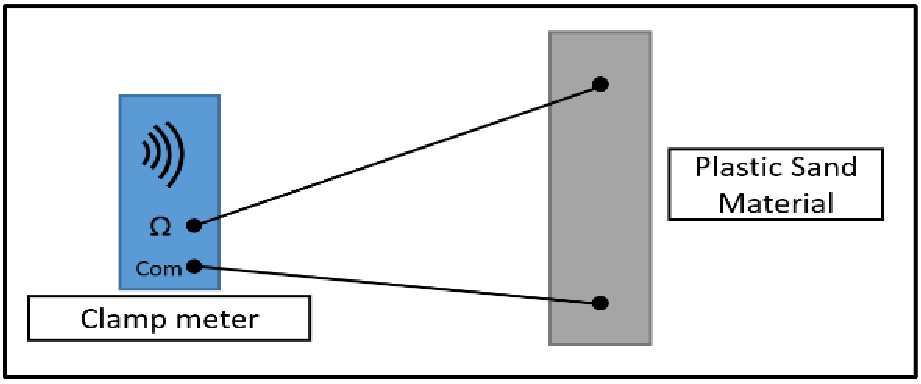


Figure 4. 24: Clamp meter connected in series with test specimen

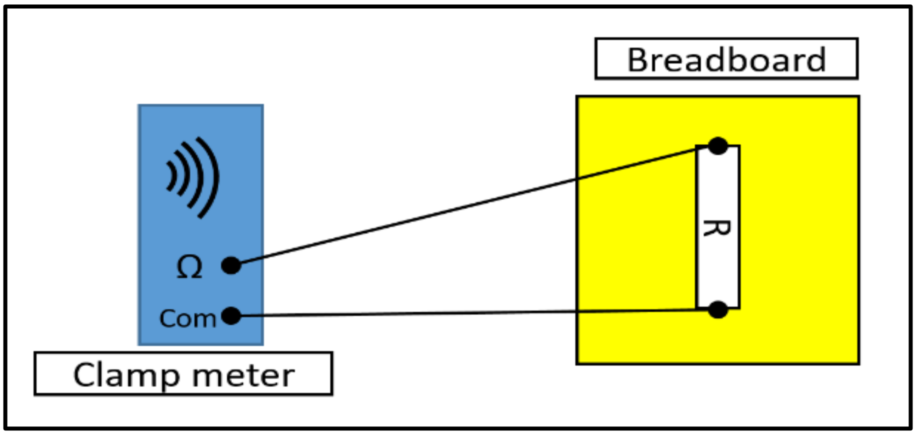


Figure 4. 25: Resistor connected in series with clamp meter

4.6.2.5 Fire resistance

The aim of the fire resistance test is to measure the linear burning rate of the composite polymer material and report on rate of burning per minute [257]. Good quality of houses and buildings that are constructed from relatable fire-resistant materials would prevent tragedies. Hence, structures constructed from these types of materials would burn slowly allowing enough time for the people to take safety measures [258].

The rate of burning for plastic samples was done according to ASTM D635 – 18, Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position [257]. Plastic in its natural form is highly susceptible to fire. However, in this study, the plastic-sand brick samples being tested is manufactured from plastic, sand and Kaolin Clay

DSF mixture. It is anticipated that the presence of sand and Kaolin clay should provide insulation.

The fire resistance test was conducted for this study under laboratory conditions to investigate the linear burning rate of the plastic-sand brick samples. The plastic-sand brick sample was marked at 6mm and 25mm from the right-hand side of the burn end as indicated in *Figure 4.26*

Figure 4. 26: Marking of the specimen

The sample was supported horizontally on a laboratory test fixture on the left end. A butane burner was ignited and the gas supply was adjusted such that it produced a yellow- tipped blue flame with a length of 20mm. The butane burner as indicated in *Figure 4.27* was placed such that the yellow- tipped flame impinges 6mm on the free end of the test sample. The flame was applied for 30 seconds without changing its positions. The burnt length and time have been recorded and the linear burning rate was calculated as follows:

$$V = 60L/t$$, where:

V= Linear burning rate, in millimeters per minute (mm/min)

L = the burned length, in millimeters (mm)

t = the time, in seconds (s)

Figure 4. 27: Fire test procedure using the butane burner

4.6.2.6 Surface Electron Microscope analysis

SEM is known to be another convenient analysis which provides information and details of the sample's surface and as well as its composition. SEM is a fast scanner that provides accurate details of all surface information. The SEM analysis was conducted by Caleb Analytical Solutions based in Johannesburg. The analysis was completed for each ratio with varying percentages of Kaolin Clay DSF to ascertain the surface details checking for any cracks, fractures or any other flaws and to provide more information of the internal and microstructural aspects of the brick samples [259] [260]. The morphological comparative study was conducted on plastic-sand brick samples using an SEM apparatus VEGA3 TESCAN scanning electron microscope operated at 20.0 kV.

4.7 Conclusion

This chapter focused on the experimental method of preparing the plastic-sand brick composite material with varying ratios of plastic and sand with the addition of 1%, 5% and 10% of Kaolin Clay DSF using the extrusion method. This methodology was carried out to investigate the effects of Kaolin Clay DSF on the mechanical and environmental properties. Nine tests were planned to evaluate the validity and reliability of this research. The SEM investigated the internal and microstructural characteristics of the composite material.

CHAPTER 5

MECHANICAL PROPERTIES: FINDINGS AND DISCUSSION

5.0 Introduction

In this chapter, the findings, interpretation, and discussion of the experimental tests conducted on the plastic-sand brick samples are presented. The focus is on the quantitative data that has been collected and analyzed. The discussion is supported by the use of tables, bar graphs, line graphs, and images to enhance the understanding and visualization of the results.

The tests were conducted on two stages of samples, each manufactured with different ratios of materials. The first stage of tests involved using only HDPE polymer and sand. The second stage of tests examined the effects of adding 1%, 5%, and 10% of Kaolin Clay DSF to the HDPE polymer and sand mixture in various ratios ranging from 60s:40p to 85s:15p.

The primary objective of adding varying percentages of Kaolin Clay DSF to the mixture was to determine the effects of the Kaolin Clay DSF on the mechanical properties of the proposed eco-friendly brick intended for use in the construction industry. By conducting the tests and analyzing the data, it was aimed to evaluate the impact of the clay additive on properties such as compressive strength, short beam strength, impact strength and hardness.

The quantitative data collected from the tests, along with the images, allow for a detailed interpretation and discussion of the results. Trends and comparisons of the performance of different ratios and additive percentages, and conclusions were made regarding the optimal combination for achieving the desired mechanical properties of the plastic-sand bricks.

5.1 Results for initial testing

5.1.1 Sieving of sand- Particle size distribution

The sorting of sand particle distribution was done according to standard sieves that were in line with the requirements of SANS 201 [261]. The sieving of sand was carried out with 4.75mm sieve in order to take the required particle size of sand. The sieving process was compulsory to remove any large size aggregates from the sand.

5.1.2 Thermogravimetric Analysis (TGA) & Differential Scanning Calorimetry (DSC)

In the TGA, it will be easier to monitor the mass of the raw materials while heat is produced at a constant rate over a certain period of time. Nitrogen was used at a ramping rate of 10 °C per minute. This aim is to measure the sample in terms of its thermal stability and its fraction of volatile components by carefully checking the changes of weight if any that occurs as the sample is heated at a constant rate [262] [263] [264].

DSC was used to measure how much energy the raw materials absorbs or releases during the period of heating or cooling. Both TGA and DSC tests were run simultaneously in order to obtain more useful information as compared to running only one of them [262] [263] [264]. Tests for the raw ingredients (TGA and DSC) were initially run before the actual sample preparation. The results for the ingredients give us information about the processing parameters of the actual samples.

Figure 5.1 shows the thermal analysis of HDPE plastic. This recycled HDPE plastic seems to be thermally stable until 390 °C. The HDPE plastic starts to decompose slowly after 390 °C until 450 °C and then there is a sharp and significant reduction in weight from 450 °C to 500 °C. The largest and only loss of mass in HDPE was found to be between 390 °C - 500 °C in which over 90% of its mass was decomposed that could be due to the burning of the plastic. Two main endothermic peaks were observed at 135°C and 485 °C which is the result of the plastic melting and burning and one exothermic reaction between 500 °C.

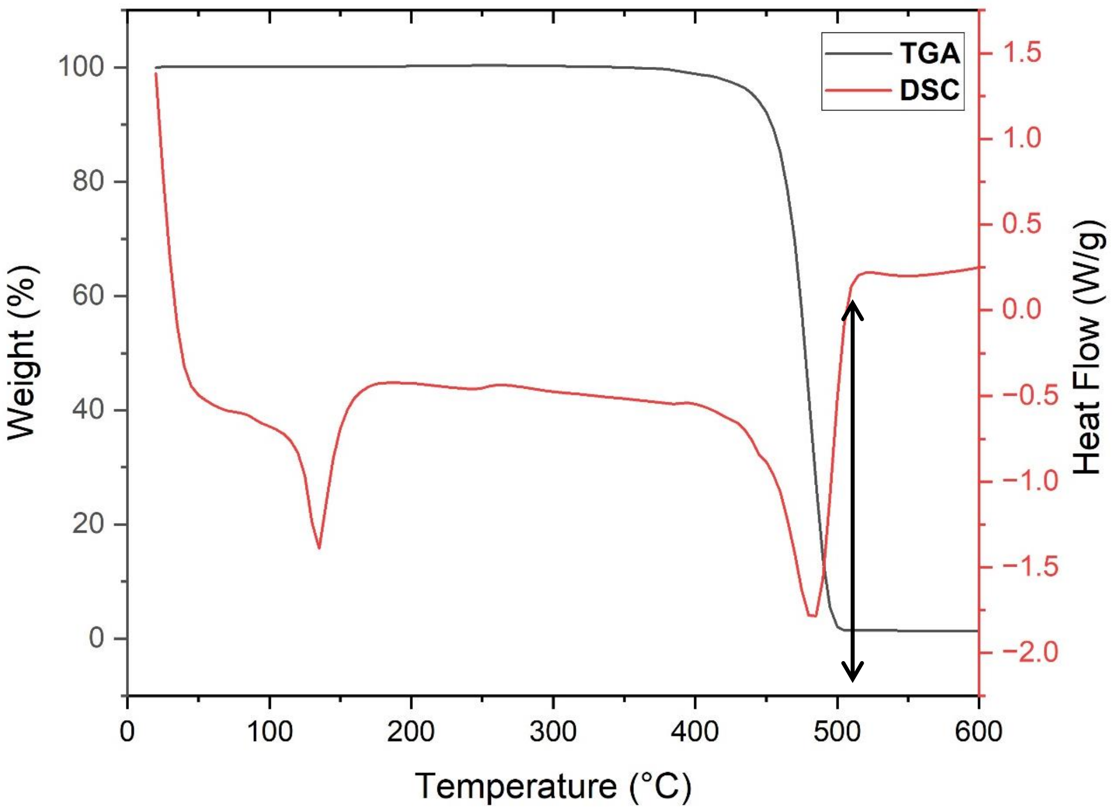


Figure 5. 1: Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) of HDPE plastic

The observations for this study were similar to other researchers. The studies conducted by Chrysafi et al. [265] using neat and recycled HDPE showed that degradation started at approximately 350 °C and ended at 540 °C. When both the neat and recycled plastic was evaluated, the results for the endothermic peaks were 144°C and 139°C respectively. The exothermic peak during cooling for the neat and recycled HDPE was observed at 108°C and 107°C respectively. This result could be attributed to crystallization. In another study conducted by Sustaita-Rodríguez et al. [266], at the 10°C /min the first change occurred at approximately 415°C and the total degradation of the HDPE plastic was observed at 492°C.

Figure 5.2 showed the thermal profile for river sand to 1000 °C. It was found that 0.16% weight of river sand was lost between room temperature and approximately 125 °C due to i) the evaporation of water that was still present in the river sand during testing. The largest loss of mass in the river sand of 0.31% was found to be between 230°C - 660 °C in which a multistage decomposition can be seen, ii) this could be due to other impurities in the river sand such as wood particles, salts and organic matter. The river sand stabilizes at approximately 665 °C and starts to lose mass gradually as the temperatures increased. River sand was analysed and it was still thermally stable up to 1000 °C since only 0.53% of its weight was lost which included impurities and water. Two endothermic reactions were noticed at 45 °C which could be the result of water evaporation and one at approximately 575 °C. The observed phenomenon can be attributed to the endothermic process of dehydroxylation or dehydration, leading to the formation of disordered metakaolin. Exothermic reaction at 1000 °C could be the development of newer crystalline phases in the sand.

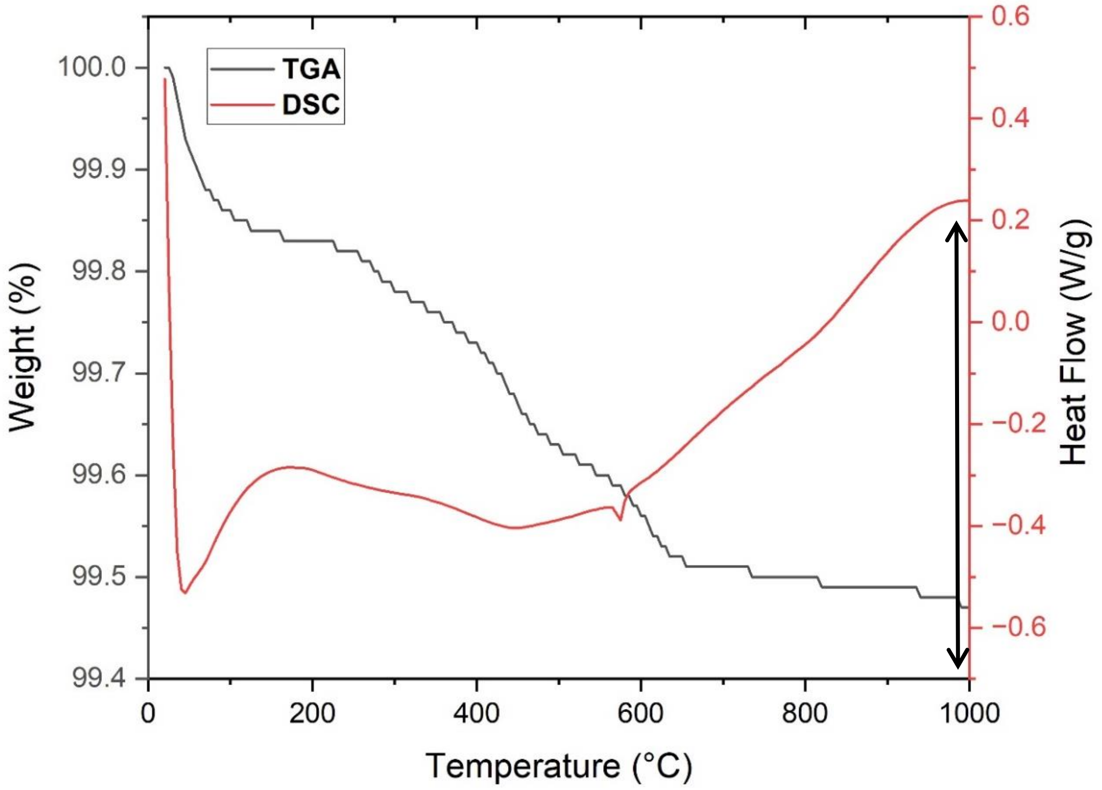


Figure 5. 2: Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) of river sand

The results of this study conducted by Meradi et al. [267], yielded findings regarding the thermal properties of the material. The TGA curves revealed three distinct mass losses. The first weight loss of approximately 3.2% observed between room temperature and 600°C. The second weight loss of approximately 2.63% occurred between 600°C - 800°C. Finally, the last weight loss of approximately 0.41% was recorded between 800°C - 1100°C.

In the DSC curve, three endothermic peaks were observed at temperatures of 68.9°C, 574.7°C, and 723°C, respectively. Additionally, one exothermic peak was observed at 935.4°C. The first endothermic peak at 68.9°C was attributed to the evaporation of absorbed water within the sand. The second peak at 574.7°C suggests the transformation of the sand into quartz. The third endothermic peak at 723°C corresponds to the formation of siloxane bridges resulting from the dehydroxylation of isolated silanol groups on the internal surface of the sand. *Lastly*, the exothermic peak at 935.4°C indicates crystallization processes taking place within the material.

The TGA was conducted for the additive Kaolin Clay DSF up to a temperature of 1000 °C in *Figure 5.3*. The first loss of 2.11% of Kaolin Clay DSF was found to be between room temperature to 120 °C. The main mass loss of Kaolin Clay DSF was found to be between 400 to 700 °C where a further 5.28% was burnt. The total weight loss of Kaolin Clay DSF at 1000 °C s is 9.03%. Two endothermic peaks were observed at 50 °C and 485 °C and one exothermic peak at 990 °C which could be attributed to the development of newer crystalline phases.

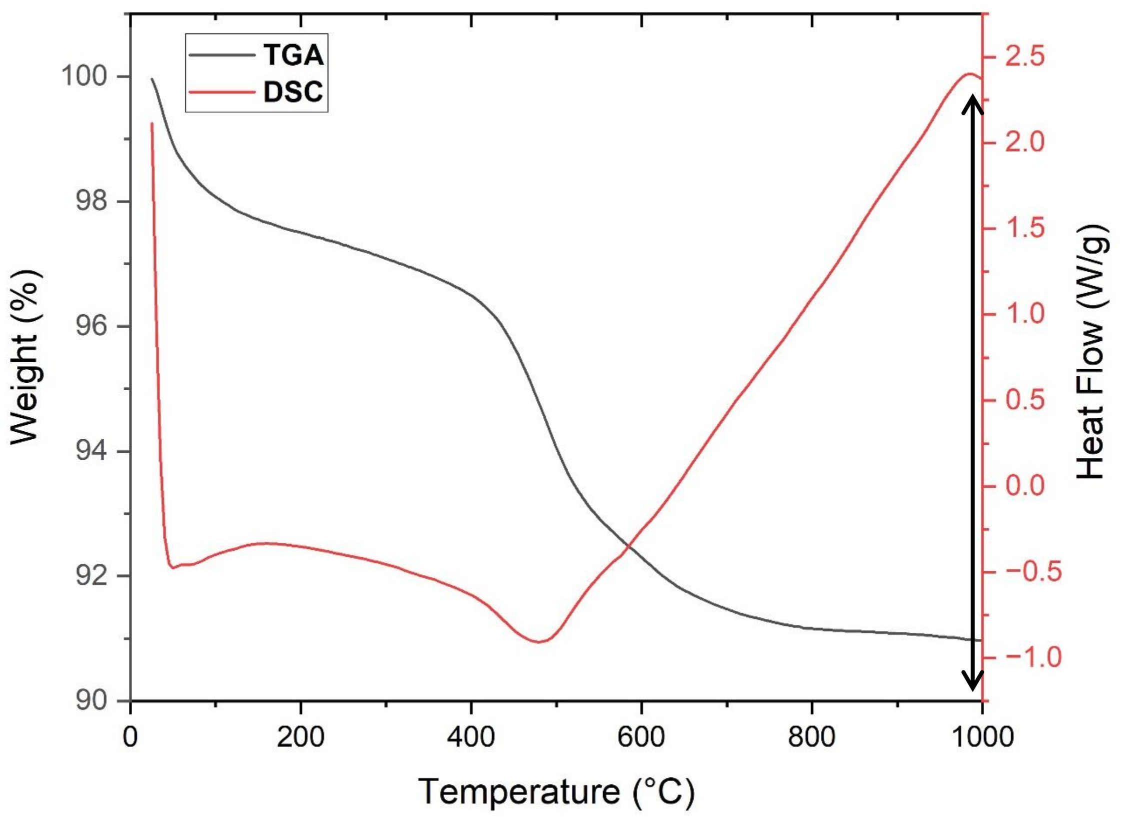


Figure 5. 3: Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) of Kaolin Clay DSF

Interestingly, two studies showed similar patterns of thermal behaviour. In the study conducted by Wang et al. [268], the thermal behavior of the kaolin samples were analyzed using TG-DTA curves in the temperature range from room temperature to 1200 °C. The first endothermic mass loss was observed between 20-200 °C, which can be attributed to the evaporation of moisture present in the sample. The main endothermic mass loss occurred in the range of 450-600 °C, with the minimum weight loss observed above 500 °C. This significant mass loss in the 450-600 °C range can be attributed to the endothermic dehydroxylation or dehydration process, leading to the formation of disordered metakaolin. The dehydroxylation process continued up to 900 °C, indicating the gradual transformation of metakaolin into a more stable phase. The exothermic peak observed above 1000 °C indicates the formation of a crystalline phase.

In another investigation conducted by Sahnoun and Bouaziz [269] the curves of the DTA thermogram of raw kaolin, exhibited two endothermic peaks between 150-520 °C, as well as an exothermic peak at 975 °C. The initial endothermic peak corresponds to the clay's dehydration process. The TG curve of the raw kaolin demonstrated a substantial weight loss of 12.5%, which is attributed to the dehydroxylation of the kaolin at 520 °C. The exothermic peak at 975 °C implies the conversion from metakaolin to mullite.

Consolidated analysis

The thermal analysis of the raw materials revealed important insights. *Firstly*, the recycled HDPE plastic exhibited degradation starting at approximately 390°C to 500°C, with over 90% of its mass decomposed. *Secondly*, river sand demonstrated excellent stability even at high temperatures of 1000°C, with only a minimal mass loss of 0.53%. *Lastly*, Kaolin Clay DSF displayed significant decomposition occurring between 400-700°C.

Considering the processing parameters of the extrusion machine, it can be concluded that all the raw materials were processed well below their respective degradation temperatures, specifically at 250°C. As a result, conducting Fourier Transform Infrared (FTIR) test analysis of the raw materials was deemed unnecessary since there were no chemical reactions expected to occur during the fabrication of the plastic-sand brick samples at 250 degrees. This aligns with the findings of Singh et al. who conducted TG-FTIR analysis on waste HDPE plastic and observed no formation of gases below 350 °C [270].

Based on these conclusions, it can be inferred that FTIR analysis was not required in this study as the thermal properties of the raw materials and the processing temperatures ensured the absence of significant chemical reactions.

5.1.3 Density and Void Volume

Density is a key property to study composite materials consisting of multiple distinct components, particularly within the context of the building and construction sector. Theoretical density is assessed by applying the composite material's rule of mixtures [271] and it is determined through the utilization of the equation below. The experimental density is determined by employing the ASTM C 271-94 standard.

$$\rho_{th} = (\left(\frac{W_{fs}}{\rho_{fs}}\right) + \left(\frac{W_m}{\rho_m}\right) + \left(\frac{W_{fc}}{\rho_{fc}}\right))^{-1}$$

Where:

ρ_{th}= Theoretical density; ρ_{ex}= experimental density; W_{fs}= weight fraction of filler sand; ρ_{fs}= density of filler sand; W_m= weight fraction of matrix HDPE; ρ_m= density of matrix HDPE; W_{fc}= weight fraction of Kaolin Clay; ρ_{fc}= density of Kaolin Clay; ρ= density; m= mass; V_v= void volume

The void volume within a composite material refers to the gaps existing between the material's components. This is a pivotal aspect that serves as an indicator of the construction material's quality. The void volume plays a significant role in determining the material's strength, weight, insulation properties, and overall performance. To quantify the void volume, the equation below was used to calculate the difference between the theoretical and experimental densities.

$$V_v = \frac{(\rho_{th} - \rho_{ex})}{\rho_{th}} * 100$$

Table 5.1 indicates the calculated densities for river sand and HDPE, whereas the density value for Kaolin Clay was obtained directly from the supplier. *Table 5.2*, on the other hand, illustrates the theoretical and experimental densities for six different ratios, each showing the additions of Kaolin Clay at levels of 0%, 1%, 5%, and 10%. As the proportion of sand increases and plastic content decreases, the density of the composite material rises [272]. The incorporation of Kaolin Clay, ranging from 1% to 10%, consistently leads to a reduction in the density of the composite material. This pattern of results is similarly observed in the experimental density measurements.

Table 5. 1: Density of materials

Material	**Density (g/cm³)**
River sand	2.68
HDPE	0.95
Kaolin Clay	0.65

Table 5. 2: Theoretical density, experimental density and void volume of composite material

MIXING RATIO	Theoretical Density				Experimental Density				Void volume			
	0%	1%	5%	10%	0%	1%	5%	10%	0%	1%	5%	10%
60s:40p	1.55	1.53	1.45	1.38	1.43	1.44	1.39	1.35	7.74	5.88	4.14	2.17
65s:35p	1.64	1.61	1.53	1.44	1.51	1.49	1.45	1.40	7.93	7.45	5.23	2.78
70s:30p	1.73	1.71	1.61	1.51	1.59	1.58	1.52	1.46	8.09	7.60	5.59	3.31
75s:25p	1.84	1.81	1.69	1.58	1.66	1.65	1.60	1.52	9.78	8.84	5.33	3.80
80s:20p	1.96	1.93	1.79	-	1.76	1.75	1.68	-	10.20	9.33	6.15	-
85s:15p	2.11	2.06	1.90	-	1.88	1.86	1.78	-	10.90	9.71	6.32	-

Upon analyzing the calculated theoretical and experimental densities, it becomes apparent that the experimental density values are consistently lower than the theoretical density values. This can be attributed to the existence of voids within the composite material, a consequence of the sample preparation process [273]. In *Table 5.2*, the void volumes were systematically calculated for the six composite material ratios. Notably, an increase in the sand content correlates with a higher void volume, given that sand possesses relatively high density within the composite material. Conversely, the incorporation of Kaolin Clay results in a corresponding reduction in void volume. This phenomenon can be attributed to Kaolin Clay which acts as a filler material, reducing pore and void spaces within the matrix [227]. This observation aligns with the findings of the SEM void analysis.

The variance between theoretical and experimental density values in the composite material primarily arises from the presence of these pore and void spaces within the matrix structure. These voids can have negative effects on mechanical properties, consequently impacting the composite material's suitability for construction applications [274]. Specifically, they can lead to reduced compressive strength, which poses a potential risk to the structural integrity of buildings and structures.

5.2 Mechanical properties

5.2.1 Compressive strength test

Table 5.3 indicates the compressive strength of different ratios of plastic and sand with varying percentages of Kaolin Clay DSF. This table will be used as a reference regarding the comparative strength values in this section. This discussion of the compressive stress-strain curves will be included as they are important and displays the relationship shared between the stress which is the force that is applied to the material and the strain which tells us the amount of deformation that occurs. From examining the stress- strain curves, we can determine many different characteristics which is important for design application. We can calculate mechanical properties such as the ultimate strength, yield strength, elongation and modulus of elasticity. These curves provide important insights to understand the behavior of the materials and for us to understand them better.

Table 5. 3: Average compressive strength (MPa)

RATIO	0% KAOLIN CLAY DSF	1% KAOLIN CLAY DSF	5% KAOLIN CLAY DSF	10% KAOLIN CLAY DSF
Sand: Plastic	**Average Force**	**Average Force**	**Average Force**	**Average Force**

	(MPa)	(MPa)	(MPa)	(MPa)
60s:40p	20,28	18,94	32,24	26,45
65s:35p	22,12	17	40,24	23,36
70s:30p	21,94	19,04	36,96	21,74
75s:25p	21,4	18,5	52,76	19,1
80s:20p	19,58	19,02	38,34	-
85s:15p	25,24	18,6	35,14	-

Plastic: sand replacement Vs Ave. Compressive strength

Figure 5.4 shows the average compressive strength of the plastic-sand brick samples and *Figure 5.5* illustrates the stress-strain curves with 0% of Kaolin Clay DSF. This indicates the highest compressive strength of 25.24 MPa in the 85s:15p ratio, without the addition of Kaolin Clay DSF. The compressive strength of the plastic-sand brick samples is predominantly influenced by the sand concentration. The compressive strength increased when the sand content increased and the plastic content decreased. The presence of the HDPE polymer as a binder and the interfacial connection with the sand particles play significant roles in achieving the desired compressive strength properties.

However, there was a significant decrease in strength, from 22.12 MPa to 19.58 MPa, as the sand content increased. This can be attributed to the concurrent reduction in plastic content from 35% to 15%. The combination of the 85% sand and 15% plastic, and 0% Kaolin Clay DSF ratio seems to exhibit a synergistic effect, where the properties of the materials work together to enhance the compressive strength.

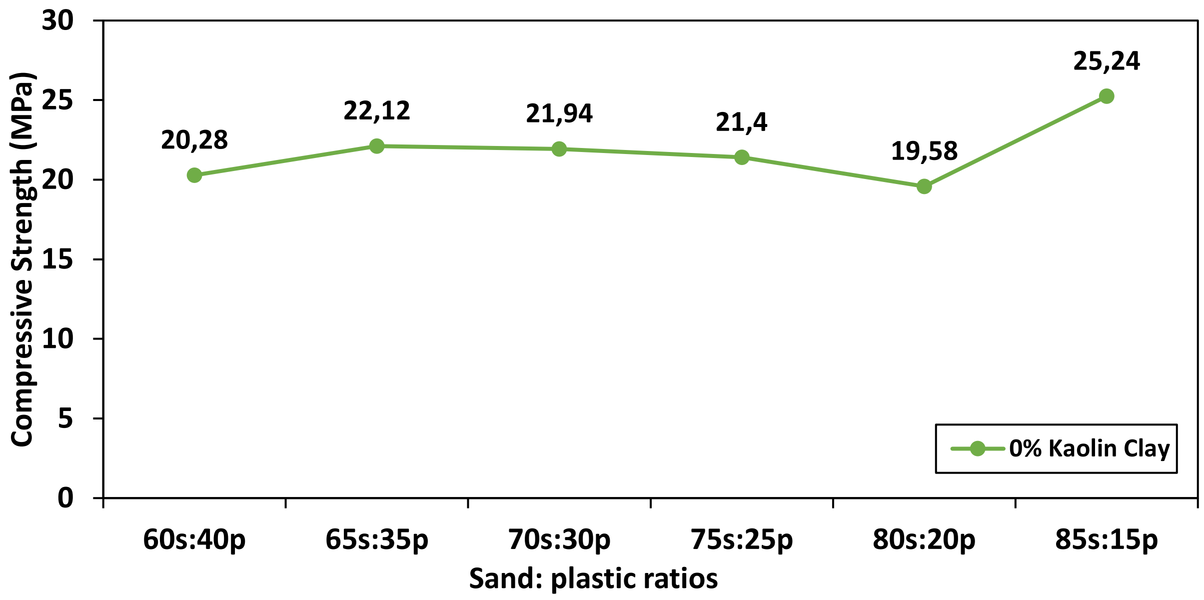


Figure 5. 4: Average compressive strength of sand-plastic mixture at 0% Kaolin Clay DSF

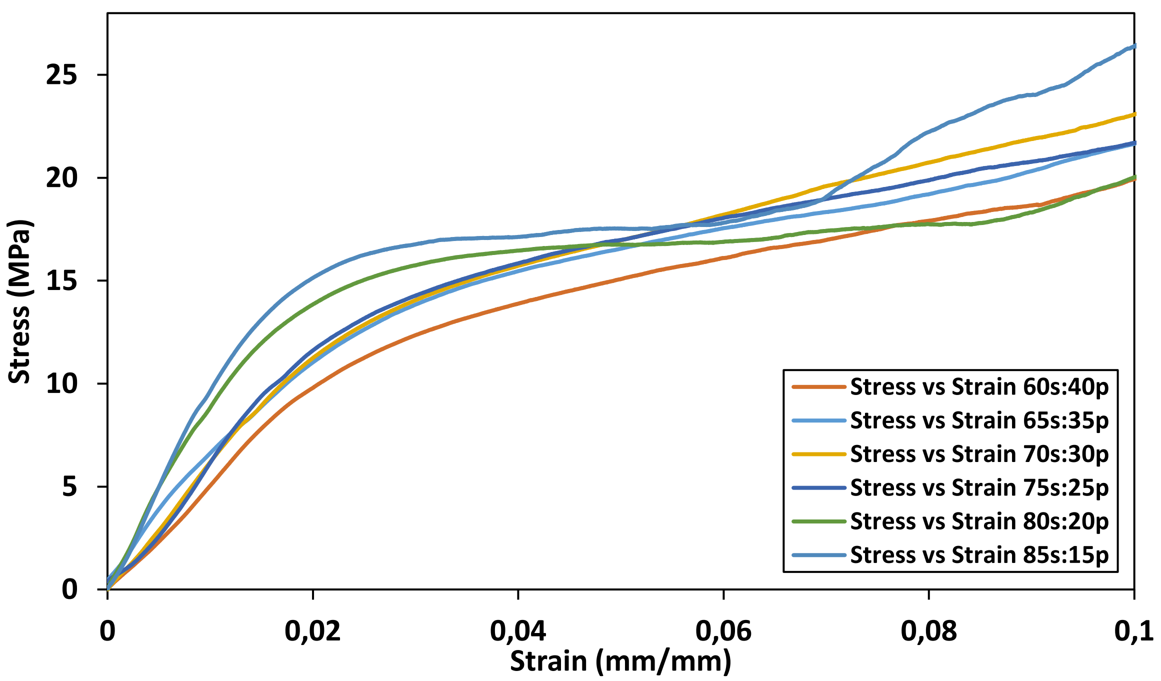


Figure 5. 5: Stress-strain curves for 0% Kaolin Clay DSF additive

Compressive strength Vs Plastic: sand ratio with varying additions of Kaolin Clay

Figure 5.6 shows the average compressive strength of the plastic-sand brick samples and *Figure 5.7* highlights the stress-strain curves when 1% of Kaolin Clay DSF is added to the plastic-sand mixture. There is a clear decrease in average compressive strength. This indicates that a small percentage of Kaolin Clay decreased the compressive strength of the plastic-sand brick sample as compared to the samples with 0% of Kaolin Clay DSF.

The notable decrease in the compressive strength of the plastic-sand brick sample with the inclusion of a minor proportion of Kaolin Clay compared to the samples containing 0% Kaolin Clay DSF can be attributed to several factors. Some of the specific reasons why this result was recorded is due to the minor percentage of Kaolin Clay, being a fine-grained mineral, might not have contribute as effectively to the binding properties within the plastic-sand matrix. Inclusion of this minor proportion may have not provided sufficient cohesion, leading to a decrease in overall compressive strength. The 1% addition of Kaolin Clay may have introduced voids within the composite material, negatively impacting its structural integrity as indicated in *Figure 5.6*. It's important to note that further reasons for this peculiar observation in the decrease in compressive strength would require a more detailed analysis of the experimental conditions, material properties, and testing methodologies.

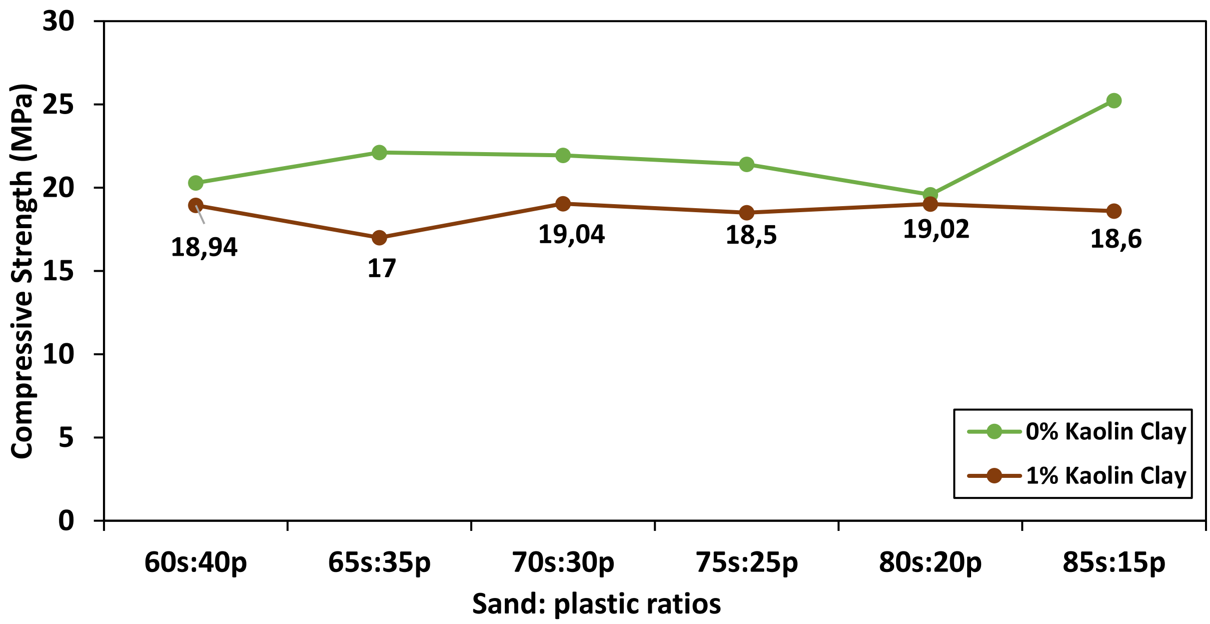


Figure 5. 6: Ratio of Sand to Plastic vs Ave. compressive strength with 0% and 1% Kaolin Clay DSF.

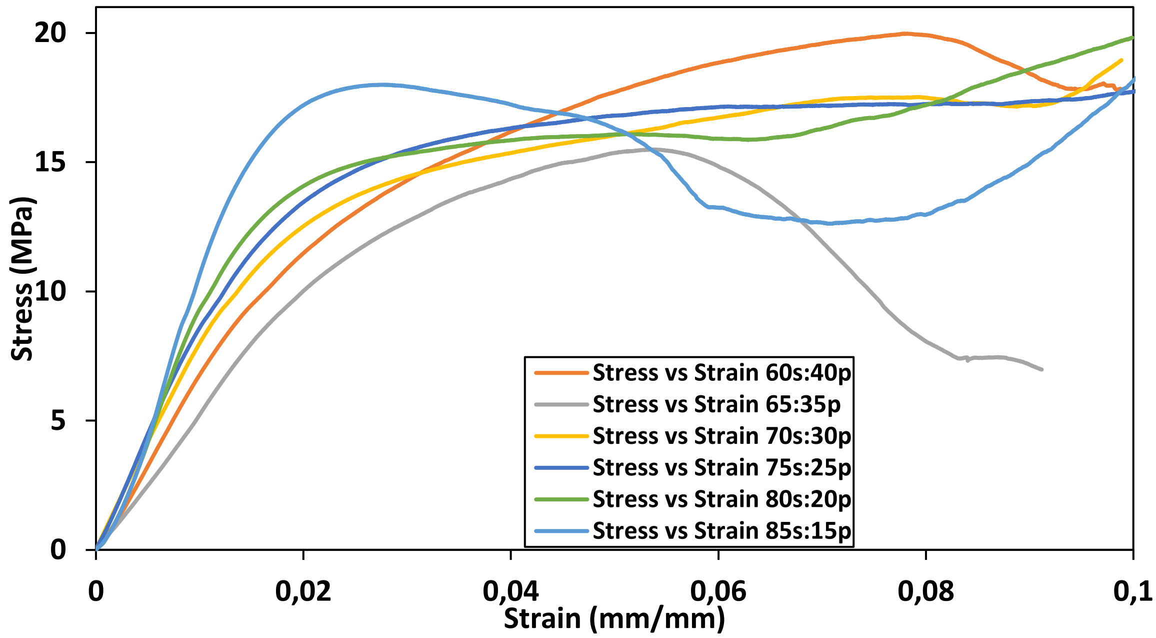


Figure 5. 7: Stress-strain curves for 1% Kaolin Clay DSF additive.

Figure 5.8 shows the average compressive strength of the plastic-sand brick samples and *Figure 5.9* highlights the stress-strain curves for the 5% addition of Kaolin Clay DSF. It shows a significant increase on the average compressive strength as compared to the 0% and 1% addition of Kaolin Clay. This shows a sharp rise in the average compressive strength with the highest being 52.76 MPa is achieved in the 75s:25p ratio. This suggests that the 5% addition of Kaolin Clay DSF has a substantial structural impact on the compressive strength property compared to the other percentages.

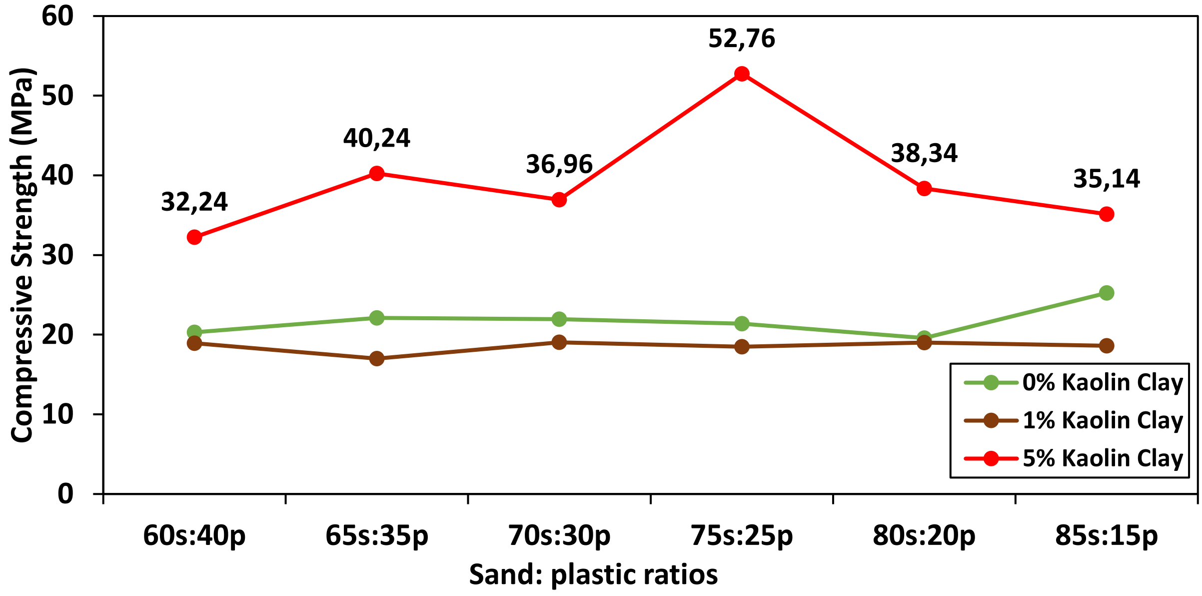


Figure 5. 8: Ratio of Sand to Plastic vs Ave. compressive strength with 0%, 1% and 5% Kaolin Clay DSF.

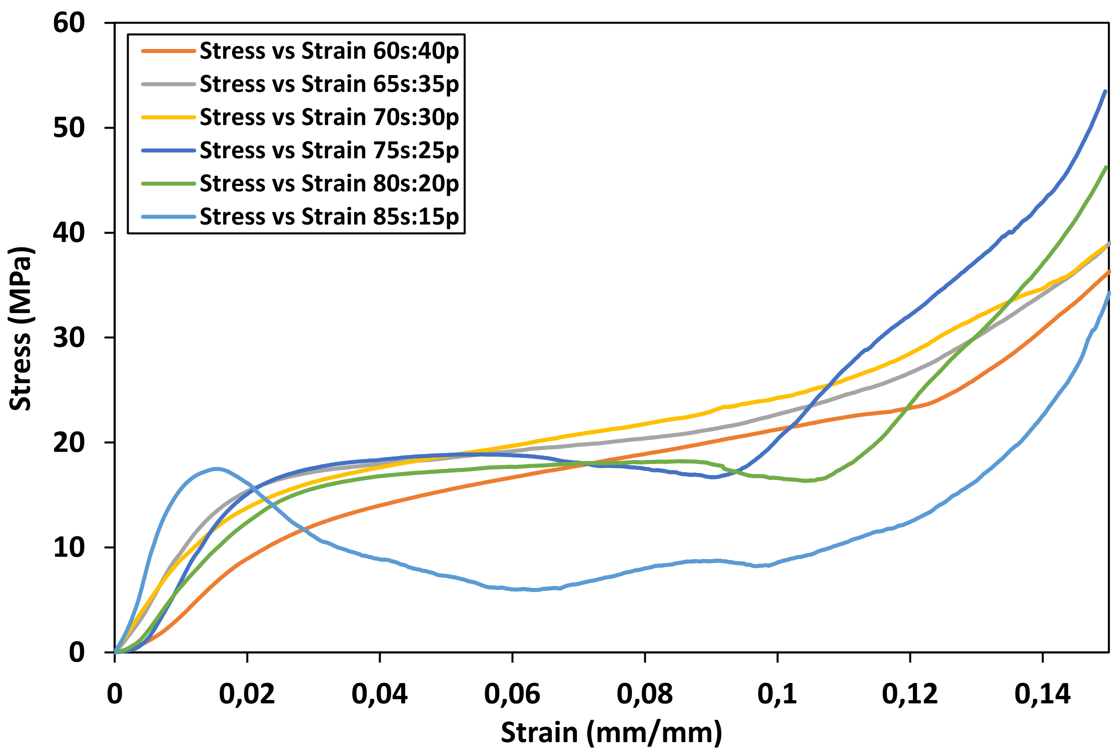


Figure 5. 9: Stress-strain curves for 5% Kaolin Clay DSF additive.

Figure 5.10 shows the average compressive strength of the plastic-sand brick samples and *Figure 5.11* depicts the stress-strain curves with 10% of Kaolin Clay DSF. The highest average compressive strength with the 10% addition of Kaolin was observed in the 60s:40p being 26.45 MPa. The average compressive strength continuously decreases with the addition of 10% of Kaolin Clay DSF in the six ratios from the 60s:40p to 75s:25p. It is observed that the average compressive strength showed a continuous decrease with an increase in the sand content.

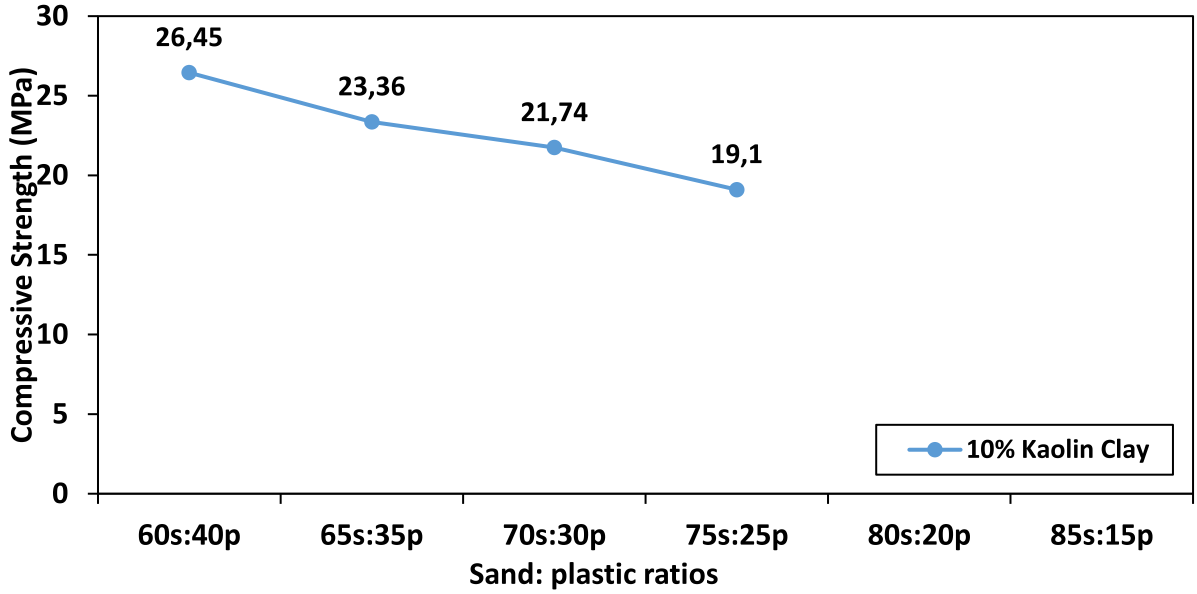


Figure 5. 10: Ratio of Sand to Plastic vs Ave. compressive strength with 10% Kaolin Clay DSF.

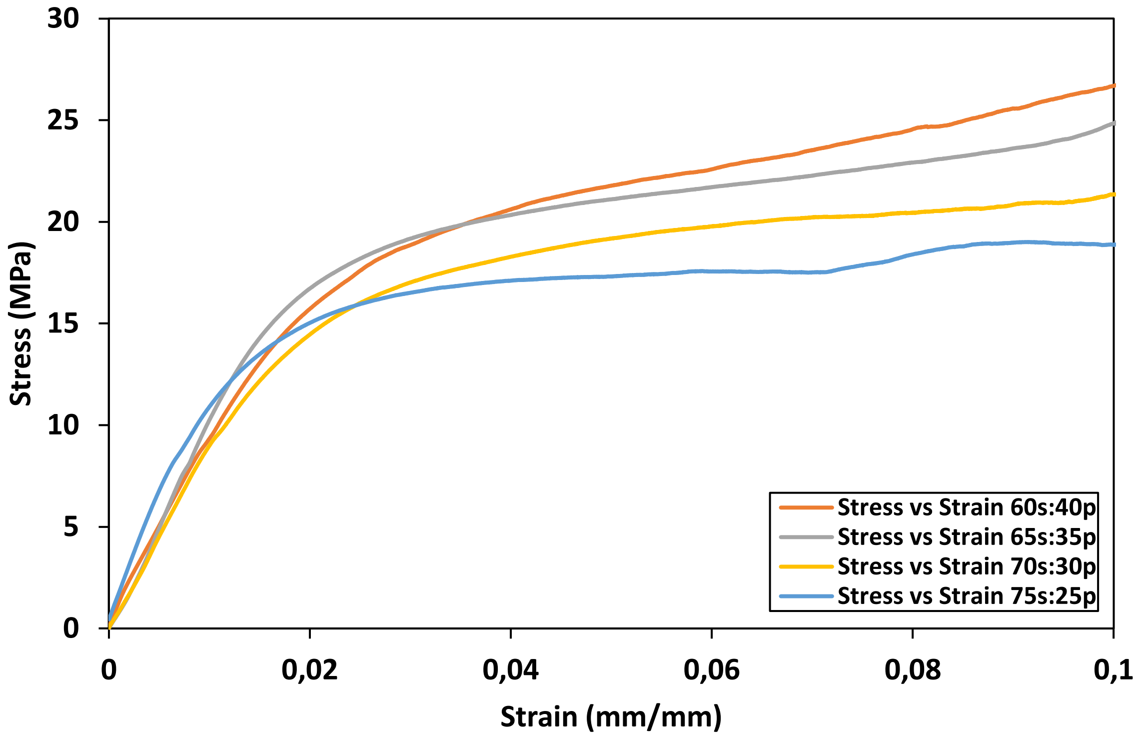


Figure 5. 11: Stress-strain curves for 10% Kaolin Clay DSF additive.

Consolidated Analysis

When the three additions of Kaolin Clay DSF (1%, 5%, and 10%) in all six ratios were compared in *Figure 5.12*, it is evident that 1% did not substantially improve the composite strength as compared to the 5% addition of Kaolin Clay DSF which yielded the highest improvement in compressive strength. The 10% addition follows, and the 1% addition is the least effective among the three. The highest compressive strength of 52.76 MPa in the 75s:25p ratio with 5% Kaolin Clay can be attributed to various factors.

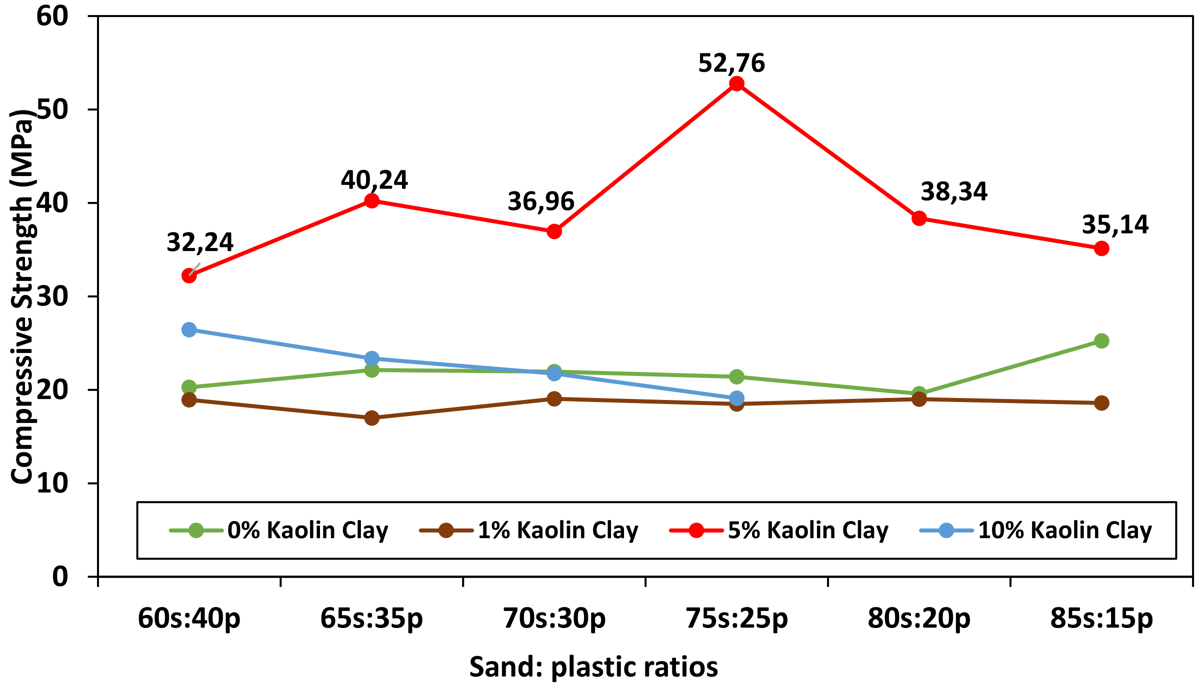


Figure 5. 12: Ratio of Sand to Plastic vs. compressive strength with 0%, 1%, 5% and 10% Kaolin Clay DSF.

Firstly, the 75% composition of sand in the plastic-sand brick played a significant role in the resulting compressive strength. Higher sand content generally leads to a higher compressive rate due to the rigid nature of sand particles which provides reinforcement in the plastic matrix. This is substantiated in the studies conducted by Woods et al. [275], Jnr et al. [276] and Kumar et al. [233] that as the percentage of sand increases, the compressive strength of the samples also increases.

Secondly, the inclusion of HDPE plastic in the mixture acts as a binder, effectively bonding the sand particles and contributing to the overall strength of the plastic-sand bricks, [277]. This indicates that the HDPE acts as a binding agent, enabling the adhesion between the sand particles and achieving maximum compressive strength. The increase in adhesion strength between the sand and polymer likely contributes to these variations. The interfacial connection between the sand particles and the HDPE polymer is vital in determining the compressive strength of the plastic-sand bricks [130].

Thirdly, Kaolin Clay DSF acts as a filler material in the HDPE plastic matrix. The presence of Kaolin Clay DSF particles helps to fill the gaps and voids between the HDPE molecules, leading to a more homogeneous and compact structure. This filler effect enhances the overall strength and rigidity of the extruded plastic-sand bricks. The use of Kaolin as a functional additive improves the strength of the mechanical properties of composite material [227].

Fourthly, the higher addition of Kaolin Clay DSF at 5% plays a crucial role in optimizing the dispersion of particles within the High-Density Polyethylene (HDPE) matrix during the extrusion process. This enhanced dispersion is instrumental in ensuring that the Kaolin Clay DSF particles are uniformly distributed throughout the entire HDPE matrix, thereby contributing to improved reinforcement in the extruded plastic-sand bricks. During the extrusion process, the thorough dispersion of Kaolin Clay DSF particles becomes more pronounced at higher concentrations, allowing for a more even integration within the HDPE matrix. This uniform distribution is essential for achieving consistent material properties throughout the extruded plastic-sand bricks. The interaction between the filler (Kaolin Clay DSF) and the matrix (HDPE) is optimized due to the even dispersion, leading to enhanced mechanical and structural properties. The improved compressive strength observed in the plastic-sand bricks can be attributed to this uniform dispersion and the resulting filler-matrix interaction. With Kaolin Clay DSF evenly distributed, the reinforcement effect is more effectively realized across the entire volume of the extruded bricks. This homogeneous distribution minimizes potential weak points or irregularities within the material, contributing to a more robust and resilient structure [278].

Fifthly, the increase in compressive strength is attributed to the bonding capacity facilitated by the addition of 5% Kaolin Clay DSF. The clay enhances the interfacial connection between the plastic and sand, leading to improved bonding and subsequently increased compressive strength. Therefore, based on these results, it is recommended to use 5% Kaolin Clay DSF to achieve the maximum improvement in compressive strength for the plastic-sand brick samples.

Lastly, the experimental study conducted by Sahani et al. [249] on plastic-sand bricks revealed that the proportions of plastic and sand, as well as the uniformity of the mixture, have a significant influence on the compressive strength of these bricks. The study's key finding indicates that the strength of the plastic-sand brick is directly influenced by the uniformity of the mixture.

5.2.2 Modulus of Elasticity

Table 5.4 shows the modulus of elasticity for the addition of 1%, 5% and 10% addition of Kaolin Clay DSF in the six ratios. The modulus of elasticity can be calculated from the compression stress- strain curves [279]. The tangent of the stress- strain curve of the compression samples within the straight portion boundary indicates the modulus of elasticity of the plastic-sand brick samples. The modulus of elasticity is the change in stress divided by the change in strain of the curve [280]. The formula is indicated below:

Modulus of Elasticity (E) = $\frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$

Table 5. 4: Yield Strength, Ultimate Strength and Modulus of Elasticity

		0% Kaolin Clay	**1% Kaolin Clay**	**5% Kaolin Clay**	**10% Kaolin Clay**
60s:40p	**Yield Strength (MPa)**	10.56 ± 0.90	10.3 ± 1.08	10.58 ± 1.38	15.90 ± 0.81
	Ultimate strength (MPa)	20.28 ± 2.05	18.93 ± 2.57	32.24 ± 7.71	28.70 ± 2.83
	Modulus of Elasticity (GPa)	0.66 ± 0.12	0.66 ± 0.07	0.67 ± 0.05	0.82 ± 0.09
65s:35p	**Yield Strength (MPa)**	9.89 ± 1.67	10.74 ± 0.64	13.2 ± 0.88	15.35 ± 0.73
	Ultimate strength (MPa)	22.11 ± 0.78	17.00 ± 2.54	40.23 ± 14.52	23.07 ± 2.88
	Modulus of Elasticity (GPa)	0.68 ± 0.11	0.66 ± 0.14	1.16 ± 0.12	0.91 ± 0.22
70s:30p	**Yield Strength (MPa)**	9.84 ±1.42	11.54 ± 0.8	11.7 ± 0.29	13.50 ± 1.04
	Ultimate strength (MPa)	21.95 ± 2.92	19.05 ± 1.67	36.95 ± 14.1	21.80 ± 1.6
	Modulus of Elasticity (GPa)	0.76 ± 0.14	0.68 ± 0.10	1.14 ± 0.15	0.95 ± 0.04
75s:25p	**Yield Strength (MPa)**	12.23 ± 0.72	11.61 ± 0.88	15.3 ± 0.88	13.49 ± 1.04
	Ultimate strength (MPa)	21.42 ± 1.78	18.49 ± 1.63	52.75 ± 7.87	19.11 ± 0.67
	Modulus of Elasticity (GPa)	0.78 ± 0.06	0.91 ± 0.13	1.16 ± 0.20	1.16 ±0.27

80s:20p	**Yield Strength (MPa)**	10.66 ± 1.03	13.14 ± 1.14	13.49 ± 1.24	-
	Ultimate strength (MPa)	19.57 ± 1.04	19.01 ± 1.76	38.34 ± 16.27	
	Modulus of Elasticity (GPa)	1.01 ± 0.07	1.07 ± 0.11	1.16 ± 0.34	
85s:15p	**Yield Strength (MPa)**	13.01 ± 1.36	14.73 ± 0.85	15.15 ± 1.46	-
	Ultimate strength (MPa)	25.23 ± 3.59	18.59 ± 0.89	35.14 ± 10.02	
	Modulus of Elasticity (GPa)	1.31 ± 0.28	1.35 ± 0.03	1.43 ± 0.60	

Table 5.4, shows there is a significant effect on the modulus in the plastic-sand brick samples. In the 0 % of Kaolin Clay DSF category, the highest modulus of elasticity was 1.31 GPa that was found in the ratio 85s:15p. In their study, Woods et al. [275] indicated that the addition of sand at higher compositions directly influenced modulus of elasticity of the composite material. Specifically, at higher compositions there is an increase in modulus of elasticity and compressive stiffness. This suggests that the load bearing capabilities and its resistance to deformation under load is improved.

There was general trend of increase in the modulus of elasticity with higher sand content in the ratios when 1% of Kaolin Clay DSF was added to the plastic-sand mixture. The highest modulus of elasticity for this addition was found in the ratio 85s:15p with a modulus of elasticity of 1.35 GPa. It is implied that the 1% addition of Kaolin Clay had further increased the level of stiffness of the plastic-sand brick sample. The same pattern emerged for the addition of 5% of Kaolin Clay DSF. This addition in all of the ratios showed an increase in the modulus of elasticity. The most significant effect was observed in the 85s:15p ratio with the highest modulus of elasticity of 1.43 GPa. This implies that the plastic-sand brick samples have exceptional strength due to increased Kaolin Clay content and can withstand significant stresses without undergoing excessive deformation. This characteristic is particularly desirable in building application where structural integrity and resistance to deformation are crucial. Similarly, the same consistent trend has developed when 10% addition of Kaolin Clay was added to all the ratios. In his study Mustafa [278] confirmed that the increased addition of Kaolin from 1% to 10% to the plastic matrix led to an increase in the modulus of elasticity.

In comparing all three additions i.e. 1%, 5% and 10% of Kaolin Cay DSF in all six ratios, the general trend in modulus of elasticity increasing significantly, was observed where there was an increase in the sand content and a decrease in the plastic content. Additionally, the modulus further increased when there was the transition from 1% to 10% of Kaolin Clay DSF. This suggests that the brick has a strong ability to withstand higher stresses and loads without excessive deformation, maintain its shape and structural integrity for applications in the building industry. It can be summarized that the increase in sand content and decrease in the plastic content has caused the sample to become stiff**.**

Further elaboration on the effects of increasing sand and clay loading on the strength and modulus are indicated below:

i) Sand is a coarse-grained material that provides structural stability and contributes to the strength of the material. Increasing the proportion of sand in a mixture can enhance the overall strength and structural integrity to the composite material. This is because sand particles interlock with each other, creating a stable matrix. Increasing the sand content is observed to increase the modulus. This is because sand particles, being larger and more rigid, contribute to a stiffer matrix. The material becomes less deformable under stress.

ii) Kaolin Clay loading on the other hand, adds cohesion to the mixture which can lead to an increase in the modulus of elasticity.

Comparing plastic-sand brick benchmark with existing standards

Table 5.5 shows the existing benchmarks for the compressive strength required for clay bricks in general building works, as per SANS 227 [217].

Table 5. 5: SANS Compressive strength requirements for burnt clay brick

Class of unit	Nominal compressive strength (MPa)	Individual compressive strength (MPa min)
Non-Facing plastered (NFP) Units suitable for general building works that is to be plastered	7.0	5.5

Houses built from clay bricks have always been in demand which sets the benchmark for these as having the greatest investment value. The minimum compressive strength for a general NFP brick as required by SANS 227 is 7MPa. It is noticed that the addition of 0%, 1%, 5% and 10% of Kaolin Clay DSF in comparison to the burnt clay brick have all yielded a higher compressive strength, with the highest being of 52.76 % MPa. In comparing this compressive strength value of 52.76 MPa with the SANS 227 benchmark range of 5.5 MPa to 7.0 MPa, it is evident that the addition of 5% Kaolin Clay DSF resulted in a substantial increase in compressive strength. The value of 52.76 MPa exceeds the upper limit of the SANS 227 range, indicating that the bricks with this composition has a significantly higher compressive strength than what is typically required for general building works.

The compressive strength of the plastic-sand brick samples exhibited higher strength than the properties of NFP bricks. Therefore, the addition of 5% Kaolin Clay DSF in this study not only met but, greatly surpassed the SANS 227 benchmark requirements for clay bricks in terms of compressive strength for general building works. This implies that the bricks produced with this composition have exceptional strength properties, making them highly desirable and valuable. This type of eco-friendly brick supports the proposed use in the building and construction industry.

5.2.3 Impact test

Table 5.6 and *Figure 5.13* shows the results obtained from the Charpy impact testing of the manufactured plastic-sand samples.

Table 5. 6: Average impact Strength (J)

Ratio	0% Kaolin Clay (Joules)	1% Kaolin Clay (Joules)	5% Kaolin Clay (Joules)	10% Kaolin Clay (Joules)
60s: 40p	4,80	4,80	3,20	4,20
65s: 35p	4.86	4,70	2,90	3,30
70s: 30p	4,40	4,64	3,80	4,30

75s: 25p	4,60	4,80	4,70	5.00
80s: 20p	4,80	4,80	4,60	-
85s: 15p	3,66	4,90	4,30	-

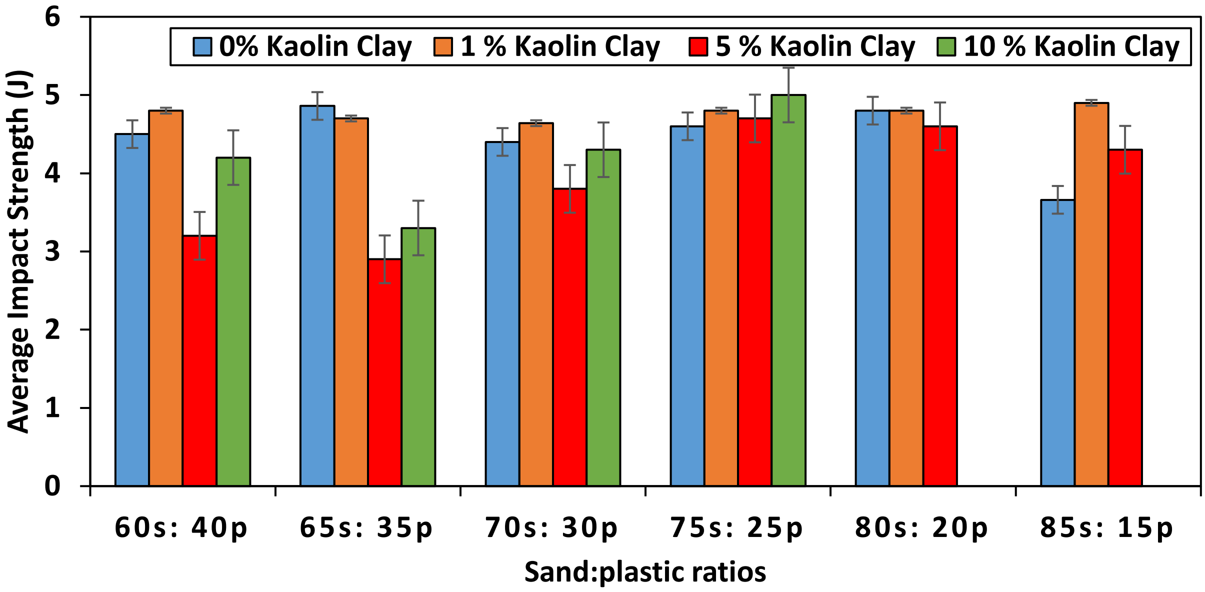


Figure 5. 13: Average impact strength of samples with 0%, 1%, 5% and 10% Kaolin Clay additive

The results obtained from *Figure 5.13* provide insights into the impact strength of the plastic-sand brick samples in different ratios, both without the addition of Kaolin Clay and with varying percentages (1%, 5%, and 10%) of Kaolin Clay added to the plastic-sand mixture. In the 0% addition of Kaolin Clay DSF, the highest average impact strength of 4.86 Joules was observed in the 65s:35p ratio. The lowest average impact strength of 3.66 Joules was recorded in the 85s:15p ratio.

When 1% of Kaolin Clay was added to the plastic-sand mixture, the highest average impact strength of 4.9 Joules was found in the 85s:15p ratio, while the lowest average impact strength of 4.64 Joules was observed in the 70s:30p ratio.

With 5% Kaolin Clay, the highest average impact strength of 4.7 Joules was observed in the 75s:25p ratio, while the lowest average impact strength of 2.9 Joules was recorded in the 65s:35p ratio. It was clearly evident that the impact strength decreased in almost all the ratios which ranged from 2.9-4.7 joules. The optimal impact strength varied depending on the ratio of sand to plastic and the percentage of Kaolin Clay added.

The 10% addition of Kaolin Clay yielded the highest impact strength of 5 Joules in the 75s:25p ratio, indicating the potential for enhanced energy absorption with this composition. The lowest was 3.3 joules in the 65s:35p ratio. The average impact strength ranged from 4.2-4.3 joules in the 6s0:40p and 70s:30p ratios respectively.

Consolidated Analysis

The results for the addition of Kaolin Clay DSF at different percentages influenced the impact strength of the plastic-sand brick samples. This can be attributed to several factors. It can be inferred that adding a higher content of Kaolin Clay DSF i.e. from 1% to 10%, led to the highest average impact strength of 5 Joules was observed in the 75s:25p ratio, while the lowest average impact strength of 3.3 Joules was recorded in the 65s:35p ratio. This increase in impact strength can be attributed to the additional energy absorption provided by the 10% Kaolin Clay DSF in the plastic-sand mixture. In the study conducted by Mustafa [278] it was reiterated that kaolin clay was effective in distributing the applied stress over a large area at the bottom of the notch, and assisted in preventing the spread of cracks by carrying the major part of the load in the vicinity of the crack.

The presence of Kaolin Clay DSF can possibly enhance certain properties, reinforcing the material and improving interfacial adhesion between the plastic and sand particles. This reinforcement can lead to improved impact strength, as observed in some ratios with kaolin clay added. This is substantiated in the study conducted by Anjana and George [229] that kaolin clay can act as a cheap and effective reinforcing agent for HDPE blends. The incorporation of this clay material improves the properties of HDPE blends.

In summary, it can be attributed that the interaction between sand to plastic ratios and Kaolin Clay DSF percentages plays a critical role in determining the stress distribution, crack propagation, and impact strength of plastic-sand brick samples. Balancing these factors is essential for achieving the desired mechanical properties and ensuring the material's performance under impact loads. The interaction between different ratios of sand to plastic and varying percentages of Kaolin Clay DSF can significantly influence the distribution of stress and crack propagation within plastic-sand brick samples, consequently affecting their impact strength. These factors may interact and impact the material's behaviour:

i) Stress Distribution:

Increasing the ratio of sand to plastic generally results in a more rigid and stiff material. This can lead to a more uniform distribution of stress within the plastic-sand brick, as the rigid sand particles help support the load and resist deformation. As per Wood et al. [275], the incorporation of sand at increased compositions has a direct impact on the elasticity of the composite material. More precisely, at higher compositions, there is a noticeable increase in both the modulus of elasticity and compressive stiffness. This indicates an enhancement in the load-bearing capabilities and increased resistance to deformation under load. The presence of Kaolin Clay, depending on its percentage, can affect stress distribution. Higher percentages may contribute to increased stiffness, influencing stress distribution within the material.

ii) Crack Propagation:

A higher sand to plastic ratio tends to make the material more brittle and prone to crack propagation. Brittle materials often exhibit faster and more extensive crack propagation under impact loads. The percentage of Kaolin Clay can influence the crack propagation behavior. While it may enhance stiffness, excessive Kaolin clay content might contribute to brittleness, affecting how cracks propagate.

iii) Impact Strength:

Lowering the sand to plastic ratio often leads to a more ductile material with better impact resistance. Ductile materials typically absorb more energy before fracture, enhancing impact strength. The impact strength can be influenced by the percentage of Kaolin Clay. While some clay content may increase stiffness, too much clay could reduce impact strength due to increased brittleness.

5.2.4 Short beam test

Based on the findings presented in *Figure 5.14*, it can be concluded that the short beam strength generally increases with higher plastic content in the mixture with 0% addition of kaolin Clay. Specifically, increasing the proportion of plastic in the mixture led to higher short beam strength in most cases. This suggests that plastic has a positive effect on the material's resistance to bending forces.

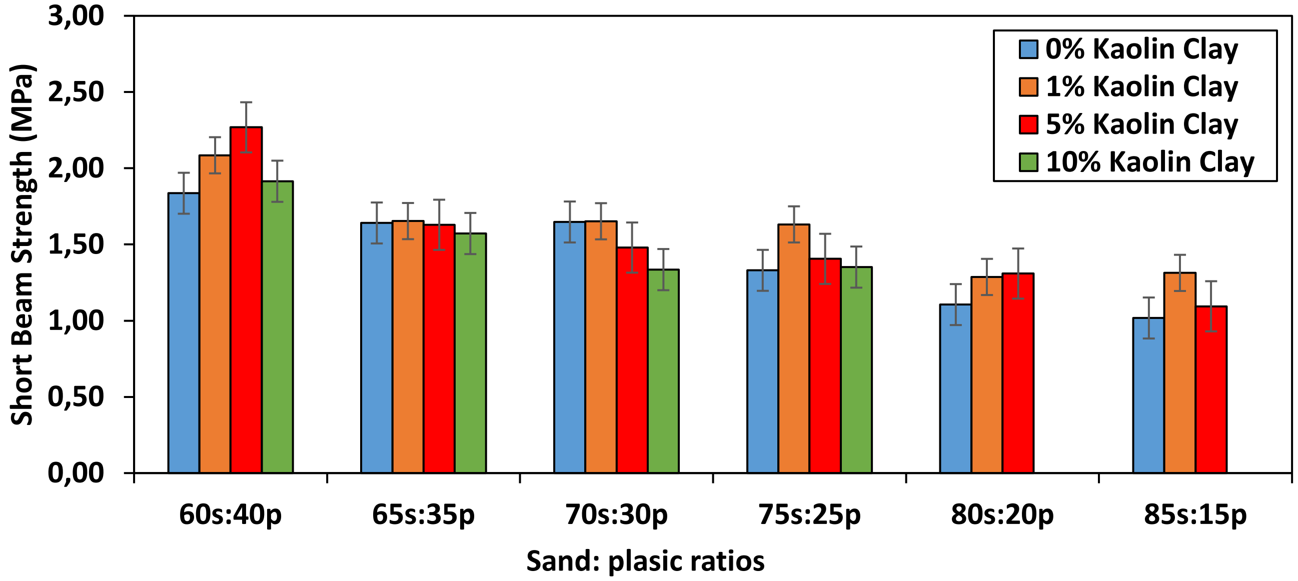


Figure 5. 14: Average short beam strength of 0%, 1%, 5% and 10% Kaolin Clay DSF additive

However, when 1% and 5% of Kaolin Clay DSF was added, a different trend emerged. The inclusion of 1% Kaolin Clay DSF resulted in an increase in short beam strength across various ratios. This indicates that even a small percentage of Kaolin Clay DSF can enhance the material's ability to withstand bending stresses. The effect was consistent across different ratios of plastic and sand. Similar to the 1% addition, the incorporation of 5% Kaolin Clay DSF showed a further improvement in short beam strength. Among all the tested variations, the highest short beam strength of 2.27 MPa was observed in the 60s:40p ratio. This result stands out as the highest short beam strength obtained in the entire study.

Consolidated Analysis

The observed results for short beam strength can be attributed to physical factors. When considering the physical factors, the increase in plastic content in the mixture contributes to the higher short beam strength. Plastics generally possess good mechanical properties, such as flexibility and toughness, which can enhance the material's ability to resist bending forces. The physical presence of Kaolin Clay particles in the mixture can act as fillers, reinforcing the plastic-sand matrix. This reinforcement effect increases the material's resistance to bending and enhances its overall strength. This is substantiated in the works of Anjana and George [229] that clay layers serve a special function by acting as “stress transfer agents” since they have the ability to withstand breakage induced by bending forces. Therefore, they allow for improved flexural strength in composite materials.

In summary, the observed results for short beam strength can be explained by the combined effects of interactions between Kaolin Clay and the plastic matrix, as well as the physical properties of plastics and the reinforcing effect of Kaolin Clay particles. The addition of Kaolin Clay DSF, even at low percentages, provides enhancements in the short beam strength of the plastic-sand mixture, ultimately improving its resistance to bending forces. Hence, the highest short beam strength of 2.27 MPa was achieved when 5% Kaolin Clay DSF was added to the mixture in a 60s:40p ratio, indicating the effectiveness of this specific combination.

5.2.5 Hardness test

The results obtained from the hardness test, involved using a nail as a scratching tool and assessing the impressions on the plastic-sand brick samples. This indicated that the samples exhibited a high level of durability and toughness across all six ratios. The minimal impressions as indicated in *Figure 5.15* caused by the nail suggest that the samples had a high resistance to scratching and deformation. This indicated that the plastic-sand brick samples possessed a hardness property that made them resilient and resistant to a certain degree of external forces.

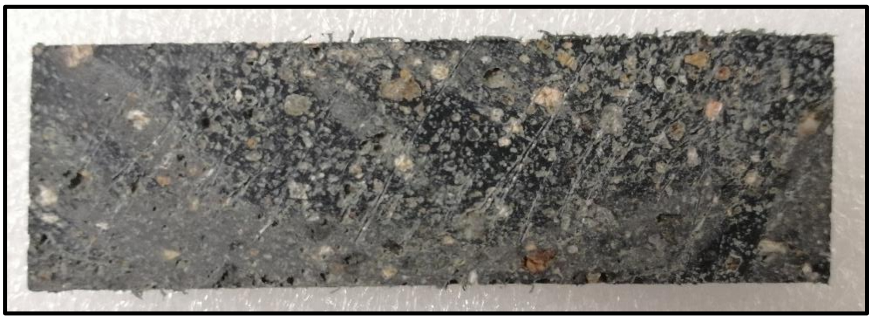


Figure 5. 15: Impression of the nail

Consolidated analysis

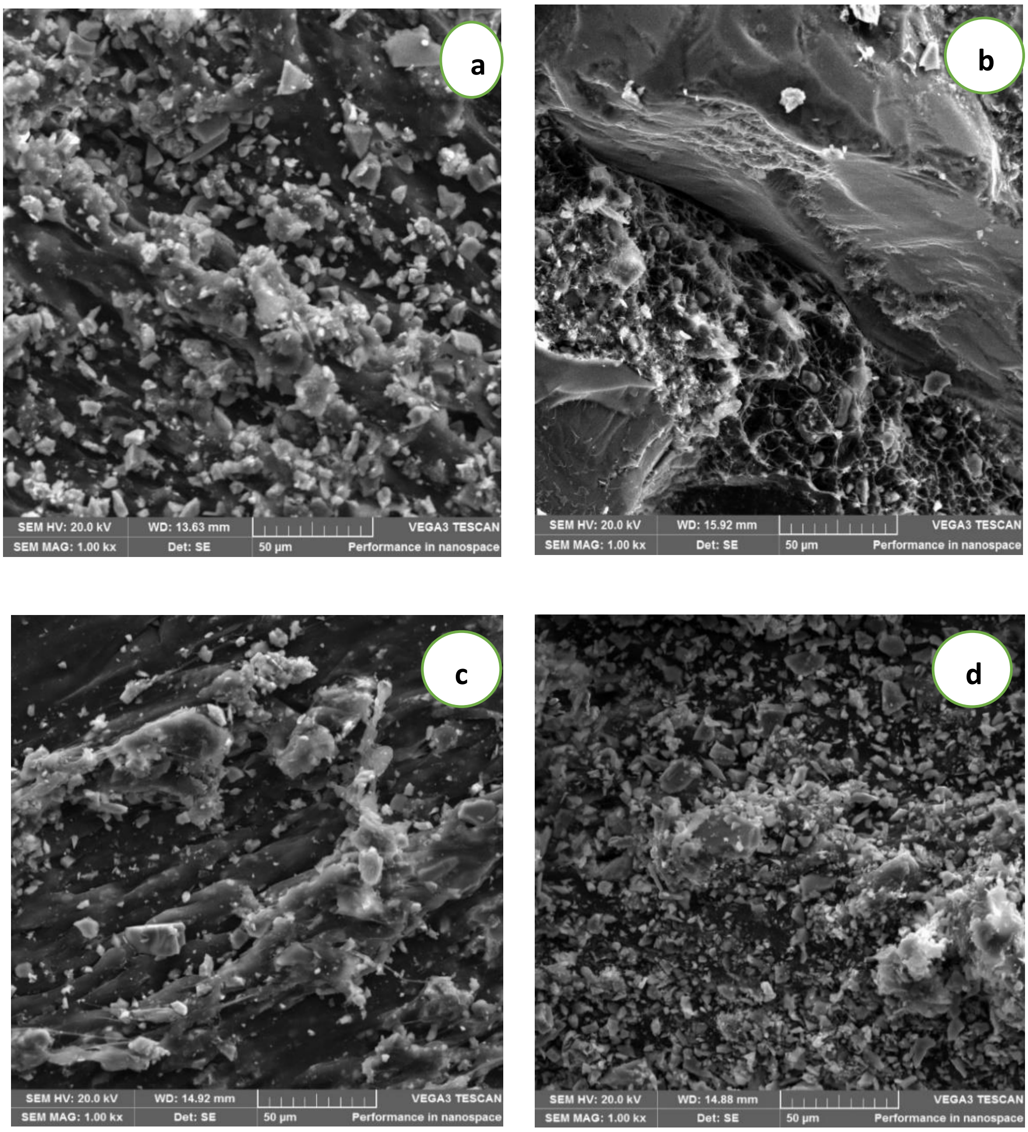
The observed durability and toughness of the samples across all six ratios can be attributed to the properties of the materials used in the mixture. Hence, the durability and toughness observed in all six ratios can be ascribed to the inherent properties of the materials incorporated into the mixture. Upon examining the indentation depth, it became apparent that the mixture with 75% sand and 25% plastic ratio exhibited the most favourable performance. In their study, Shebani et al. [281] indicated that HDPE is rigid due to its high degree of crystallinity. The combination of plastic and sand likely contributed to the overall strength and hardness of the samples, resulting in their ability to withstand scratching and maintain their structural integrity. This observation is linked to Al-Sinan and Bubshait [142], who indicated that when plastic waste is used as a binding material in combination with sand and other fillers, they become very hard and durable bricks,

The ratios of sand to plastic in the plastic-sand mixture play a crucial role in determining the specific hardness properties and the material's ability to resist scratching and deformation in plastic-sand brick samples. The sand-to-plastic ratio influences these characteristics. Increasing the sand content generally leads to higher abrasion resistance and scratch resistance in plastic-sand brick samples. Sand particles are harder than the plastic matrix and can act as abrasives, making the material more resistant to scratching. There is an optimal balance between sand and plastic in the 75s: 25p ratio to achieve the desired level of abrasive resistance. Excessive sand content may result in a brittle material that is prone to cracking upon scratching. Hence, the optimal ratio balances strength and flexibility, contributing to the material's ability to resist deformation under load. Achieving the desired combination of specific hardness properties, scratch resistance, and deformation resistance in plastic-sand brick samples involves finding the right balance between sand and plastic content.

Overall, the hardness test results indicated that the plastic-sand brick samples exhibited excellent hardness characteristics, making them suitable for applications where durability and toughness are essential. The results of the hardness test in this study correlates with the investigation conducted by Solomon [282] who states that there was no impression visible on the surface of the sample during the scratching process.

5.2.6 Scanning electron microscopy

The morphology of plastic-sand brick samples with 6 different ratios of river sand and HDPE with the addition of 5% Kaolin Clay DSF is presented in *Figure 5.16* (a-f).



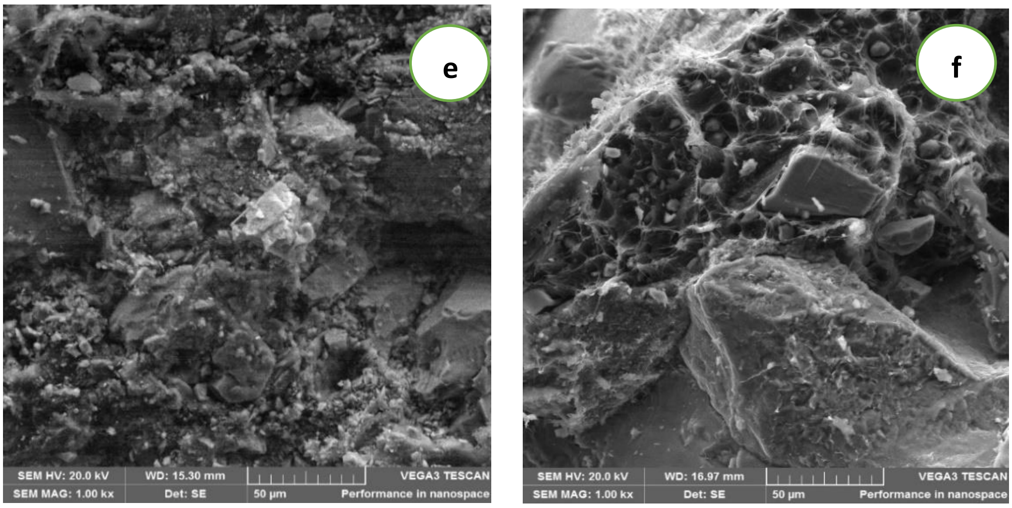


Figure 5. 16: Scanning electron micrograph of 5% addition of Kaolin Clay (a) 60s:40p, (b) 65s:35p, (c) 70s:30p, (d) 75s:25p, (e) 80s:20p and (f) 85s:15p

The most significant changes were observed in the plastic-sand brick sample for the 75s:25p ratio because it reveals a well compacted interface with the mix indicating a dense surface. This means that the HDPE inclusion coated the river sand particles. With the addition of 5% Kaolin Clay DSF, it further improved the bonding between the sand and plastic particles. This suggests good interfacial bonding within the matrix of the plastic and sand structure as well as filling the pore spaces within the matrix structure. This observation is particularly visible in *Figure 5.16*(d) in the 75s:25p ratio which resulted in the highest compressive strength of 52.75 MPa. This implies that the pore spaces in the sample *Figure 5.16*(d) was minimized drastically in comparison to *Figure 5.16(a), (b), (c), (e)* and *(f)* causing it to comparatively possess the highest strength from all the test samples. The plastic-sand brick sample formed a tight matrix structure that is also well interconnected within the surface and the inner part of the sample. The plastic-sand brick sample rendered more of a homogenous solid matrix structure.

However, small clumps of material can be seen in *Figure 5.16(e)* and *5.16(f)* that accounts for a lower compressive strength. Also, the large increase in the proportion of river sand significantly reduces the mechanical properties in the 85s:15p ratio which is represented in *Figure 5.16 (f).* Perhaps this attributed to the relatively low volume of HDPE plastic being insufficient to encapsulate and bind the river sand particles with the 5% Kaolin Clay, thereby resulting in a lower compressive strength.

It can be inferred that the variations in the proportions of sand to plastic, especially in ratios that exhibit lower compressive strength i.e in the 85s:15p ratio, impacted the distribution and coating of High-Density Polyethylene (HDPE) on sand particles in plastic-sand brick samples. This, in turn, affects the interfacial bonding and the overall morphology of the material. Hence, these variations may influence the distribution, coating, and interfacial bonding in the following ways:

i) Distribution of HDPE on Sand Particles:

With higher sand content, achieving uniform distribution of HDPE on sand particles might be challenging. The excess sand may compete for coating by HDPE, leading to uneven coverage and potential agglomeration of sand particles. The lower plastic content may result in insufficient HDPE to coat all sand particles adequately. This can lead to regions with limited or no HDPE coating, affecting the overall homogeneity of the plastic-sand mixture.

ii) Coating Thickness and Uniformity

The ratio of sand to plastic would influence the thickness of the HDPE coating on sand particles. In cases of lower plastic content such as in the 85s:25p ration, the coating thickness may be insufficient to provide effective encapsulation and bonding. Achieving a uniform coating of HDPE on sand particles would become more challenging with lower plastic content. Variations in coating thickness may lead to areas with weak interfacial bonding and compromised overall strength.

iii) Interfacial Bonding

The interfacial bonding between HDPE and sand particles may be weaker when the sand content is higher. The presence of excess sand particles may limit the contact points between HDPE and sand, affecting bonding efficiency as in the 85s:25p ratio. In this study, the plastic content is lower in the 85s:25p ratio, the interfacial bonding between HDPE and sand particles may be compromised. This can result in reduced adhesion and cohesion at the interface, impacting the overall strength of the material.

iv) Overall Morphology

Uneven distribution and coating of HDPE on sand particles, especially in cases of higher sand content, may lead to agglomeration of particles. Agglomerates can act as stress concentration points, influencing the overall morphology and mechanical properties. Further, the inadequate coating of sand particles, particularly with lower plastic content, would result in the formation of porous regions within the plastic-sand brick samples. These porous areas can weaken the material and reduce its overall density.

Overall, the morphology of the plastic-sand brick samples displayed variations in compactness, bonding, and interfacial characteristics. The 75s:25p ratio demonstrated the most favourable morphology, with a well compacted solid matrix structure exhibiting excellent compressive strength. The observations from *Figure 5.16* highlights the importance of appropriate ratios and the role of Kaolin Clay DSF in enhancing the bonding and mechanical properties of the plastic-sand brick samples.

5.2.7 SEM Void analysis

The results obtained from the SEM analysis, as presented in *Figure 5.17(a)*, illustrate the existence of numerous irregularly sized pores within the neat 75s:25p ratio. In contrast, *Figure 5.17(b)* illustrates that the introduction of 5% Kaolin Clay into the HDPE matrix effectively fills the gaps between the sand and plastic particles. This, in turn, results in the reduction of porosity and leads to a more uniform and solid structure within the matrix. It can be inferred from this observation that Kaolin Clay occupies the interstitial spaces among the particles, reducing the formation of air pockets or voids. This decrease in voids and porosity plays a significant role in enhancing the overall structural integrity of the brick sample.

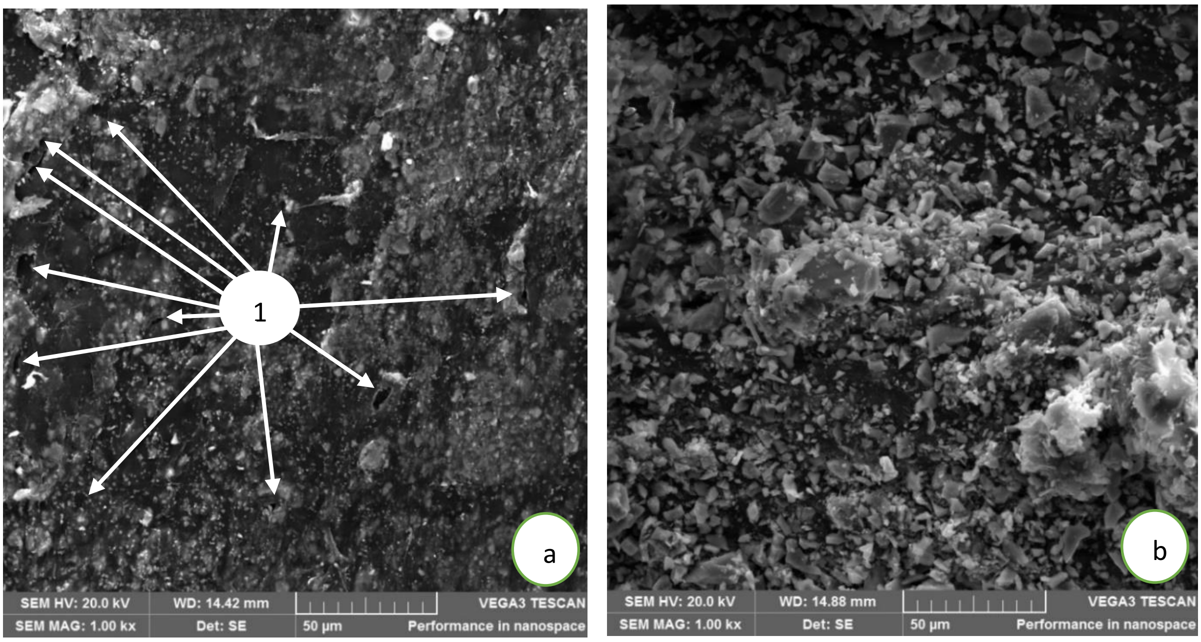


Figure 5. 17: SEM analysis of (a) 0% and (b) 5% addition of Kaolin Clay in the 75s:25p ratio. Number 1 indicates voids in the material

5.3 Summary

Figure 5.18 shows the summary of the mechanical properties of the plastic-sand brick.

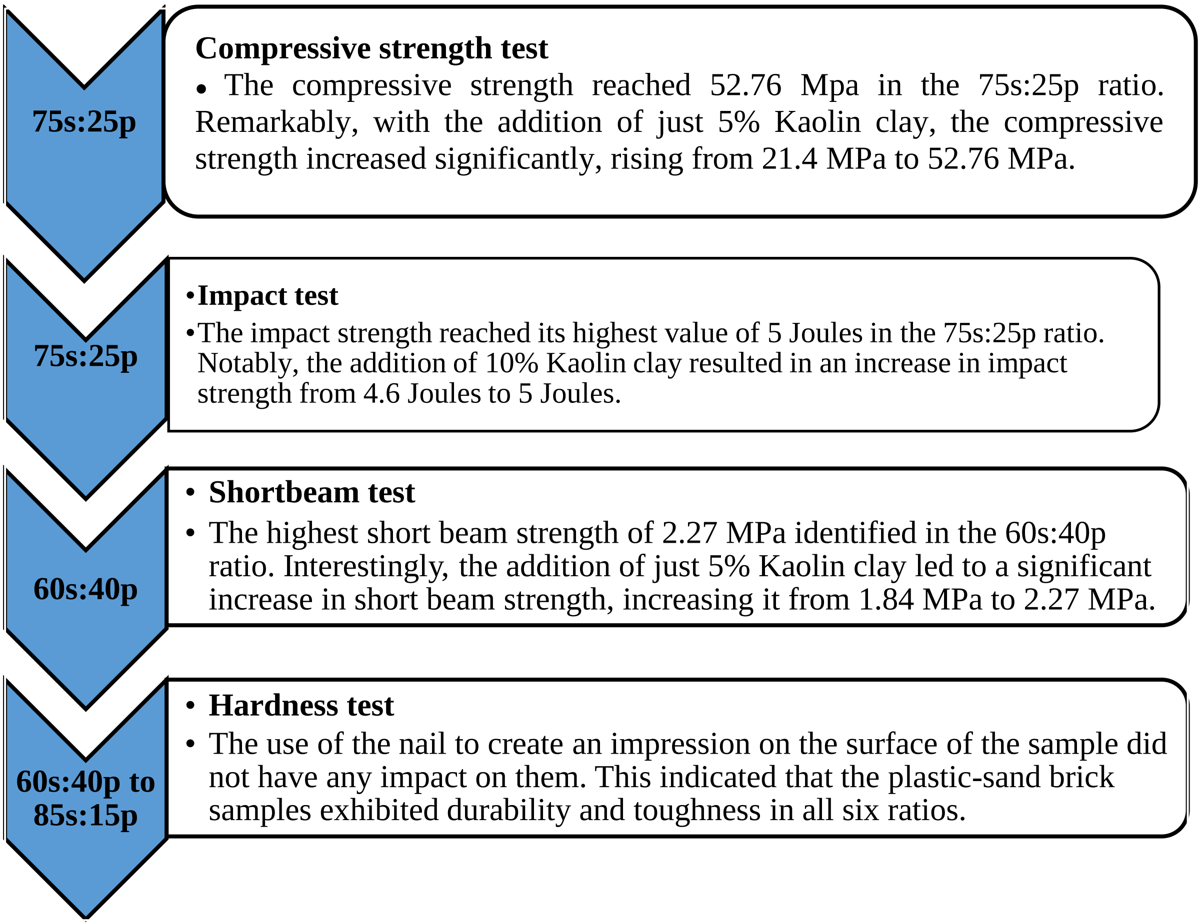


Figure 5. 18: Mechanical properties results

5.4 Conclusion

The results demonstrated that the mechanical properties of the plastic-sand bricks were influenced by both the plastic-sand ratio and the inclusion of Kaolin Clay DSF. Rasib et al. [283] indicate that fillers such as kaolin clay can be added to thermoplastic polymers to improve their mechanical properties and to ensure that the costs of the composite material is reduced.

The findings also indicated that the plastic-sand bricks possess unique mechanical properties that have the potential to benefit the construction industry as emphasised by Patil et al. [140]. Recycled HDPE plastic-sand bricks can be used in load bearing contexts [220]. Sarwar et al. [237] highlighted that the use of HDPE as an alternative binder assist to produce greener building products in the construction industry. The use of recycled plastic to produce plastic-sand bricks reduces the use of natural resources to achieve sustainability and sustainable development. The results of their study also showed that plastic-sand bricks comprising up to

35% of HDPE could serve as the standard brick in the construction industry. It was found that more than 35% of HDPE included in the plastic-sand brick reduces the quality of the brick and should be excluded from the construction industry. Reason being, plastic bricks containing higher than 35% of HDPE would reduce load-bearing capacity of the materials.

Overall, this innovative plastic-sand bricks with such mechanical properties demonstrated that plastic can be used as an alternative binder in the construction sector.

CHAPTER 6

ENVIRONMENTAL PROPERTIES: FINDINGS AND DISCUSSION

6.0 Introduction

This chapter presents the findings, interpretation and discussion of the 5 experimental tests which were conducted on the plastic-brick samples. The discussion of the tests was enhanced by the use of tables, bar graphs, line graphs and images. Two stages of tests were conducted on the different ratios of samples which were manufactured are explained below. *Firstly*, using only HDPE polymer and sand. *Secondly*, the tests were conducted on the use of HDPE polymer, sand with the addition of 1%, 5% and 10% of Kaolin Clay DSF in the different ratios varying from 60s:40p to 85s:15p. The reason for the addition of varying percentages of Kaolin Clay DSF to the mixture is to ascertain the effects of the clay on the environmental properties of the proposed eco-friendly brick to be used in the construction industry.

6.1 Water absorption test

In this test, the weight of the samples was initially taken in dry conditions after they were dried in the oven. It can be summarized, that the absorption test showed excellent performance of the plastic-sand brick.

Figure 6.1 indicated that within the first 24 hours, all six categories exhibited low water absorption values, ranging from 0.134% to 0.341%. The 65s:35p category had the lowest water absorption, while the 85s:15p category had the highest. After 7 days, the average water absorption rate increased across all categories. The values ranged from 0.402% to 0.792%, with the 65s:35p category demonstrating the lowest absorption and the 85s:15p category showing the highest. After 21 days, the average water absorption rate slowly increased. It ranged from 0.639% to 1.589% with the lowest being in 60s:40p category and the highest in the 85s:15p category.

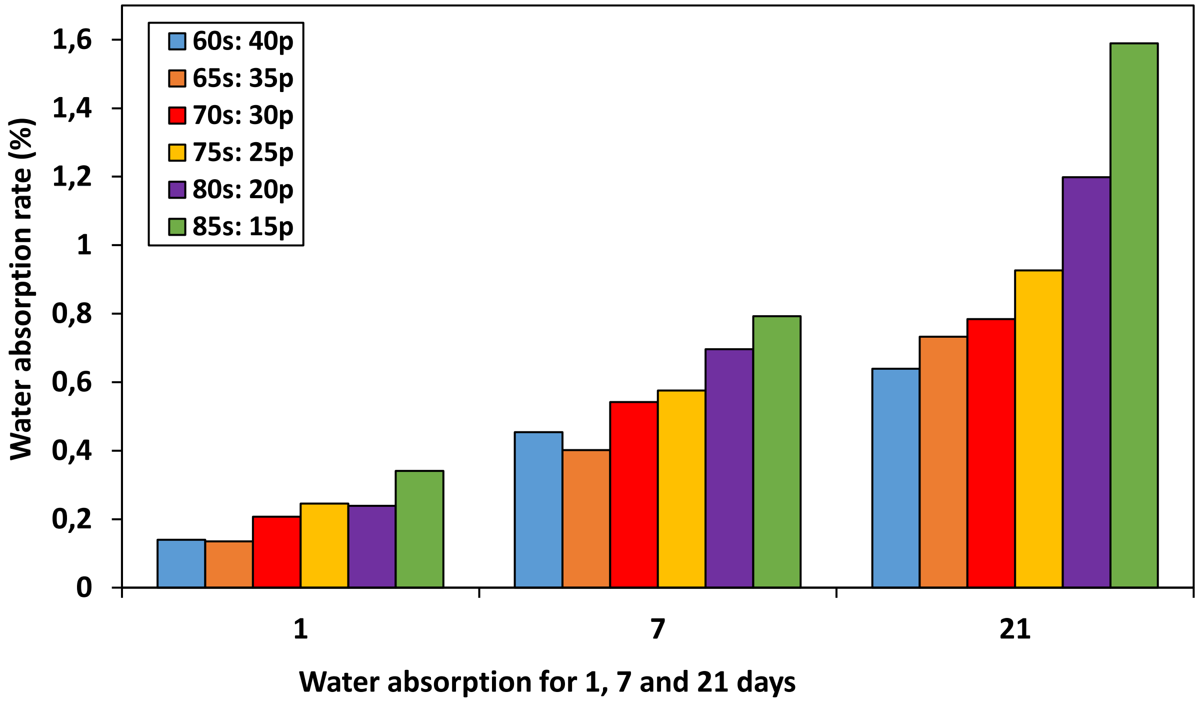


Figure 6. 1: Water absorption for sand: plastic with 0% Kaolin Clay DSF

These results suggest that as the sand content increases and the plastic content decreases, the rate of water absorption tends to rise. This can be attributed to the increased porosity between the sand particles within the composite material. The presence of more sand particles creates additional pathways for water to penetrate and be absorbed by the material. Overall, the water absorption rate shows a gradual increase over time in all the tested ratios, with the highest values observed in the 85s:15p category after 21 days.

Figure 6.2 shows the evaluation of the water absorption properties for the plastic-sand mixture with the addition of 1% Kaolin Clay DSF. Within the initial 24 hours, the water absorption values ranged from 0.134% to 0.269% across all six categories. The 65s:35p ratio exhibited the lowest absorption, while the 75s:25p ratio had the highest. After 7 days, the average water absorption rate increased for all ratios. It varied from 0.329% to 0.626%, with the 60s:40p category demonstrating the lowest absorption and the 85s:15p ratio showing the highest. By the end of 21 days, the average water absorption rate continued to rise gradually. The values ranged from 0.476% to 1.020%, with the 60s:40p category having the lowest absorption and the 85s:15p category having the highest.

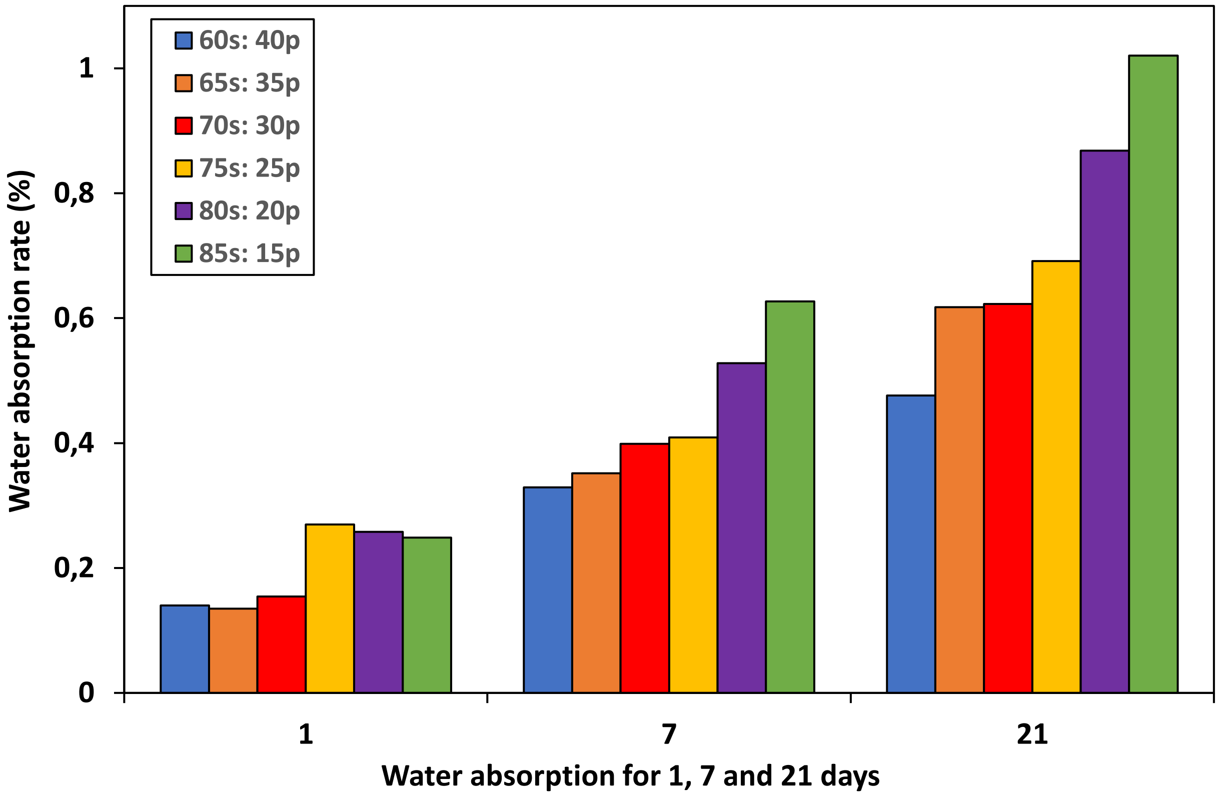


Figure 6. 2: Water absorption for sand: plastic samples with 1% Kaolin Clay DSF

In general, the water absorption rate tended to increase with higher sand content and lower plastic content across most ratios. This can be attributed to the increased porosity between the sand particles within the composite material. As the number of sand particles increases, more pathways for water penetration are created, leading to higher water absorption rates. Overall, the water absorption rate exhibited a gradual increase over the tested time periods of 24 hours, 7 days, and 21 days, respectively, for all ratios. The highest water absorption values were observed in the 85s:15p category after 21 days.

Figure 6.3 shows the water absorption properties for the plastic-sand mixture with the inclusion of 5% Kaolin Clay DSF. Within the initial 24 hours, the water absorption values ranged from 0.214% to 0.402% across all six ratios. The 70s:30p ratio exhibited the lowest absorption, while the 85s:15p ratio had the highest. After 7 days, the average water absorption rate increased for all ratios. It varied from 0.319% to 0.882%, with the 60s:40p ratio demonstrating the lowest absorption and the 85s:15p ratio showing the highest. After 21 days, the average water absorption rate slowly increased. It ranged from 0.430% to 1.254% with the lowest being in the 70s:30p ratio and the highest being in the 85s:15p ratio.

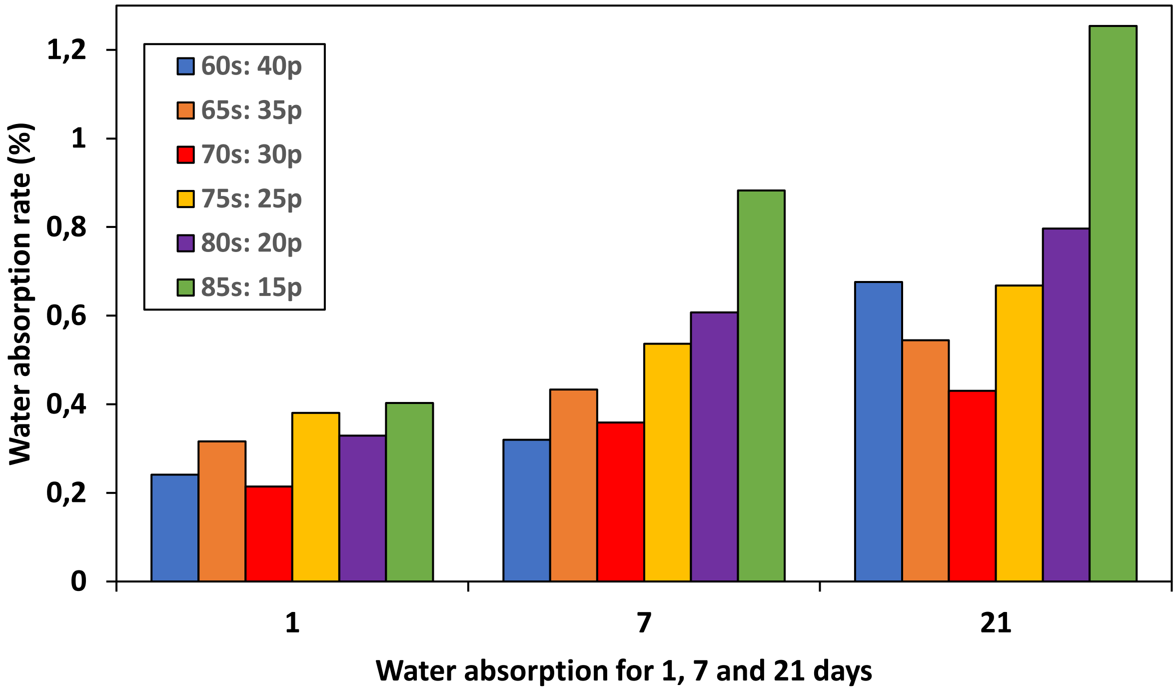


Figure 6. 3: Water absorption for sand: plastic samples with 5% Kaolin Clay DSF

Overall, the water absorption rate was different from the 0% and 1% addition of Kaolin Clay DSF. It was observed that the water absorption rate decreased from 60s:40p to 70s:30p and thereafter, increased gradually for the remaining ratios. The highest water absorption values still remained in the 85s:15p category after 21 days.

Figure 6.4 presents the water absorption characteristics for the plastic-sand mixture incorporating 10% Kaolin Clay which was similar to the 0% Kaolin Clay. During the initial 24-hour period, the water absorption values ranged from 0.134% to 0.341% across all six ratios. The lowest absorption was observed in the 65s:35p ratio, while the highest was recorded in the 85s:15p ratio. After 7 days, the average water absorption rate increased, ranging from 0.402% to 0.792%. The ratio with the lowest absorption was 65s:35p, whereas the highest was observed in the 85s:15p ratio. It was noticed that after 21 days, the average water absorption rate showed a constant increase, which ranged from 0.639% to 1.589%. The ratio with the lowest absorption was 60s:40p, while the highest was observed in the 85s:15p ratio.

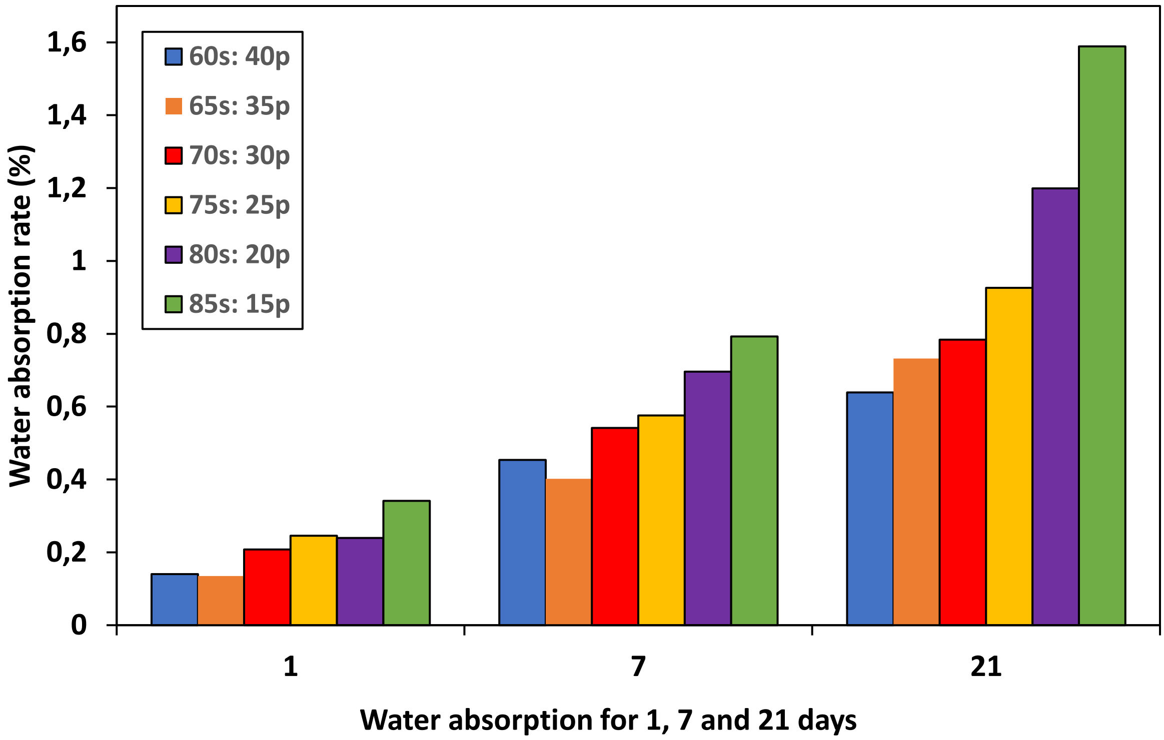


Figure 6. 4: Water absorption for sand: plastic samples with 10% Kaolin Clay DSF

Overall, the rate of water absorption tended to increase with higher sand content and lower plastic content across most ratios. The 85s:15p ratio still demonstrated the highest water absorption values after 21 days, while the 60s:40p ratio had the lowest absorption rate.

Consolidated Analysis

From the 0%, 1%, 5% and 10% addition of Kaolin Clay DSF in the six ratios, two major observations were considered significant. *Firstly*, it was observed that the lowest water absorption rate of 0.43% was shown in the 70s:30p ratio due to the addition of 5% Kaolin Clay DSF. The observed results for water absorption in the plastic-sand mixture with the inclusion of 5% Kaolin Clay DSF can be attributed to several factors which are explained below. This means that the recorded outcomes or measurements related to water absorption in a plastic-sand mixture, where 5% Kaolin Clay DSF is incorporated, can be explained or linked to various factors. In other words, the observed results regarding water absorption are likely influenced by several elements or aspects associated with the presence of 5% Kaolin Clay DSF in the mixture. This implies that the inclusion of Kaolin Clay DSF is a potential factor affecting the water absorption properties of the plastic-sand mixture. This can be attributed to several factors namely: i) the nature of kaolin Clay, ii) the hydrophobic nature of HDPE, iii) the interlocking and bonding capacity of Kaolin Clay and iv) the synergistic effect of Kaolin Clay, river and HDPE plastic.

i) The nature of Kaolin Clay influences water absorption in plastic-sand bricks through different mechanisms. Kaolin Clay is a naturally hydrophobic material, meaning it has a low affinity for water [222]. When added to the plastic-sand brick mixture, Kaolin Clay particles create a barrier that restricts the infiltration of water into the bricks [278]. The clay particles close in the gaps in between the sand and plastic particles, decreasing the porosity and producing a more solid structure. This results in fewer pathways for water to enter the bricks, successfully reducing water absorption.

ii) HDPE plastic is also characteristically hydrophobic in nature [284] and exhibits low water absorption properties. When combined with river sand, the HDPE plastic acts as a binder, encapsulating the sand particles and forming a matrix that is resistant to water penetration. The dense and closely packed structure of the plastic-sand mixture helps to minimize the porosity of the plastic-sand bricks, making them less porous to water. The presence of plastic as the binder material in the brick restricts water absorption and enhances the brick's plasticity [163]. In his study, Ursua [174] indicated that when there is an increase in plastic content there is a corresponding decrease in the percentage of water absorption rates. This was also confirmed in another study conducted by Maneeth et al. [285] that the water absorption decreases with an increase in the percentage of plastic content, as observed from the results of the water absorption test on plastic-sand bricks.

iii) The addition of 5% Kaolin Clay DSF is attributed to have enhanced the interlocking and bonding between the sand and plastic particles. This may result in a more compacted structure with reduced porosity, which can slightly mitigate water absorption. However, the overall trend of higher water absorption with higher sand content and lower plastic content still prevails. In the study conducted by Solomon et al. [282], the water absorption rate also increased when the quantity of sand increased in the plastic-sand brick. This resulted in the increase in porosity of the plastic-sand bricks.

iv) The addition of 5% Kaolin Clay, 70% sand and 30% HDPE plastic in the plastic-sand brick synergistically improves the water resistance of the material. Voids, the dispersion of Kaolin Clay and sand in the plastic-sand bricks have a significant impact on their water absorption properties. Proper dispersion of these components promotes a more compact structure with reduced porosity, leading to lower water absorption rates. HDPE plastic and Kaolin Clay are both hydrophobic material which provides strong water resistance of the bricks.

Secondly, the observed results for water absorption in the plastic-sand mixture with the inclusion of 10% Kaolin Clay DSF can be attributed to the following factor. The incorporation of 10% Kaolin Clay DSF, indicates a similar pattern of increasing water absorption rate as observed in the case of 0% Kaolin Clay DSF. This shows that the addition of 10% Kaolin Clay DSF did not significantly alter the water absorption behavior of the plastic-sand bricks. This suggests that the presence of the high filler content (10%) of Kaolin Clay DSF did not effectively reduce the water absorption capacity of the plastic-sand brick composite material.

The 10% Kaolin Clay DSF caused a saturation effect and resulted in increased water absorption rate due to agglomerations in the composite material. Agglomeration refers to the phenomenon where the particles of Kaolin Clay DSF clump forming larger clusters or aggregates within the composite material. In his study, Mustafa [278] confirmed that the emergence and development of agglomerations within the material has an increasing effect on the water absorption rate.

This is attributed to the difficulties in achieving a uniform distribution of Kaolin Clay, mainly caused by the high filler content.

The existing benchmarks of the Clay Brick Association of South Africa [252] for water absorption required for clay bricks in general building works, must not exceed 20%. This characteristic is an important environmental property since it measures the ability of a composite material to endure water uptake. It was observed that the addition of 5% Kaolin Clay had a significant change on the water absorption of the plastic-sand brick samples. The water absorption of 0.430% was the lowest in the 70s:30p ratio.

A notable difference was observed when the water absorption value of 0.430% was compared to the requirements of the Clay Brick Association of South Africa's benchmark of not exceeding 20% for clay bricks. It is evident that the addition of 5% Kaolin Clay resulted in a significant decrease in water absorption. The value of 0.430% does not exceeds the upper limit of the Clay Brick Association of South Africa. This implies that the plastic-sand brick samples have exceedingly lower water absorption than what is typically required for general building works for clay bricks. By implication, the plastic-sand brick is rendered to be a good alternate eco-friendly brick.

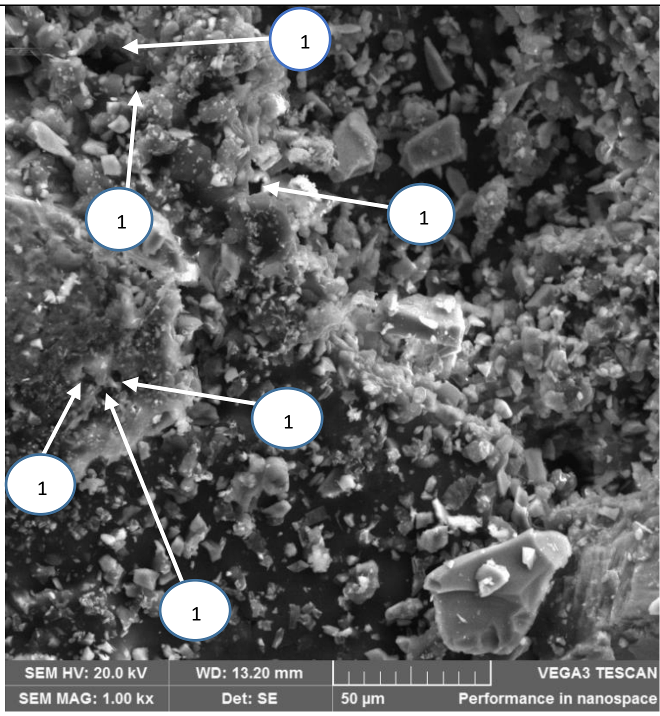
6.2 SEM Analysis

Figure 6.5 shows the effect of 0% and 5% of Kaolin Clay on the micro structure of plastic-sand brick specimens in respect of water absorption. It is observed that there are more voids in *Figure 6.5(a)* as compared to *6.5(b)* due to the absence of 5 % Kaolin Clay in the 70s:30p ratios respectively. The filling of void spaces in *Figure 6.5(b)*, can be attributed to the addition of 5% Kaolin Clay that fills voids and reduces porosity within the plastic-sand brick mixture. By occupying the empty spaces between particles, it minimizes the presence of air pockets or gaps. This reduction in void spaces in *Figure 6.5 (b)* enhanced the structural integrity of the brick and decreased water absorption. However, it should be reiterated that void content is just one of the factors that influence the properties of plastic-sand brick samples. Another crucial factor is filler distribution that also govern the properties of the composites [286].

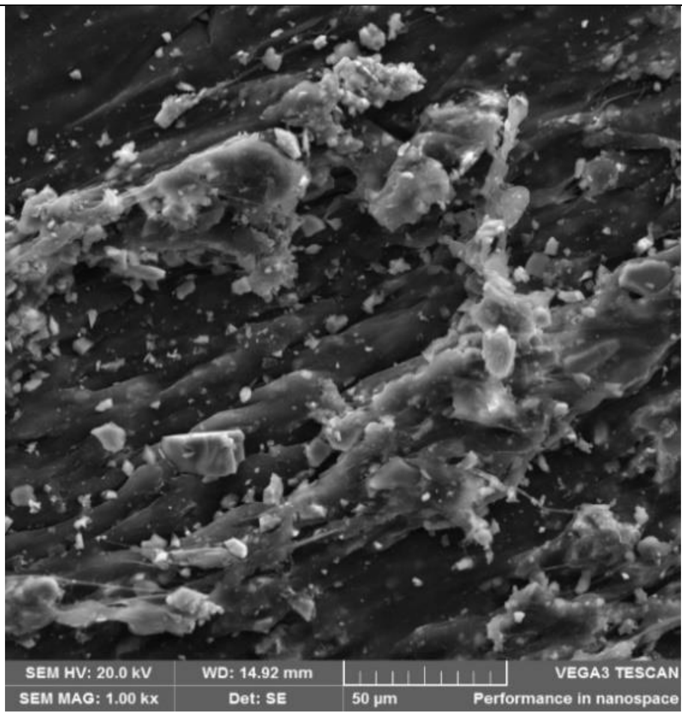
Filler distribution, in conjunction with other factors, impacts the properties of plastic-sand brick samples in the following ways:

i) The homogenous distribution of fillers, such as Kaolin Clay DSF, within the plastic-sand mixture is critical. Homogeneous filler distribution ensures that the properties of the material are consistent throughout the brick. Non-uniform distribution can lead to localized areas of weakness or inconsistency.

ii) The dispersion of filler particles plays a role in the overall microstructure of the material. Well-dispersed fillers can contribute to a more interconnected network within the matrix, influencing properties like strength, stiffness, and resistance to environmental factors. The sand particles should have an optimal size distribution. This ensures proper compaction and packing of particles, contributing to the overall density and strength of the material.

70s:30p **(Without Kaolin Clay)**	 (a)

70s:30p
(With 5% Kaolin Clay)



(b)

Figure 6. 5: SEM images of a) 0% and b) 5% Kaolin Clay DSF in the 75s:25p ratio. Number 1) indicated voids within the material structure.

It can be inferred that the dispersion of Kaolin Clay DSF and sand in plastic-sand bricks in *Figure 6.5 (b)* significantly influenced the water absorption properties. The even distribution and proper dispersion of these components play a crucial role in determining the brick's ability to resist water penetration. Proper dispersion of Kaolin Clay DSF is important as it can act as a filler material and impact the porosity of the bricks. When the clay particles are well-dispersed, they can effectively fill the gaps between the sand and plastic particles, reducing the pathways for water to enter the brick. This results in lower water absorption rates as the clay helps create a more compact and less porous structure.

The dispersion of sand particles is crucial in controlling water absorption. Uniform dispersion of sand ensures that it is evenly distributed throughout the brick matrix, leaving fewer voids or open spaces. This reduces the potential pathways for water to infiltrate the bricks, leading to lower water absorption values. The dispersion of sand thus plays a role in water absorption properties. Proper dispersion of sand with the clay particles together in the plastic matrix, forming a coherent structure that is less permeable to water.

To achieve optimal water resistance, it is important to employ suitable mixing techniques and processing parameters that promote the uniform dispersion of all components. Careful attention should be given to achieving a homogeneous distribution of Kaolin Clay DSF, sand, and plastic throughout the mixture to minimize the porosity and enhance the water resistance of the plastic-sand bricks.

Therefore, when integrating the observed microstructure changes as indicated in Figure 6.5 with the observed variation in water absorption as indicated in *Figure 6.3*, it is clearly evident that the inclusion of 5% Kaolin Clay DSF plays a crucial role in influencing the water absorption properties of the plastic-sand mixture. The SEM microstructural changes, notably the dispersion of Kaolin Clay DSF within the matrix, have a direct impact on the observed variations in water absorption. The dispersion of 5% Kaolin Clay DSF in the plastic-sand mixture introduces microstructural alterations as seen in the images in *Figure 6.5*. The microscopic examination of these images reveals that when the Kaolin Clay DSF is well-dispersed, it creates a more connected network within the composite material. This network, characterized by the dispersed clay particles, influences the porosity and overall structure of the plastic-sand mixture.

The interconnected network of Kaolin Clay DSF contributes to reduced voids and improved compaction as seen in the microstructure images in *Figure 6.5 (b)*. This means that the pathways for water absorption are impeded or restricted by the presence of the dispersed clay particles. This reduction in available pore spaces and the hindrance of water pathways contribute to a decrease in water absorption by the plastic-sand mixture.

6.3 Water contact angle

Table 6.1 shows the readings of the contact angle captured by the Ossila Contact Angle Goniometer. It was noticed that all values were greater than 45°. This means that the plastic-sand brick sample is hydrophobic i.e. it resisted the absorption of water. Water cannot dissolve in hydrophobic compounds such as the plastic-sand brick. The physical property of the plastic-sand brick seemingly repelled the droplet of water. Hydrophobic substances or samples such as the plastic-sand bricks cannot be mixed with or dissolved in water. Hence, the ability of the plastic-sand brick to repel water was evident.

Table 6. 1: Water contact angle results

Category	Water contact angle					
Ratio	**Left Angle**	**Right Angle**	**Average left & right Angles**	**Average contact angle**	**Hydrophobic**	**Hydrophilic**
60s: 40p	80.4	86.42	83.41	92.218	✓	
	82.25	78.28	80.265			
	96.64	107.9	102.27			
	91.03	75.58	83.305			
	115.48	108.2	111.84			
65s: 35p	85.41	90.18	87.795	90.112	✓	
	92.53	104.79	98.66			
	86.18	94.85	90.515			
	104.59	84.93	94.76			
	70.32	87.34	78.83			
70s: 30p	84.77	80.33	82.55	106.342	✓	
	108.42	140.04	124.23			
	114.52	118.23	116.375			
	105.88	100.24	103.06			
	99.12	111.87	105.495			
75s: 25p	105.79	113.21	109.5	107.062	✓	
	88.08	79.09	83.585			
	101.44	113.56	107.5			
	104.39	93.09	98.74			
	138.35	133.62	135.985			
80s: 20p	104.26	89.23	96.745	107.474	✓	
	95.01	94.04	94.525			
	129.71	139.74	134.725			
	88.57	105.2	96.885			
	117.27	111.71	114.49			
85s: 15p	99.88	114.96	107.42	106.053	✓	
	103.86	116.75	110.305			
	111.68	101.93	106.805			
	92.18	97.43	94.805			
	108.93	112.93	110.93			
1% Kaolin						
60s: 40p	76.61	81.15	78.88	97.896	✓	
	91.92	119.67	105.795			
	92.72	92.74	92.73			
	104.34	113.25	108.795			

	102.93	103.63	103.28			
65s: 35p	99.31	89.56	94.435	99.976	✓	
	96.09	107.67	101.88			
	102.88	99.19	101.035			
	108.09	105.92	107.005			
	97.21	93.84	95.525			
70s: 30p	136.55	125.47	131.01	116.256	✓	
	108.48	100.04	104.26			
	105.11	103.41	104.26			
	114.71	107	110.855			
	138.02	123.77	130.895			
75s: 25p	113.99	120.4	117.195	125.12	✓	
	145.35	130.57	137.96			
	132.48	129	130.74			
	110.37	118.12	114.245			
	130.82	120.1	125.46			
80s: 20p	113.13	120.06	116.595	115.775	✓	
	129.51	130.53	130.02			
	114.47	108.07	111.27			
	109.47	123.35	116.41			
	104.42	104.74	104.58			
85s: 15p	133.95	125.01	129.48	115.168	✓	
	112.84	105.86	109.35			
	112.49	106.26	109.375			
	108.29	103.9	106.095			
	117.86	125.22	121.54			
5% Kaolin						
60s: 40p	93.78	96.42	95.1	97.173	✓	
	120.3	99.7	110			
	102.45	108.68	105.565			
	75.78	83.19	79.485			
	98.76	92.67	95.715			
65s: 35p	133.38	132.12	132.75	109.925	✓	
	114.89	107.25	111.07			
	115.87	113.3	114.585			
	74.89	70.01	72.45			
	115.28	122.26	118.77			
70s: 30p	123.58	110.26	116.92	111.79	✓	
	85.08	96.1	90.59			
	127.32	118.26	122.79			
	106.27	111.27	108.77			
	118.1	121.66	119.88			
75s: 25p	129	127.62	128.31	119.28	✓	
	118.02	119.21	118.615			
	125.79	111.7	118.745			
	104.29	104.02	104.155			

	117.47	135.68	126.575			
80S : 20p	130	119.13	124.565	114.418	✓	
	109.37	114.99	112.18			
	99.99	100.69	100.34			
	123.73	102.79	113.26			
	121.08	122.41	121.745			
85s: 15p	126.29	120.26	123.275	103.672	✓	
	118.34	103.58	110.96			
	89.59	97.38	93.485			
	110.68	94.52	102.6			
	86.19	89.89	88.04			
10% Kaolin						
60s: 40p	100.9	100.72	100.81	94.283	✓	
	85.79	71.49	78.64			
	115.28	116.91	116.095			
	92.64	90.7	91.67			
	71.39	97.01	84.2			
65s: 35p	73	62.08	67.54	98.502	✓	
	114.28	118.48	116.38			
	94.02	118.4	106.21			
	93.25	99.13	96.19			
	99.07	113.31	106.19			
70s: 30p	94.37	84.41	89.39	104.016	✓	
	58.31	90.31	74.31			
	112.56	114.71	113.635			
	101.13	116.84	108.985			
	138.33	129.19	133.76			
75s: 25p	109.89	92.46	101.175	103.7	✓	
	98.16	96.62	97.39			
	98.81	131.63	115.22			
	108.21	106.32	107.265			
	106.19	88.71	97.45			

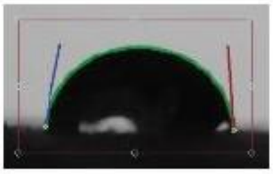
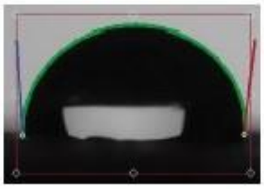
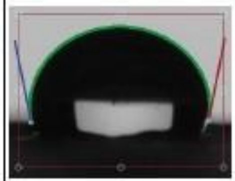
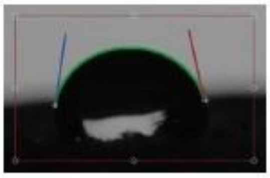
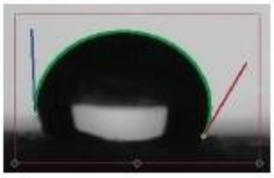
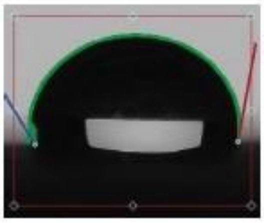
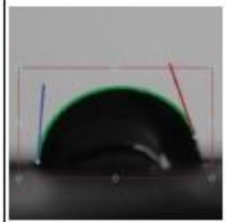
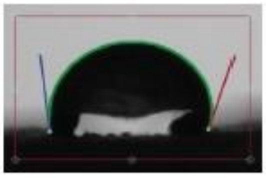
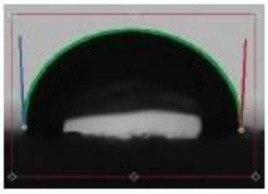
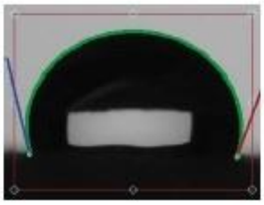
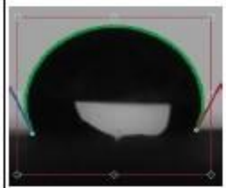
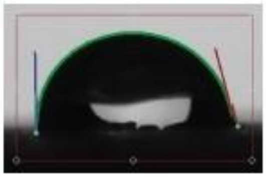
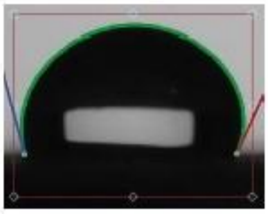
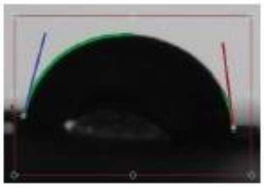
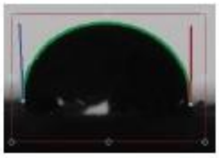
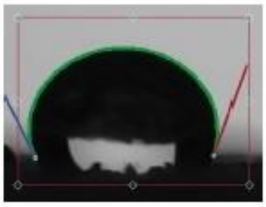
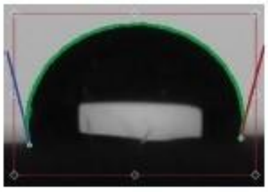
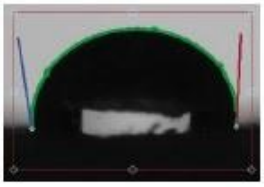
Consolidated analysis

Hydrophobic substances, including the plastic-sand brick, have a limited affinity for water and do not easily mix or dissolve in it. This is attributed *firstly*, to the physical properties of the HDPE plastic in the sand brick which generates a repulsive interaction with water molecules, preventing their absorption. Consequently, the plastic-sand brick effectively repels water, demonstrating its hydrophobic nature [284].

Secondly, Kaolin Clay repels water due to its hydrophobic properties [222]. This is confirmed by Mustafa [278] who stated that Kaolin was not considered as a hydrophilic material, Therefore, it resisted the instantaneous absorption of water.

Table 6.2 shows the images of the angles of the water droplets for the 60s:40p ratio with the addition of 1%, 5%, and 10% addition of Kaolin Clay DSF only. This process was conducted for all the ratios of plastic and sand. The images for the remaining ratios showed the same pattern that the plastic-sand brick samples all repelled water (*Appendix D*).

Table 6. 2: Water contact angle for 60s:40p with 1%, 5%, and 10% addition of Kaolin Clay

	A- 60:40			
Sample No.	0% Kaolin Clay	1% Kaolin Clay	5% Kaolin Clay	10% Kaolin Clay
1				
2				
3				
4				
5				

The water contact angle results as indicated in table 6.2 and the discussion on water absorption as indicated in section 6.1 are intricately connected and provide insights into the hydrophobic nature of the plastic-sand brick samples. The hydrophobic nature observed in the water contact angle test aligns with reduced water absorption in the composite material. The hydrophobic surface of the plastic sand brick repels water, preventing or minimizing its penetration into the composite material. As a result, the material shows lower water absorption characteristics. The water contact angle results complement the water absorption test conducted in section 6.1 by providing additional information on the surface characteristics of the plastic-sand brick samples. While the water absorption test assesses the material's ability to absorb water, the water contact angle test focuses on the material's interaction with water at the surface. Together, these tests offer a comprehensive understanding of the material's response to water. A hydrophobic surface can act as a protective barrier, reducing the likelihood of water access and contributing to the material's resistance against environmental factors.

6.4 Efflorescence test

Figure 6.6 shows the results of the efflorescence test in all 6 ratios with 0%, 1%, 5%, and 10% Kaolin Clay DSF indicated that the plastic-sand brick samples did not display any form of efflorescence. This lack of efflorescence is attributed to various physical reasons.

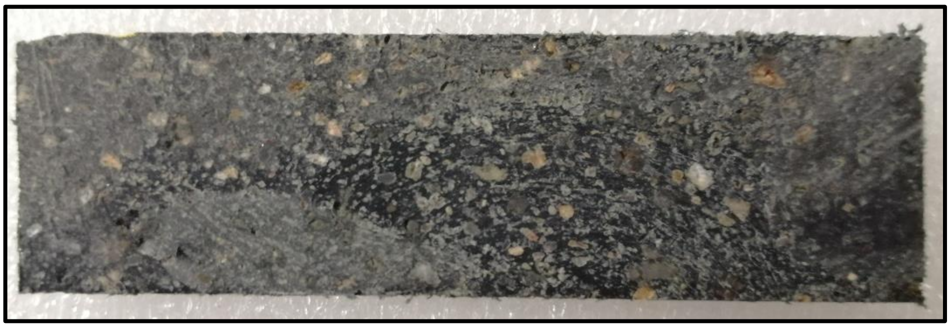


Figure 6. 6: Efflorescence test

Consolidated analysis

Firstly, efflorescence is often caused by the migration of soluble salts to the surface of the material. In the case of plastic-sand bricks, soluble salts, such as alkalis or other salts, within the bricks were not visible on the surface during the drying process. In their study, Selvamani et al. [163] observed that the plastic-sand bricks displayed no signs of efflorescence. This absence of efflorescence is attributed to the low amount of soluble salts present in the plastic material.

Secondly, the low water absorption prevented possible dissolved salts within the plastic composite to be transported to the surface during the drying process, leading to the lack of efflorescence.

Thirdly, the lack of efflorescence could also be as a result of no movement of water through the plastic-sand brick composite materials. The reasons for the lack of efflorescence is also confirmed in other studies [249] [287] [142].

6.5 Electrical resistance

Table 6.3 indicates the readings of the samples that were tested for electric resistance. When 1%, 5%, and 10% of Kaolin were added to the plastic-sand mix in all the ratios in the first test, the chain polymer structure of sand and plastic did not allow the free movement of electrons. The consistent readings of the plastic-sand brick samples were 0.01 ohms in all the ratios which exhibited a high level of electrical resistance. Hence, the plastic-sand brick samples displayed insulating properties since it is made up of non-conductive materials

Table 6. 3: Electrical resistance results

Sand: Plastic	0% Kaolin Clay DSF		1% Kaolin Clay DSF		5% Kaolin Clay DSF		10% Kaolin Clay DSF		Clay brick	
Ratio	Reading (Ohms)	Status	Reading (Ohms)	Status	Reading (Ohms)	Status	Reading (Ohms)	Status	Reading (Ohms)	Status
60s: 40p	0.01	Insulator	0.01	Insulator	0.01	Insulator	0.01	Insulator	0.01	Insulator
65s: 35p	0.01	Insulator	0.01	Insulator	0.01	Insulator	0.01	Insulator		
70s: 30p	0.01	Insulator	0.01	Insulator	0.01	Insulator	0.01	Insulator		
75s: 25p	0.01	Insulator	0.01	Insulator	0.01	Insulator	0.01	Insulator		
80s: 20p	0.01	Insulator	0.01	Insulator	0.01	Insulator	-	-		
85s: 15p	0.01	Insulator	0.01	Insulator	0.01	Insulator	-	-		

The findings for the second test further supported by the data presented in *Table 6.3*, where the electrical resistance reading of the clay brick, composed of non-conductive materials, is also recorded as 0.01 ohms. The electrodes that were connected to each of the specimens means that the plastic-sand brick sample in each of the ratios are insulators. No ringing sound was observed which means that there is no continuity in the circuit and there is a break in it. This additional evidence confirms that the plastic-sand bricks exhibit insulating characteristics, as they are unable to facilitate the flow of electrons.

Consolidated analysis

Kaolin, a clay mineral composed mainly of kaolinite which has an electrostatically neutral structure. This means that the mineral particles within kaolin do not carry a net electric charge. The neutral structure of kaolin particles plays a significant role in various applications and industries, more especially in this study where the absence of electrical charges is desirable [288]. Plastics, including the HDPE plastic used in plastic-sand bricks, are known for their thermal and good insulating properties [277]. These materials have high electrical resistivity, meaning they impede or resist the flow of electric current. Both kaolin's electrostatically neutral structure and plastic's insulating properties collectively contribute to impeding the flow of electrons through the material. The overall electrical resistance of plastic-sand bricks is influenced by the electrostatically neutral structure of kaolin and the insulating properties of plastic. Hence, plastic is now viewed as an electrical insulator, which means that it resists the movement of electric current [289].

Therefore, when comparing the readings for 0% and 1%, 5%, and 10% of Kaolin Clay additions in all the ratios with the clay fired brick, it was established that the reading for the clay brick was also recorded as 0.01 Ohms which makes it an insulator.

6.6 Fire test

Table 6.4 and *Figure 6.7* shows the fire resistance test results and the effects of adding different percentages of Kaolin Clay DSF to the sand: plastic ratios.

Table 6. 4: Linear burning rate of the plastic-sand bricks samples with the addition of 0%, 1%, 5%, and 10%

Ratio	0% Kaolin Clay DSF (mm/min)	1% Kaolin Clay DSF (mm/min)	5% Kaolin Clay DSF (mm/min)	10% Kaolin Clay DSF (mm/min)
60s:40p	11.68	10.80	10.25	8.86
65s:35p	11.54	10.40	10.05	7.33
70s:30p	11.53	10.50	9.37	4.01
75s:25p	10.52	10.45	9.38	2.10
80s:20p	9.67	9.76	9.19	-
85s:15p	8.93	8.51	8.08	-

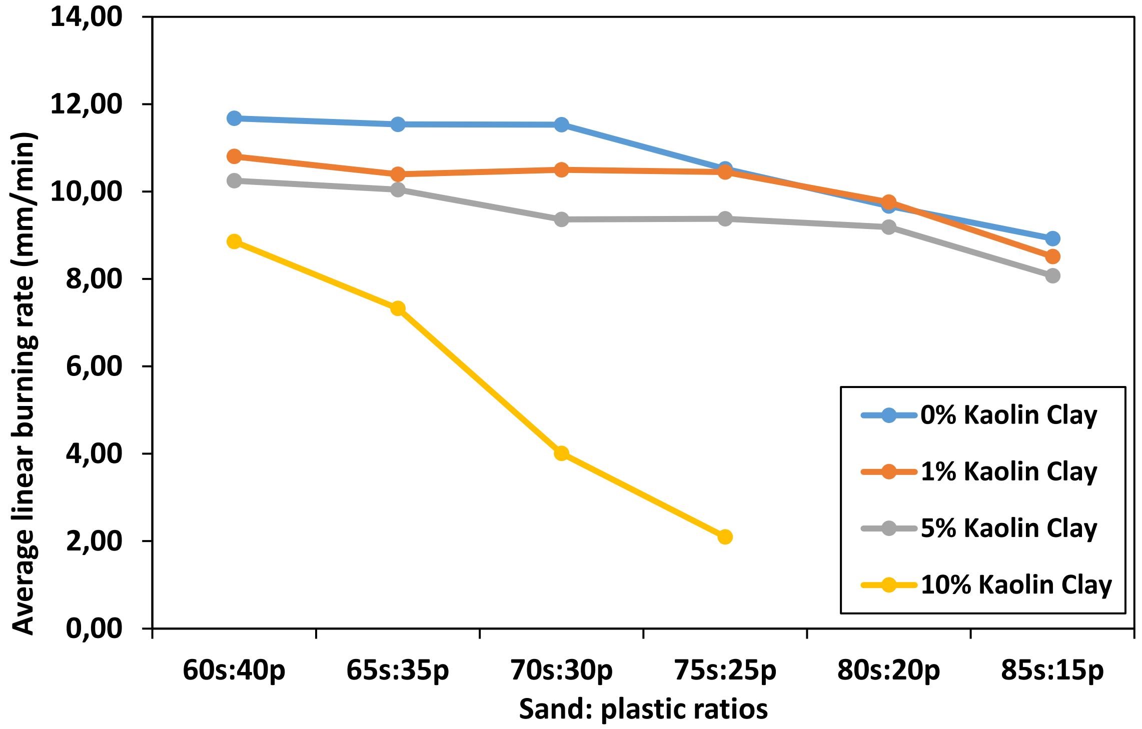


Figure 6. 7: Average linear burning rate in the six ratios with 0%, 1%, 5%, and 10% Kaolin Clay DSF

The burning rate of the composite material with Kaolin Clay was investigated at different proportions with the following findings. At 0% addition of Kaolin Clay, the burning rate was 8.93 mm/min, which was the slowest in the 85s:15p ratio. When 1% of Kaolin Clay DSF was added, it caused a decrease in the burning rate for all ratios except 80s:20p. The lowest burning rate observed was 8.51 mm/min in the 85s:15p ratio.

The addition of 5% Kaolin Clay DSF resulted in a further decrease in the burning rate for all ratios, with the lowest burning rate of 8.08 mm/min found in the 85s:15p ratio. This addition had a considerable impact on all ratios, leading to an average decrease in the burning rate of approximately 11%. With the addition of 10% Kaolin Clay DSF, a substantial decrease in the burning rate was observed. For instance, the burning rate decreased from 10.52 mm/min to 2.10 mm/min in the 75s:25p ratio. This addition caused an average decrease in the burning rate of approximately 81%.

Overall, the addition of Kaolin Clay DSF had a notable effect on decreasing the burning rate across different ratios, with the most significant impact seen at higher percentages of Kaolin Clay DSF.

Consolidated Analysis

When 1%, 5%, and 10% Kaolin Clay DSF was added to the six sand: plastic ratios, the burning rate was the slowest in the 10% addition of Kaolin Clay which can be attributed to the following factors:

Firstly, the addition of Kaolin Clay DSF to the plastic-sand brick mixture can enhance its fire resistance properties. Kaolin Clay is known for its ability to act as a flame retardant by releasing water vapor and creating a barrier that inhibits the spread of flames. In their study, Zhang et al. [290] established that Kaolin Clay has the ability to significantly improve the fire retardant property of polymer composite.

Secondly, the composite material benefits from a higher percentage of sand (75%), as it contributes to better insulation and acts as a heat sink. The presence of sand, a non-combustible filler, effectively reduces the rate of burning for the mixture, enhancing its overall fire resistance [291]. The incorporation of sand into the mixture contributed significantly to the bricks' ability to withstand higher temperatures, addressing the plastic's inherent susceptibility to fire. The presence of sand enabled the bricks to function as efficient thermal insulators, making them suitable for thermal insulation purposes [230]. The thermal resistance test conducted by Sahani et al. [249] revealed that the bricks' capacity to resist heat increased with higher amounts of sand.

Sahani et al. [249] recorded that the plastic-sand brick with a ratio of 1: 5 demonstrated the best thermal resistance, withstanding temperatures up to 181.30 °C. The structural properties of the plastic-sand brick with ratios of 1: 3, 1: 4, and 1: 5 remained unchanged up to temperatures of 1100°C, 1490°C, and 1800°C, respectively. This can be attributed to the superior thermal resistance of the sand component, which provided effective insulation against heat [249]. In assessing sand and plastic, it is found that sand has a much lower flammability property compared to plastic. Therefore, increasing the sand content in the plastic-sand brick can promote better results for thermal resistance. The study conducted by Solomon et al. [282] emphasized that sand has thermal resistant characteristics that imparts insulation in the plastic-sand brick. This is also confirmed in the research of Sahani et al. [249] and Babatunde et al. [292]. Sand serves to be an insulator, decreasing the composite's susceptibility to fire.

Thirdly, while the plastic component provides binding and shaping properties to the brick, a higher proportion of plastic is highly susceptible to fire. The lower plastic content in the 75s:25p ratio, will promote thermal-resistance which results in a slower burning rate [282].

Lastly, the combination of the 75% sand and 25% plastic, and 10% Kaolin Clay DSF ratio seems to exhibit a synergistic effect, where the properties of the materials work together to enhance fire resistance. The 10% addition of Kaolin Clay DSF in the 75s:25p ratio may have provided the optimal balance of flame retardancy, resulting in the slowest burning rate. Although, the 75s:25p ratio was identified as the most significant in terms of fire resistance in this particular study, further research and testing would be needed to validate these findings and explore the underlying mechanisms in more detail. The fire resistance of plastic-sand bricks is now becoming an area for further research [158].

6.7 Summary of environmental properties

Figure 6.8 shows a summary of the environmental properties of the plastic-sand brick.

70s:30p

- **Water absorption test**
- The ratio of 70s:30p exhibited the lowest rate of water absorption after 21 days. Notably, the addition of 5% Kaolin clay led to a significant decrease in the rate of water absorption, reducing it from 0.78% on day 1 to 0.43% on the 21st day. This suggests that the plastic-sand brick samples are of good quality, since they absorbed less than 20% of their total weight, a desirable characteristic for high-quality bricks.

60s:40p to 85s:15p

- **Water contact angle test**
- The readings of the contact angle were greater than 45° in all the ratios. These readings also indicated that the plastic-sand brick sample is hydrophobic i.e. it resisted the instanteous absorption of water for the 0%, 1%, 5%, and 10% of the addition of Kaolin Clay DSF.

60s:40p to 85s:15p

- **Efflloresence test**
- There is no visible deposit of alkalis present in all six ratios on the surface of the plastic-sand brick samples. This implies that the plastic-sand brick samples have long term durability.

60s:40p to 85s:15p

- **Electrical Resistance Test**
- The readings in all the ratios of the samples showed a consistent resistance of 0.01 ohms. The addition of 1%, 5%, and 10% of Kaolin DSF to the plastic-sand mix in all ratios hindered the free movement of electrons within the polymer structure. As a result, the composite material exhibited insulating properties, preventing the flow of electric current.

75s:25p

- **Fire Test**
- The addition of 10% Kaolin Clay DSF had the most effect in the 75s: 25p ratio which decreased the burning rate significantly from 10.52 mm/min to 2.10 mm/min respectively. There was an average decrease in the burning rate of approximately 81%.

Figure 6. 8: Environmental properties results

6.8 Conclusion

The findings revealed that the environmental properties of the plastic-sand brick were influenced by both the plastic-sand ratio and the inclusion of Kaolin Clay DSF. Hence, the introduction of the innovative plastic-sand bricks with such advantageous environmental properties holds tremendous potential and offers several advantages that can transform the local and global construction landscape. In their study, Aneke and Shabangu [166] indicated that plastic-sand bricks do have an advantage over burnt clay bricks, since they have high hydrophobic characteristics which makes them comparatively stronger against chemical degradation.

CHAPTER SEVEN

COMMERCIALISATION OF PLASTIC-SAND BRICK

7.0 Introduction

This chapter highlights the increasing demand for a more sustainable and economically viable solution that has led to the development of plastic-sand bricks made from recycled materials. It presents a conceptual model that outlines a novel strategy for sustainable building and construction materials utilizing recyclable HDPE plastic. The model seeks to mitigate the harmful effects of toxic waste on the environment and society from an economic perspective. The chapter explains the potential of the composite material in addressing the challenges posed by the four global crises, particularly within the South African context.

The chapter also outlines the steps required to transition from laboratory scale brick samples to full-scale marketing and production, as well as launching it in the public domain at a commercial and industrial level. Additionally, it addresses initial concerns and challenges associated with establishing the plastic-sand brick as a viable and environmentally friendly option in the construction industry. The chapter also identifies opportunities for expansion and improvement. Finally, the efficacy of forming plastic-sand material or building blocks has been explored towards contextual application of the composite material in the construction industry.

7.1 Model promoting Sustainability and Sustainable Development

Figure 7.1 shows the proposed model aimed at presenting individuals and companies with an engineering solution that encourages and promotes sustainability and sustainable development through the production of eco-friendly plastic-sand bricks. Furthermore, this engineering solution will have a positive effect on the four crises discussed in Chapter 2.

a. Plastic waste is hazardous and is experienced as one of the most worrying environmental issues because it is increasing at an alarming rate and society has lost their firm grip on tackling the issues of plastic pollution. Plastic pollution is now a local and global problem affecting millions of people since it is found ubiquitously. Plastic waste accumulate in the environment because of its increased production, changed lifestyles and poor practices, and lack of effective and proper disposal methods [293]. Therefore, plastic pollution, has become detrimental to living organisms. Plastic pollution eventually changes the patterns of ecosystems, people's lifestyles, food security, poses serious health issues and is a threat to sustainability. On one hand, it is understood that plastic pollution results in serious environmental threats, whilst on the other hand, it presents many economic opportunities to individuals and companies which can be remoulded into new products and simultaneously reducing global challenges [294]. The proposed model advances plastic waste as valuable material that can be converted into useful materials such as plastic-sand bricks.

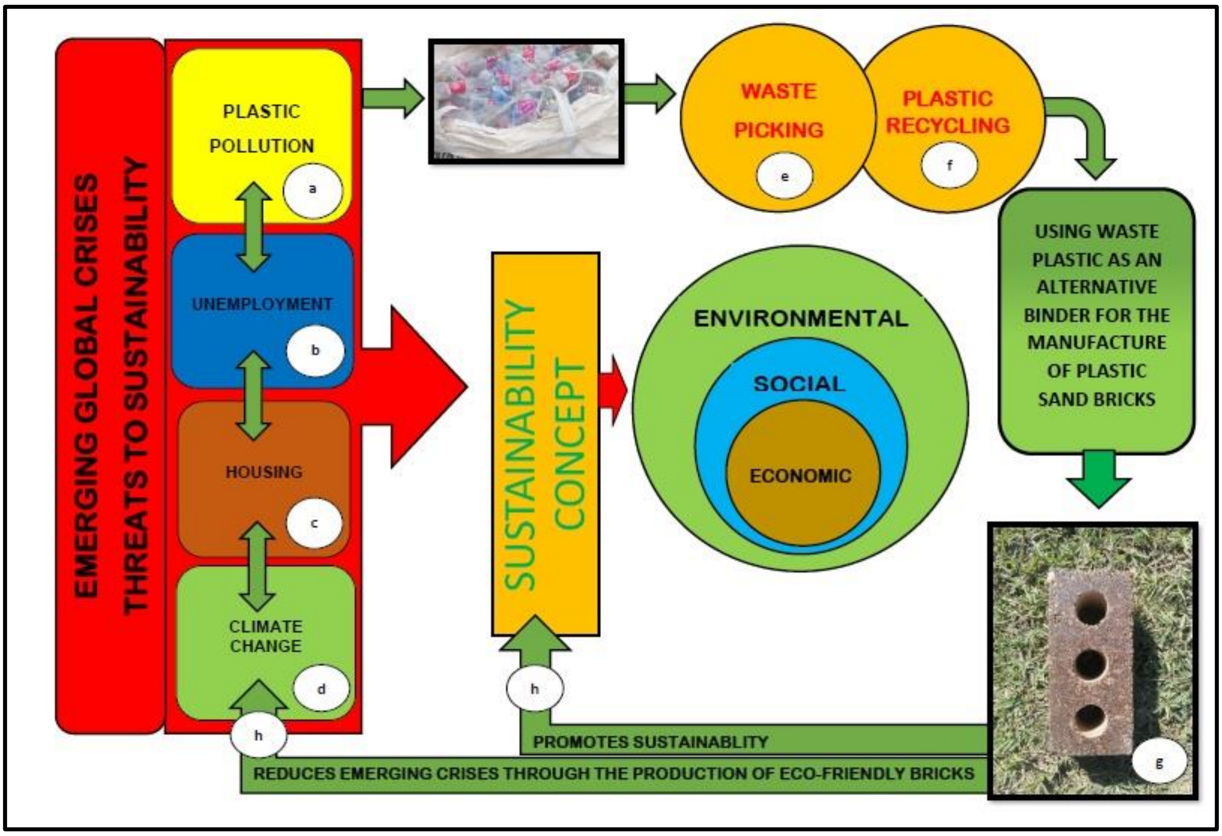


Figure 7. 1: Proposed model of promoting sustainability and sustainable development

b. Unemployment is a crucial economic factor since it signals a weakening state of a country's economy. A high rate of unemployment affects millions of households and contributes to increasing poverty more especially to the underprivileged communities. Also, if more people are unemployed, it implies that the production rate of the economy is affected and less workers mean less total economic production. South Africa's status regarding unemployment is no different. The unemployment rate increased to 32.9% during the initial quarter of 2023. The danger of this scenario is that it can lead to unintended consequences such as more people who are left starving which will lead to crime, violence, and unrest. Government, business, municipalities and ordinary citizens have an important role to play in order to create jobs so that people are able to earn a living and contribute to the economic growth of the country. It is conceivable that the production of plastic-sand bricks has the capacity to create jobs for waste pickers, machine operators and encourage small business industries to develop.

c. Housing is regarded as a basic human need. Currently, the demand for affordable housing is on the rise and ownership is becoming difficult for a large number of people both locally and globally. Governments are finding it difficult to match the demand of housing with affordability since the ongoing challenge of rising building costs and other related factors such as fraud and corruption still prevails [295]. Millions of people live in temporary dwellings, migrating to urban areas causing greater stress to themselves and the local municipality. Lack of affordable housing means that people and communities will experience problems of food, security, dignity and not having a stable family unit. Businesses and political leaders need to have the will to provide solutions to this problem. One example of solving the housing challenge is the manufacturing of plastic-sand bricks that will assist towards greener and more affordable housing schemes. Therefore, this model highlights that recycling has the potential of reducing the waste plastic and its inclusion in brick production could be valuable for the provision of affordable and eco-friendly housing in many countries.

d. Traditional houses being built from clay and cement brick can be traced back to production of much dangerous carbon emissions and resultant pressure on the depleting natural resources such as sand and clay from river banks. These emissions are trapped in the earth’s atmosphere, which results in global warming and contributes to climate change across the globe. Disruptions in the ozone layer causes catastrophic changes in the weather patterns causing flash floods, heatwaves, droughts and melting of the ice-caps resulting in a rise of sea levels [296] [297] [298]. Evode, et al. [299] argues that there are several problems due to insufficient recycling of plastic waste. Therefore, reducing plastic waste can be increased to prevent atmospheric pollution and to reduce the negative impact it causes on our climate leading to devastation to life on earth. Therefore, instead of dumping plastic waste or using incineration methods to dispose plastic, there must be a strategy to reduce air, marine and land pollution. One such strategy is recycling, which can be used to transform plastic waste into alternative building material, for example, the plastic-sand bricks as proposed in this study.

e. This model recognises the value of waste pickers in encouraging and promoting environmental, social and economic sustainability. Clearly, the waste pickers whilst living in poverty, have for decades played a significant role towards social, economic, and environmental benefits more especially to the circular economy goals and sustainable development goals in developing nations. The role of waste pickers has mostly been unappreciated on most platforms and their challenges ignored [300].

Waste pickers globally gather, transport, separate and sell waste to earn their living but are largely excluded, marginalised and live within the underprivileged sections of society. Waste pickers organisations (WPOs) have always pioneered to support waste pickers to provide economic, social and environmental sustainability [301]. Waste pickers continue to make a huge environmental, social and economic contribution, diverting waste from landfills even though their image is not received positively by all stakeholders. It is recorded that informal pickers in South Africa are estimated to have saved municipalities huge costs between R309.2 – R748.8 million in landfill airspace (in 2014) by diverting waste material away from landfill, at ± 16-24 tons per annum [302].

f. Recycling gives rise to numerous environmental, social and economic benefits. It helps save our natural resources, reduce energy consumption, and lowers greenhouse gas emissions. Al-Maaded et al. [303] argues that recycling is the preferred solution for plastic waste management because it has a lower impact on the environmental, global warming and on human toxicity levels. Plastic-sand bricks also creates a platform for job creation and new products. It embodies a potential for production of innovative alternative products for the building industry such as pavers, manhole covers, tiles, partition walls, window frames and scaffolding boards.

g. Several studies have indicated that plastic-sand bricks have many advantages when compared to conventional bricks in respect of having higher compressive strength, reduced water absorption and no visible signs of efflorescence. They are also light in weight and have good insulating properties. Therefore, the results from this study are significant and this means that plastic-sand brick can assist to decrease environmental contamination, reduce the amount of clay that is required to manufactured bricks and also presents an option as alternative eco-friendly bricks at affordable prices [304].

h. Chapter 3, section 3.5 demonstrates how the manufacturing of plastic-sand bricks would lessen the impact of the four crises as depicted in *Figure 7.1 (a-d),* viz., plastic pollution, unemployment, the shortage of affordable housing, and climate change as acknowledged locally and globally as a threat to sustainability and sustainable development.

7.2 Meeting the envisaged need at a global and local level of the four crises

It is with great optimism for the building industry that the experimental work carried out in this study using HDPE plastic revealed that there are advantages and economic potential for the use of recycled plastic as a constituent in the production of plastic-sand bricks. This study has shown that the recycling of plastic waste into valuable plastic-sand bricks can assist in reducing the impact of the four global crises in a number of ways as indicated Chapter 3, section 3.5 "Envisaged impact of plastic-sand bricks."

Firstly, the inclusion of plastic waste in the manufacturing of plastic-sand bricks will certainly help in the reduction of plastic waste from land, air and water pollution. This is the result of large quantities of plastic waste being recycled and converted into eco-friendly plastic-sand bricks. The results of the experimental work conducted in this study is in line with the result of Sarwar et al. [237] which emphasised that the manufacturing of plastic-sand bricks using HDPE could be used as an alternative binder to traditional brick. The manufacturing of plastic-sand bricks could decrease the accumulation of plastic waste in the environment which eventually protects our land, oceans and helps the environment recover. This HDPE plastic makes it possible to promote an eco-friendly environment.

Secondly, plastic-sand brick manufacturing will successfully contribute to the removal of waste plastic in all areas of the environment, rivers, oceans and landfills by providing job opportunities to "waste pickers." This would also undoubtedly create other jobs such as machine operators and general workers in the plastic-sand brick plants and reduce unemployment in South Africa.

Thirdly, the potential of using plastic waste into plastic-sand brick production increased the viability of "greener material" in the building of affordable houses. Plastic-sand brick is a promising building material that may positively contribute to the affordable housing objective across the world by decreasing the cost of building construction [305].

Fourthly, plastic-sand bricks will certainly assist in the reduction of GHG emissions and global warming since plastic waste will no longer be incinerated. The use of high energy intensive processes in kilns during the curing of clay bricks will be reduced. Most of the gas emissions released into the environment are ascribed to the use of energy due to the incineration of coal in kiln and the burning of diesel during transportation. The CO^2 emissions is found to be the largest percentage of all gases released into the air [139]**.**

Plastic-sand bricks assist in the reduction of natural resources that are used during the production of burnt clay bricks and also reduces the pollution which is generated from kiln during brick manufacturing. The plastic-sand brick can be used as an alternative building material [306].

7.3 Commercial roll-out to the industrial market

Careful consideration is required to fully implement a commercial roll-out plan of plastic-sand brick value-chain. Many salient aspects must be looked into such as technical expertise, market willingness, sustainability practices, manufacturing compliance, and effective partnership involvement. It is possible to successfully launch the plastic-sand brick in the commercial market. However, scaling up the manufacturing process of plastic-sand brick would require an investment in advanced machinery such as an extruder. The extrusion machine serves an important function in converting waste plastic into plastic-sand bricks. The most important advantage of the extruder is that it does not directly pollute the environment due to the use of electricity. It can be operated without any constraints [306].

It is necessary to conduct a full cost analysis to establish the most suitable price for plastic-sand bricks. It is important to calculate the total cost of raw materials and brick production. Quality monitoring and quality assurance, including logistical costs with delivery arrangements are all related market planning steps that must be considered. The vision to keep production costs as low as possible will assist in making the plastic-sand brick competitive in comparison to conventional construction materials and attractive to potential buyers.

Before the roll-out of the plastic-sand brick as a new initiative, it is compulsory to ensure that it meets all requirements of a brick. The municipal building regulations, standards relating to the environment, waste management framework and specific certifications that are required to comply to alternative building standards must be satisfied. There needs to be collaboration with regulatory bodies and industry institutions to circumnavigate any regulatory challenges and obtain necessary approvals. SABS is the regulatory body which is responsible for the establishment of national standards, ensuring that quality assessment services are provided and adhered to in South Africa. It also constantly develops standards for the building industry, which must be aligned to all building regulations.

In 2011, the SABS introduced the South African National Standard (SANS 10400). Part X of the SANS 10400 takes care of environmental sustainability issues, and Part XA examines the energy use in buildings. The core business of the SABS is to ensure that all components and systems that are either produced or used in the building and construction industry comply with the relevant approved standards. Properties of the plastic-sand bricks must be kept in line with SANS 10400 to ensure that buildings that are constructed from plastic-sand bricks are safe, strong, and sustainable, while simultaneously protecting all aspects of the environment and conserving our natural resources [307] [308] [309].

There needs to be consultation with Agrément South Africa, as established in the National Building Regulation and Standards Act, 1977 (Act No. 103 of 1977) to endorse and provide certification for innovative building products such as the plastic-sand bricks, and also to ensure that clients are protected against unacceptable practices [21].

Teamwork and partnerships play a pivotal role especially during initial roll-out. Therefore, forging this strong relationship with building and construction companies, architects, and other industry role-players will pave the way to integrate plastic-sand bricks not only in housing but into projects such as construction of recreation facilities. The success of plastic-sand brick manufacturing rests on realizing the value this has to waste pickers and the industry. Hence, this partnership and integration of them into the formal economy would ensure a steady supply of plastic waste as raw materials and would provide alternative job opportunities in the formal economy to support themselves and their extended families [310].

Going forward into the future, there needs to be more communication and collaboration between municipalities, government, industry, and university to prioritize all aspects of plastics such as separation, collection and upscaling of manufacturing technologies. It is essential that academia and industry venture into some form of partnerships to create manufacturing technologies that are more sustainable. It is insufficient to only speak of innovations without having a proposed business model in place. Furthermore, international stakeholders, contract, and local-government should be involved in taking this plastic-sand brick initiative to a higher level [311].

Plastic-sand bricks promote sustainability and sustainable development. Therefore, the roll-out would highlight the sustainable properties of plastic-sand bricks, such as making use of recycled plastic, assisting in reducing carbon footprint, and waste deviation from landfills. The plastic-sand brick's alignment to circular economy and sustainable construction practices would be emphasised. Furthermore, completion of the plastic-sand brick's life-cycle to measure its environmental advantages in comparison to conventional building materials would be an ongoing task. For these reasons, it is essential to empower and educate society to act jointly to minimize plastic pollution and use this and similar alternative building products. This type of paradigm shift must be encouraged and possibly made compulsory in the near future [5].

It is imperative to continuously seek improvements and adaptation to keep abreast of alternative building materials. Staying updated with evolving technologies, new materials, and keeping a close watch on current market trends would assist in greater acceptance of plastic-sand bricks. Therefore, the continuous investment in future research and development to improve the mechanical and environmental properties of the plastic-sand brick is necessary. It is important to explore the potential of using the plastic-sand brick's formulation in new applications and to respond and embrace the requests and views of customers, industry experts, and other stakeholders so that sustainability and sustainable development can be achieved. However, Ogundairo et al. [312] warns that research work should not be exclusively limited to a paper exercise. He suggested that pilot-scale projects should be undertaken and implemented to achieve construction industry sustainability.

7.4 Concerns and/or challenges for plastic-sand brick take-off as a viable alternative building product

7.4.1 Scalability and cost-effectiveness of manufacturing plastic-sand bricks

The scalability and cost-effectiveness of manufacturing plastic-sand bricks with Kaolin Clay DSF need to be evaluated. The manufacturing process, including the collection and conversion of waste materials, and energy requirements should be enhanced to ensure efficient and economical production on a large scale. Waste plastic, is found everywhere, and results reveal that it has the potential to be put to real use in brick making. Therefore, the manufacturing of plastic-sand bricks presents an alternative option to the clients at affordable rates [153]. In their study, Dhanjode and Nag [313] highlighted that rapid growth and movement of people from rural to urban areas have necessitated the need for building of houses at large scale. Bricks in general, being one of the key building materials renders themselves to be manufactured at mass level as a matter of necessity.

7.4.2 Market acceptance and perception

The acceptance and perception of plastic-sand bricks in the construction industry and among potential buyers play a significant role in their adoption. Sanchez-Echeverri et al. [12] in their study, showed that 100% of the participants surveyed were eager to purchase alternative cobbles produced from recycled plastic. It was noted that the main reason why people would purchase the recycled products resulted from the decrease in negative environmental impacts when making use of recycled plastic and due to its high durability properties. It was also interesting to discover that the same survey also revealed that 67% of participants were keen to pay a higher price for cobble stone that favored the environment. Therefore, addressing these concerns and/or challenges will be critical for the production of the plastic-sand bricks to establish themselves as a viable option and be widely accepted as an alternative building material in the construction industry.

7.4.3 Waste pickers

Plastic-sand brick manufacturing hinges strongly on integrating waste pickers into the process of collecting plastic for successful manufacturing of plastic-sand bricks. Waste pickers presents their own set of concerns and challenges. In South Africa, waste pickers are vulnerable to the general public more especially being harassed by metro police, ill-treated by urban residents when collecting recyclables and sworn at by passing motorist. Such differentiated attitudes displayed by many stakeholders are largely due to the waste picker policy on integration not being understood by them, i.e. as people who are working for a common purpose. This unfortunate situation stems from the poor state of inclusion of waste pickers into the formal waste management system, which is faced with lack of mutual cooperation, poor acceptance by all stakeholders and the lack of valid identification documents [314].

Based on the study carried out in Durban, South Africa in 2011, the general view among informal street traders revealed that all levels of government (national, provincial and local) did not understand them. In addition, such officials failed to appreciate and support their work activities, yet they contributed to the city's economy. There was tension, lack of trust and good faith by city officials. The Metro Police's poor understanding and misunderstanding of policy has further disadvantaged the informal sector. The tension and conflict between members of the informal sector and police was present because it was mandatory for the law enforcement officials to enforce the relevant informal sector bylaws [315]. Waste pickers often face social stigma and discrimination by citizens and police. The police harass them because they are assumed to be thieves. The general public look down upon waste pickers and see them as animals [316].

The quality and uniformity of the plastic collected poses serious problems. Waste pickers collect their waste from toxic and contaminated environments. Plastics are often polluted with fats, oils and organic substances that need chemicals or soap to be cleaned [317]. Waste pickers continue to make a huge environmental, social and economic contribution, diverting waste from landfills even though their image was not received positively by all stakeholders.

Addressing these concerns and challenges requires a comprehensive and collaborative approach involving various stakeholders, including waste pickers, manufacturers, local communities, NGOs, and government agencies. By providing a supportive and inclusive framework, it is possible to integrate waste pickers into the collection process and for them to contribute to the successful implementation of plastic-sand bricks as a viable alternative building product.

7.5 Room for improvement

The findings of the study conducted by Al-Sinan and Bubshait [142] indicated that there is room for improvement in plastic-sand brick manufacturing. This encourages us to examine our future possibilities and expand this possibility of implementing this new innovation into practice, also discovering new strategies for decreasing plastic pollution. Utilisation of plastic waste in building materials has the potential of combating global warming, while simultaneously taking care of our natural environment. However, this study emphasizes that there is room for improvement, which need to be addressed in future studies such as the following:

- Investigating different ratios and types of plastic for optimal results;
- Obtaining a deeper understanding of the long-term performance of plastic-sand bricks;
- Improving the flammability and fire resistance properties of plastic-sand bricks;
- The absence or the lack of suitable standards and regulations for converting plastic waste into plastic-sand bricks.

This study also advances some areas for improvement in the development and production of plastic-sand bricks:

i) Exploration of different shapes and sizes of HDPE plastic materials and the inclusion of other clay additives to improve the properties of the plastic-sand bricks should be considered.

ii) Experimentation with additional ratios and/or types of plastics as well as comprehensive testing to identify the optimal balance that ensures highest strength, lowest water absorption, and other optimized characteristics to achieve the desired properties of the bricks.

iii) Investigation of advanced techniques for compaction of the molten mortar towards minimization of defects.

iv) Improvement of the manufacturing process to enhance efficiency, consistency, and quality control is essential.

v) Automation and technological advancements can be explored to streamline the production process and optimize the plastic-sand brick production and value-chain.

Continuous research, development, and innovation are crucial towards improving plastic-sand bricks and advancing their adoption as a sustainable and durable alternative in the construction industry [318].

7.6 Proposed alternate opportunities

7.6.1 Plastic-sand brick

An innovative approach has been explored with an endeavour to bridge the gap between research and the industry. After laboratory-scale material testing to determine the most optimal ratio that balances mechanical and environmental properties, a plastic-sand brick of 75s:25p ratio with 5% Kaolin Clay has been proposed. The properties were validated through laboratory testing to ensure that the designed material either meets or exceeds industry standards. The most suitable plastic-sand brick ratio with advanced properties have been designed using SolidWorks software. By utilising a computer-aided design (CAD) software, a detailed design as illustrated in *Figure 7.2* was drawn, which closely resembles the final product that can be used in the industry. *Appendix E* shows the drafted design of the plastic-sand brick conforming to a typical/conventional/traditional brick. This approach ensures that the design is not only feasible but is also compatible with the already existing industry products and building systems.

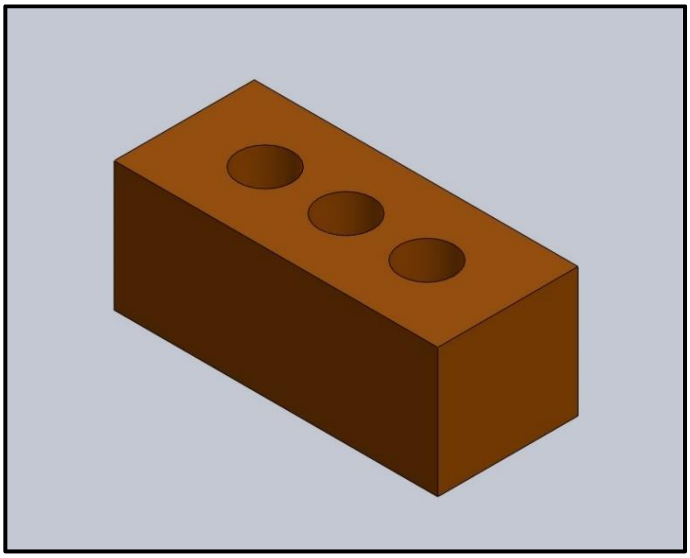


Figure 7. 2: Illustration of the plastic-sand brick for market entry

Since standard brick dimensions tailored to the building and construction industry were used, it could be seamlessly integrated into existing building practices without requiring major modifications. The actual brick sample was manufactured using the final design and formulation of the plastic-brick. The actual brick sample in *Figure 7.3* confirms the possibility of manufacturing bricks from recycled plastic and sand. This could now be used in the building and construction industry depending on the varied applications.

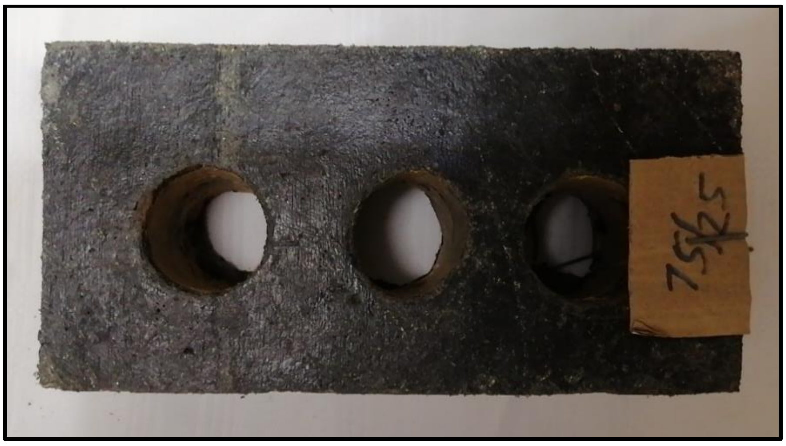


Figure 7. 3: Sample of the innovative full-scale plastic-sand brick

7.6.2 Interlocking compressed fit plastic-sand bricks

In a study by Bredenoord [319] it was proposed that interlocking bricks or building blocks can serve as an option for building houses. It was indicated that bricks are easily accessible or are being produced in various sizes and shapes. Accurate specifications of these interlocking bricks can be manufactured. These bricks, like plastic-sand bricks can be pressed onto each other and such process requires little to no cement.

This alternate opportunity of making interlocking plastic-sand bricks could be reused in other building and construction works. Therefore, using plastic-sand brick in this way allows for the construction of houses in lesser time. Another advantage is that the interlocking plastic-sand bricks can be used as building material for the construction of temporary or emergency housing as and when the need arises**.** It is feasible to produce interlocking type plastic-sand bricks, which offer advantages in construction projects due to their lightweight nature and cost-effectiveness [289].

This section presents a paradigm shift for the building of houses using the extended proposal of interlocking bricks. This new architype as illustrated in *Figure 7. 4* has countless potential to contribute to huge saving in building costs, construction time, increased output, sustainability and sustainable development, socio-economic-environmental advantages in the building and construction industry. *Appendix F* shows the draft design of the interlocking compressed-fit plastic-sand bricks. Additionally, these promotes the construction of houses using robotics technology that has found its niche in the building and construction industry. Various laying methods for interlocking brick construction can be seen in *Figure 7.5*.

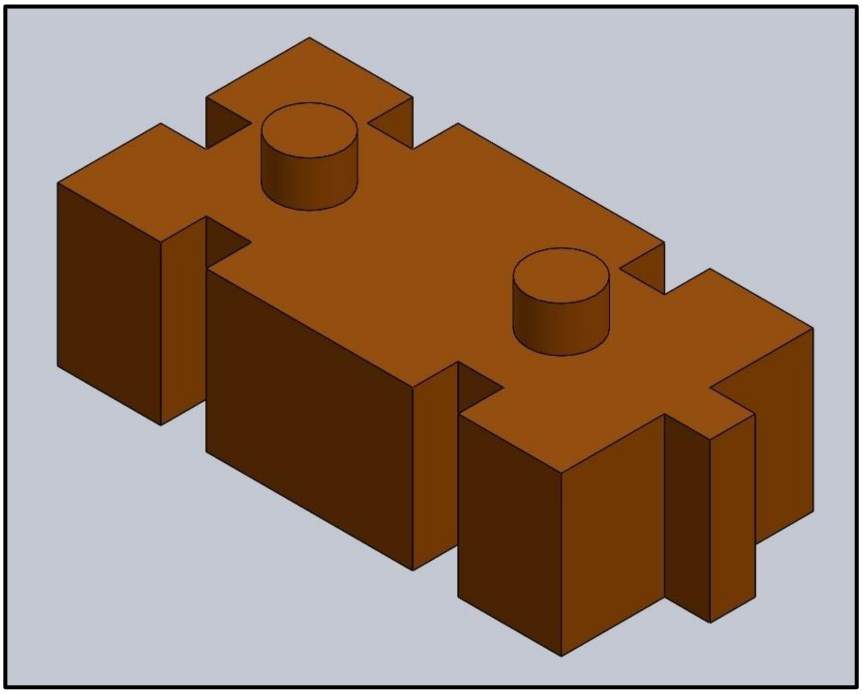


Figure 7. 4: Design of the innovative interlocking plastic-sand bricks using pressure fit

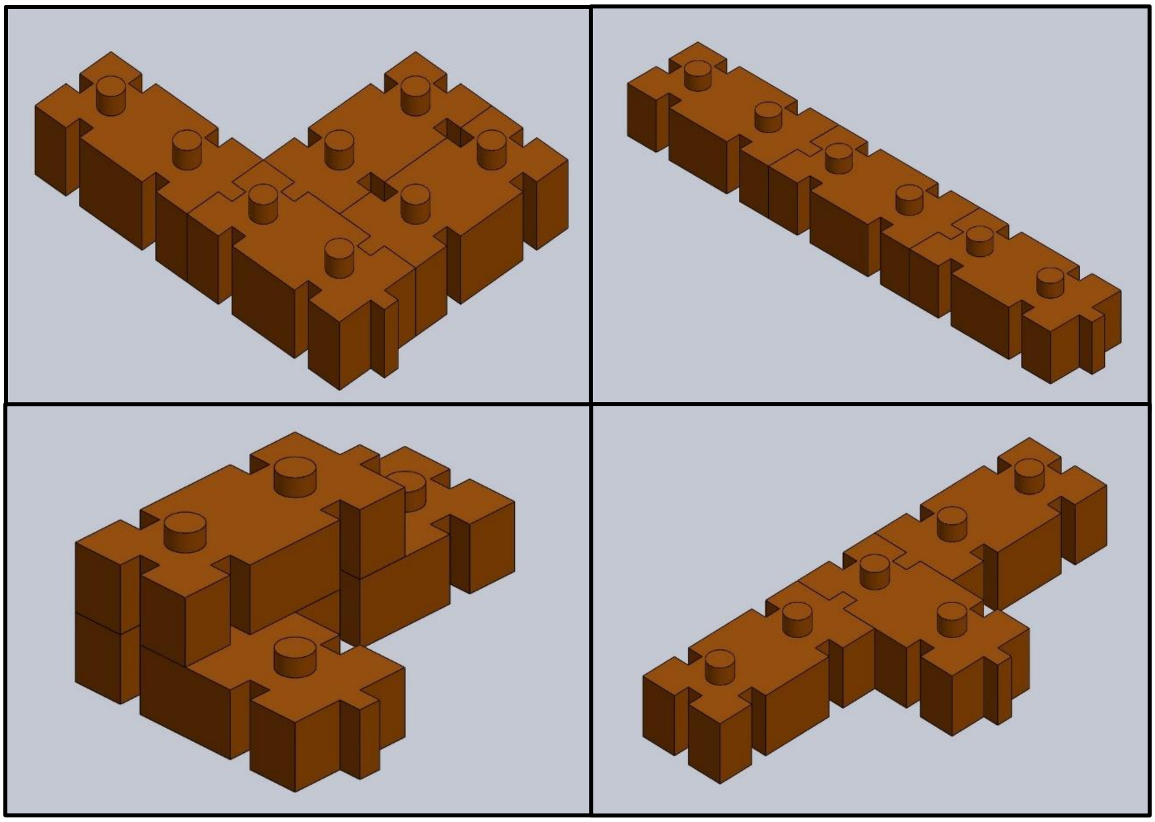


Figure 7. 5: Laying methods for interlocking brick construction

Hence, this proposed sample presents a valuable contribution to the building and construction industry since it provides an “integrated-combination” of previously three separate opportunities:

i) Uses of “HDPE plastic” in brick manufacturing [146] [161] [320] [321].

ii) Provides the extended opportunity of using interlocking “compression techniques” [322] [323] [324] [325] [326] and

iii) Renders itself to investigation with advanced technology such as robotic installation [327] [328] [329] [330].

Notwithstanding that this proposal has been realized during the initial experimental stage, further consideration is still required in customized specifications, design features for compression and type of mould before this proposed idea can be applied in modern day building practices, Therefore, it is possible to modify the plastic-sand brick from this study combined with many inter-locking features which will not require any cement or mortar, as illustrated in *Figure 7.6*.

Figure 7. 6: Sample of the innovative interlocking plastic-sand brick using pressure fit

Benefits of using plastic-sand interlocking compression fit bricks

(a) This interlocking plastic-sand brick in *Figure 7.7* is composed of 75s:25p with 5% addition of Kaolin Clay. There are several benefits for the building and construction industry i) they are very robust and durable due to its high compressive strength. ii) require little to no cement depending on the context. iii) are also less susceptible to the absorption of water. iv) are faster and convenient to install as compared to the traditional burnt clay bricks, and v) are relatively less heat-intensive due to their manufacturing process.

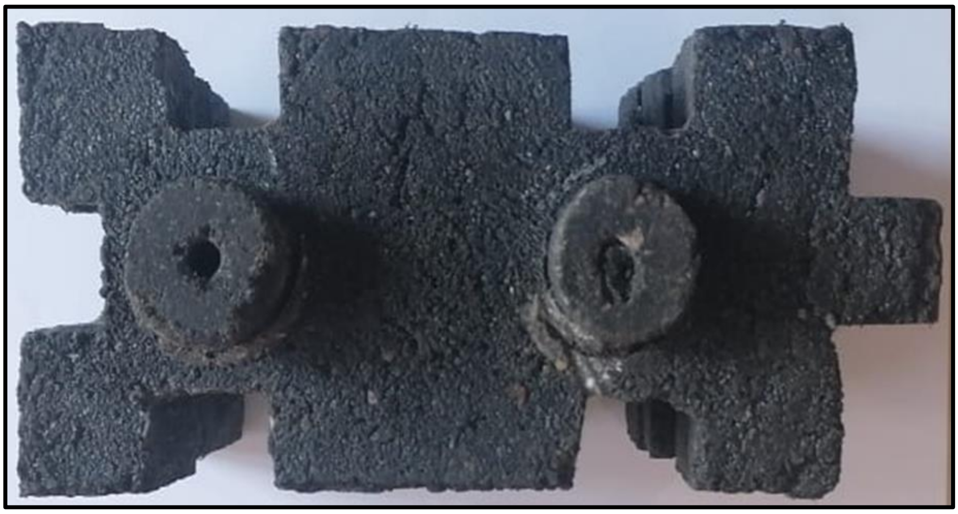


Figure 7. 7: Interlocking plastic-sand brick

(b) Mainly, these interlocking plastic-sand bricks are the enhanced version of the traditional cement and clay burnt bricks. They could also be compressed fit using robotics technology due to the unique design features. It has interlocking features from all sides including the compressed fit from above and below. The self-locking mechanism can be varied from a simple "U- shaped" to more complex interlocking designs. Interlocking bricks are formulated with a smooth finish and texture. These interlocking plastic-sand bricks used in the construction of walls would not necessarily require plastering. A thin layer of durable paint could be used to conceal the interlocking border-lines or designer boards could be fixed to it, varying its texture and design on the inside or outside. This type of brick gives opportunities for do-it-yourself (DIY), unskilled or semiskilled workers to be employed since they align themselves perfectly horizontally and vertically in a continuous course, or at the corners of any building. A building constructed of plastic-sand interlocking bricks can be disassembled and reused without much damage. This paradigm shift in the building and construction industry from cement and burnt clay bricks to high-quality interlocking compressed fit plastic-sand brick is a concept towards a greener, less carbon footprint and a sustainable economy.

Ways of using plastic-sand interlocking compression fit bricks

The new innovative bricks can easily be laid as indicated in *Figures 7.8 to 7.11* namely:

i) Straight line walling,

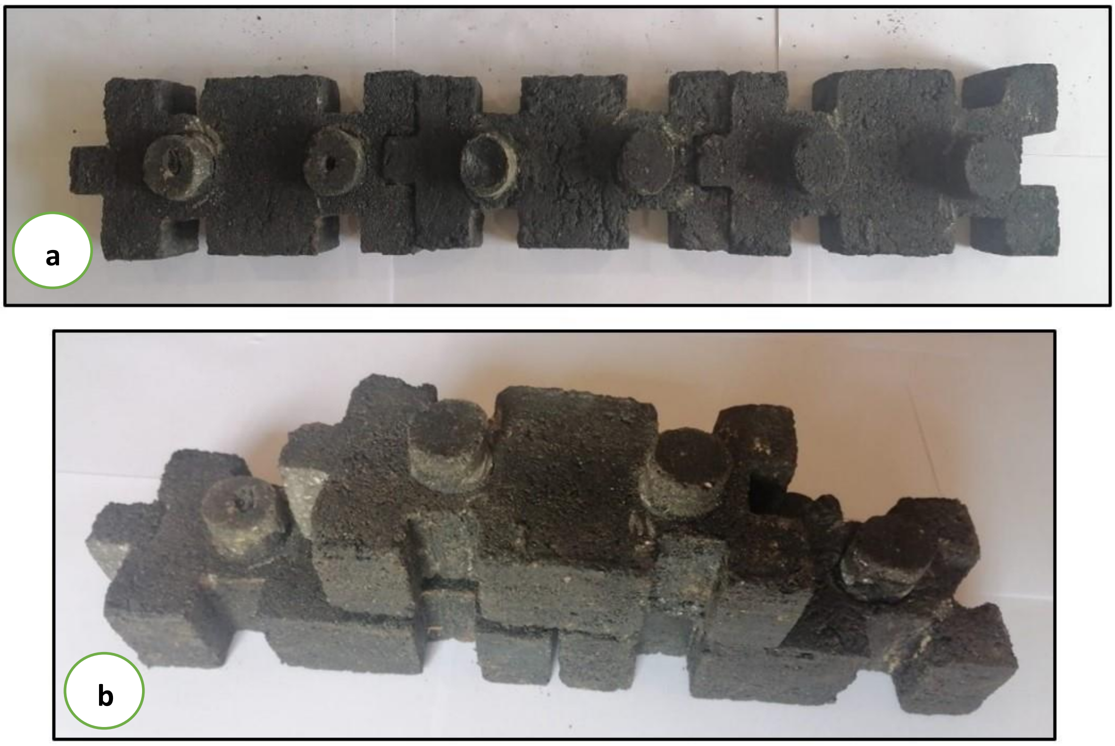


Figure 7. 8: a) Horizontal and b) vertical straight line walling

ii) at right angles without any modification.

Figure 7. 9: Isometric view of right angled walling

iii) T- intersections can be constructed at ease due to is modular design.

Figure 7. 10: T-section construction

iv) Columns or pillars can be constructed due to its compress fit design.

Figure 7. 11: Column construction

7.7 Conclusion

This chapter concludes with a practical model which elucidates the transformative potential of converting waste plastic materials from the environment into valuable building products, such as plastic-sand bricks, despite the numerous adverse impacts of plastic waste on the environment, society, and the economy. The inclusion of waste pickers in the recycling process will enhance the production of plastic-sand bricks. It is increasingly apparent that these eco-friendly bricks hold promise for widespread use in the construction industry, thereby fostering sustainability and sustainable development at both national and global levels by replacing traditional clay bricks with plastic-sand bricks. The production of plastic-sand bricks serves as a tangible solution that aligns with the urgent calls for action to mitigate the effects of the four global crises. This study finds support in the research of Silviyati et al. [146] who advocates for the use of plastic as a binding agent in lightweight brick mixtures. Additionally, Abdel Tawab et al. [212] conclude that the concept of sustainability is gradually gaining significance in the construction industry, both locally and globally.

It succinctly outlined a pathway for the commercial rollout of the material, transitioning it from a small-scale sample to full-scale production in the industrial market. Additionally, the chapter addressed immediate concerns and challenges associated with adopting the plastic-sand brick as a viable alternative building product in the construction industry. Finally, it proposed the exploration of interlocking bricks as an additional option for constructing houses and suggested potential areas for further improvement.

CHAPTER EIGHT

CONCLUSION

8.0 Introduction

Section A provides a comprehensive overview of how the developed composite material effectively addresses the research objectives. Section B succinctly explains how the study aligns itself with the interventions prescribed by the South African National Strategy at the local level. Furthermore, it triangulates the study's outcomes with the calls for action and global decrees articulated at the UN World Conferences of sustainability held between 1972 to 2022 *(Refer to Annexure A)* as well as the interventions required by National Development Plan (NDP) 2030. The findings of the study demonstrate significant progress in utilizing HDPE as an alternative binding material.

SECTION A: ADDRESSING THE RESEARCH OBJECTIVES

8.1 Meeting the research objectives

a) To identify the most optimal ratio of a suitable plastic to be mixed with sand in manufacturing a plastic-sand brick that is durable, high strength, less water absorption.

The evaluation of the plastic-sand bricks was based on two very important benchmark tests: compressive strength and water absorption. The compressive strength test measures the ability of the brick to withstand external forces and is an important indicator of its structural integrity. The water absorption test assesses the brick's ability to resist water penetration, which is crucial for durability and resistance to moisture-related damage. To ensure accuracy and validity, five samples were prepared and tested for each ratio with varying additions of Kaolin Clay. This replicability helps to account for any variability and provides a more reliable representation of the material's properties that have been tested.

Based on the results of the tests, it was determined that the combination of 75% sand and 25% plastic, with the addition of 5% Kaolin Clay DSF, yielded the most optimal plastic-sand bricks in terms of compressive strength and water absorption. This indicates that this particular combination provided the desired mechanical properties and environmental performance, making it a suitable choice for manufacturing durable and low-water-absorption bricks.

Based on the systematic experimental plan and the analysis of the test results, the most optimum ratio for the plastic-sand brick was found to be 75% sand and 25% plastic (75s:25p). Additionally, the most optimal additive quantity of Kaolin Clay DSF was determined to be 5% when added to each of the six ratios.

b) To settle on a suitable additive and quantity that could enhance the binding capacity of plastic in molten state and to achieve a mix with better binding quality.

A thorough process was followed to identify the most suitable additive for the plastic-sand brick samples. This included consulting numerous local and international companies, and evaluating multiple additive products. Other factors for the improvement in mechanical and environmental properties such as fire retardation, increased compressive strength, reduced water absorption, logistic and additive costs were considered.

A range of additives were considered during this research study, including Bentonite, Shelsite 30B, Montmorillonite Nanoparticles, Montmorillonite 15A Nanoparticles, Montmorillonite Clay, Nanoclay Modified Asphalt Materials, Nanofil 116, Cloisite C++, various clay groups, and Kaolin Clay DSF. The focus was on additives that primarily consisted of silica and those that had the ability to enhance bonding properties in polymers.

Further research was conducted specifically on potential additives that could improve the binding properties between plastic and sand molecules. As a result, it was discovered that Kaolin Clay DSF, sourced from Cape Town was used in polymer compounds and other commercial products. The high volume of silica present and its capability to enhance bonding in polymers made Kaolin Clay DSF a favorable choice as an additive for the plastic-sand bricks.

After considering the multiple factors, extensive research, and the availability of Kaolin Clay DSF at low cost, it appeared to be a suitable additive for enhancing the properties of the plastic-sand bricks.

c) To reduce plastic waste through plastic-sand brick production that causes pollution on air, land, seas, and rivers because it is a great threat to the sustainability of all ecological systems.

It is found that the manufactured plastic-sand bricks in this study provided a sustainable solution for managing plastic waste. Instead of allowing plastic to accumulate in landfills or pollute the environment, it could be recycled and transformed into a valuable construction material. This waste diversion not only reduces air, land and water pollution but also extends the lifespan of plastic materials, reducing the demand for natural resources. The reduced demand for river sand and clay extraction helped protect natural habitats and ecosystems. Sand and clay mining leads to the destruction of wildlife habitats, loss of biodiversity, and disruption of ecological processes. By utilizing plastic waste in the manufacturing of plastic-sand bricks, the pressure on natural habitats is alleviated, supporting the conservation of all ecological systems.

d) To reduce the consumption of natural resources such as river sand and clay for the manufacturing of bricks that resulted in the depletion of natural resources and environmental damage through greenhouse gas emission.

As indicated in this study, the manufacturing of plastic-sand bricks contributed to the reduction of natural resource consumption, such as river sand and clay, and mitigate environmental damage caused by traditional brick manufacturing processes. Plastic-sand bricks use a combination of sand and plastic waste as raw materials. By replacing a portion of river sand with plastic waste, the demand for natural sand can be reduced. Additionally, it reduces the need for sand extraction from rivers, which can cause habitat destruction and disrupt aquatic ecosystems. Traditional clay brick manufacturing requires a significant amount of clay, which is often sourced through mining or excavation. The inclusion of plastic in brick manufacturing helps preserve clay deposits, which are finite resources, and minimizes the environmental impact associated with clay extraction. Plastic-sand bricks help to reduce the consumption of clay in brick manufacturing [153].

The manufacturing process of plastic-sand bricks typically requires less energy compared to traditional brick manufacturing methods, such as firing in kilns. This results in lower greenhouse gas emissions and air pollution. By avoiding the high-temperature firing process, the production of plastic-sand bricks contributes to a smaller carbon footprint and helps mitigate climate change.

By adopting the manufacturing of plastic-sand bricks, we can significantly reduce the consumption of natural resources, promote waste recycling, and mitigate environmental damage associated with traditional brick manufacturing processes. This sustainable approach contributes to resource conservation, waste management, and the transition towards a more environmentally conscious construction industry. This approach not only conserves the valuable sand/clay resources extracted from river beds or mines but also provides an effective means to prevent the accumulation of non-biodegradable plastic waste, benefiting the environment [155].

SECTION B: CONCLUSIONS WITHIN THE SOUTH AFRICAN AND GLOBAL CONTEXT

8.2 Addressing the national strategy for sustainable development in South Africa

Five strategic priorities of the NSSD [210] have been carefully reformulated within the current prevailing context with the hope of enhancing sustainable development. Careful consideration has been noted of increasing global concerns and obstacles indicating unemployment, plastic pollution, depletion of natural resources, GHG emission, global warming and ways of steering safely towards a greener economy. Four out of the five priorities have been selected to address how it is linked to this study. The priorities are indicated in *Figure 8.1*:

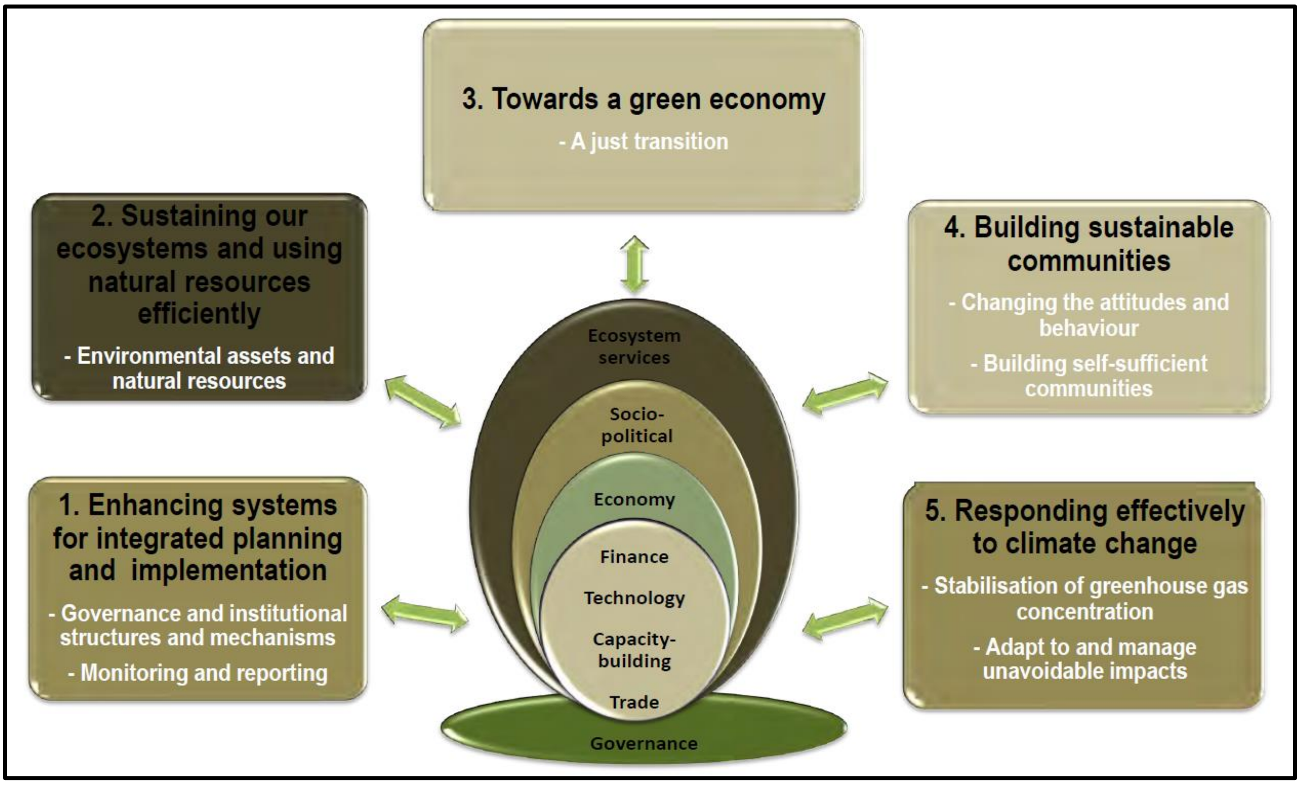


Figure 8. 1: National Strategy for Sustainable Development and Action Plan [210]

There is a direct link between the priorities of sustainable development implemented in South Africa [210] and this research study.

Table 8.1 brought attention to Priority 2 of the National Strategy for Sustainable Development and Action Plan. This requires the interventions on the irreversible loss and degradation of marine, terrestrial, and aquatic ecosystems caused by the irresponsible disposal of waste plastics at the local level. The study also addressed several obstacles in our ecosystem, particularly the depletion of natural resources like river sand, which poses challenges for socioeconomic goals. Managing the use of river sand becomes crucial to ensure its sustainability for the future. Furthermore, reducing air pollution by minimizing the incineration of certain waste plastics was identified as a necessity to protect human well-being as indicated in *section 2.1*.

Table 8. 1: Priority 2- Sustaining our ecosystems and using natural resources efficiently

Priority 2: Sustaining our ecosystems and using natural resources efficiently	
Objectives	Value, protect and continually enhance environmental assets and natural resources.
Goals	• Manage the use of all of the natural resources to ensure their sustainability. • Protect and restore scarce and degraded natural resources. • Prevent the pollution of air, water and land resources so that community and ecosystem health is not adversely affected. •Avoid the irreversible loss and degradation of biodiversity. (marine, terrestrial, aquatic ecosystems).
Intervention	1. Natural resource management. 2. Waste management. • Implementation of the National Waste Management Act No. 59 of 2008. • Ensuring the effective implementation of WM legislation. • Implementation of waste minimisation programmes and the provision of appropriate facilities and incentives to support them.

The study also referenced important global conferences, such as the one in Johannesburg in 2002 and the UN Environment assembly in Nairobi in 2022, which focused on sustainability and sustainable development. These conferences highlighted the growing issue of plastic pollution worldwide. The resolution recognized the entire lifecycle of plastic, from production to waste, and established an Intergovernmental Negotiating Committee (INC) to develop a legally binding document by the end of 2024, exploring alternatives and promoting reusable and recyclable products (*Appendix A*).

This study addressed these challenges. *Firstly*, it proposed the incorporation of plastic waste into valuable plastic-sand bricks, effectively replacing a portion of sand or clay traditionally used in brick manufacturing. This approach allows waste plastic to remain in its natural environment while offering a solution that reduces the accumulation of plastic waste at the local and global levels. *Secondly*, by utilizing HDPE from the environment along with Kaolin Clay DSF in the production of plastic-sand bricks, the study demonstrated a scientific method for repurposing plastic waste. Ultimately, the study concluded that waste plastics can serve as a viable alternative binder material for the construction industry, providing a sustainable solution to address environmental concerns.

Table 8.2 shed light on Priority 3 of the National Strategy for Sustainable Development and Action Plan that requires the interventions to unemployment as a major crisis both at the national and global levels as indicated in *Chapter 2*.

Table 8. 2: Priority 3- Towards a green economy

Priority 3: Towards a green economy	
Objectives	A just transition towards pro-employment growth path.
Goals	• Create and protect jobs.
Intervention	• Promotion of programmes that create green jobs.

The NY Summit, held on 16 September 2005, resulted in the adoption of several resolutions by the General Assembly [237] at a global level. Unfortunately, the situation in Africa, particularly in the regions south of the Sahara, continues to struggle with the pressing issue of providing decent employment opportunities, particularly for women and the youth (*Appendix A).*

This study addressed the critical issue of job creation, as emphasized in local and global conferences. *Firstly*, by recognizing the role of waste pickers in the informal sector, and *secondly*, by enabling individuals and small to medium enterprises to participate in the production of eco-friendly alternative building materials, thereby contributing to a greener economy. The manufacturing process of plastic-sand bricks would require employing material handlers, machine technicians, supervisors, and production technicians. The importance of job creation as a means to alleviate poverty and reduce inequality was highlighted in the President's State of the Nation Address (SONA) in 2022, the Finance Minister's budget speech in 2022 and the national development Plan (NDP).

State of the Nation Address supports sustainability

President Cyril Ramaphosa, in his SONA, held on 10 February 2022, at the Cape Town City Hall [331] highlighted the vision for the nation's call to rebuild South Africa and making it more prosperous, united and an equal society. He has endorsed the economic reconstruction plan which focused on job creation which will be one of the ways to economic recovery. Government in their efforts continues to reboost the economy by creating and encouraging small and medium businesses and industries which will eventually be able to create employment for many people. Still focused on the major challenges of our country, the president called for combined efforts from all stakeholders to reduce poverty, inequality and unemployment. The president's speech was reassuring to ordinary citizens when he called for people with experience and expertise to be part of job creation. This research study promotes the use of an alternative binder material for the construction industry, and presents opportunities for the creation of jobs in the recycling and the manufacturing industry.

Finance minister supports economic reconstruction and recovery

The finance minister, Enoch Godongwana, has also reiterated that we were in a period economic stagnation for many decades and much needed jobs can only be created through economic sustained growth. Creating jobs will assist in the reduction of poverty and the eradication of inequality assisting us to accomplish our goal of a better, healthier and stable life for all. As indicated in the public employment sector, R76 billion will be set aside for programmes for the creation of jobs. The budget speech concluded with an optimistic view of a people centered recovery programme that is saving lives, improving people's lifestyles and ensuring long term progress and prosperity for our citizens. Unfortunately, nothing has been announced regarding money being set aside to reduce global warming and increasing plastic pollution. However, this research study of creating an alternative building material for the construction industry will have a positive impact for the creation of much needed jobs in the recycling and the manufacturing industry [332].

National Development Plan

The main aim of the NDP is to eradicate poverty and reduce inequality by 2030. We will be able to resolve complex problems in line with the NDP and SDGs, if we work collectively in a united way through all South Africans, tapping on their skills, expertise and energies of the citizens. We also need to ensure that we grow an inclusive economy, build capacities in people, empowering state and leader's capabilities in working harmoniously together in all sectors of society. The NDP acknowledges that poverty has engulfed the majority of the people more especially the poor and we sadly remain an unequal society in respect of capital, education, health and welfare, employment, land ownership, job opportunities and so on [27].

The NDP [333] aims to eradicate poverty and reduce inequality through a multidimensional framework which will promote a cycle of development. As indicated in *Figure 8.2*, increasing the living standards to an acceptable level is emphasised in the NDP and this will be dependent on increasing employment, promoting high income levels through sustainable growth, promoting a social wage and good service delivery. In order for the NDP to be realised it requires people of strong leadership an active and participative citizenship as well as an effective, efficient and proactive government that can initiate and drive all forms of development in an environment which all people are working together towards a common goal for a prosperous and a better life for all.

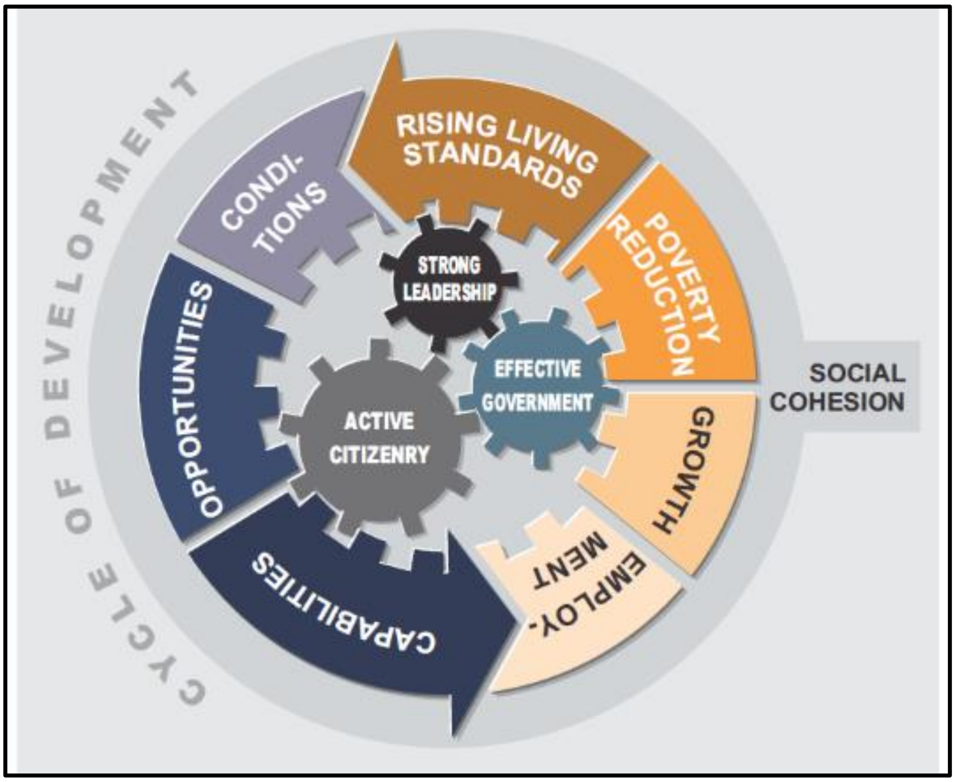


Figure 8. 2: Key priorities of the National Development Plan 2030 [333]

This study fulfils the key priorities of NDP 2030 of South Africa [334]. The NDP recognizes that unemployment is a significant challenge in South Africa, particularly affecting the youth. To address this issue, this study has the potential to reduce the unemployment rate by 2030 which creates opportunities for waste pickers and sorters, machine operators in the plastic-sand brick manufacturing industry. It proposes several strategies to promote job creation. It also stimulates economic activity and creates jobs in the construction, building and related sectors. The NDP emphasizes the crucial role of small-medium enterprises. This study advocates for individuals or groups to establish their own small brick manufacturing enterprises and waste pickers to establish buy back centres where possible.

The NDP recognizes the importance of adequate affordable housing and well-planned human settlements to improve living conditions for South Africa's citizens. This study provides access to affordable housing for all South Africans, particularly low-income households, through various means such as government-supported housing using reasonably priced eco-friendly building material such as plastic-sand bricks.

Table 8.3 highlights Priority 4 of the National Strategy for Sustainable Development and Action Plan that requires the interventions to increasing use of plastics and its detrimental impact on the environment. This is discussed in *Chapter 2, section 2.1.1* that projects a significant rise in plastic consumption and waste generation in the coming decades. Consequently, plastic has become a major source of environmental pollution both at the national and global levels.

Table 8. 3: Priority 4- Building sustainable communities

Priority 4: Building sustainable communities	
Objectives	Create community awareness and participation, and work together to protect the environment through changing attitudes and behaviour in consuming resources sustainably and responsibly.
Goals	• Enhance spatial planning to promote social cohesion and integration between communities, as well as between communities and the natural environment.

Intervention	• Implementation of local waste collection/recycling initiatives.

Global environmental conferences organized by the UN, such as the UN Environment Assembly in Nairobi [244], have issued warnings regarding the escalating problem of plastic waste accumulation. The conferences emphasized the urgent need to address the severe global consequences of plastic pollution and called for immediate real, effective and serious action at local and global levels. The conferences concluded with a strong call to promote sustainable design practices, focusing on waste reduction, recovery, reuse, remanufacturing, recycling, and overall minimizing waste generation (*Appendix A*).

This research study emphasis the need for the implementation of local waste collection and recycling initiatives to ensure plastic-sand brick production. Notably, the integration of waste pickers into the formal sector in South Africa has played a crucial role in collecting plastic waste for the production of plastic-sand bricks. Godfrey and Oelofse [56] projected an increase in the number of waste pickers, reaching around 215,000 by 2017, and this number continues to grow. The South African Government, along with industry and various stakeholders from academia, research, and business, acknowledges the significant contribution of waste pickers in diverting plastic waste away from landfills and towards recycling, reuse, and recovery [247]. This study allows for building of more durable and affordable houses to meet the basic needs of the people of our country and be sensitive to the ecosystems and natural resources that exist. Due to urbanization and industrialization, there is a need to increase the quantity and quality of houses. More attention must be given to housing as it is a global crisis.

Table 8.4 focuses on Priority 5 of the National Strategy for Sustainable Development and Action Plan that requires the interventions against the extensive disposal and incineration of plastics on a daily basis, leading to environmental damage, air, land, and water pollution, as discussed in Chapter 2. Additionally, the manufacturing process of clay bricks and the use of coal in production significantly contribute to greenhouse gas (GHG) emissions and global warming.

Table 8. 4: Priority 5- Responding effectively to climate change

Priority 5: Responding effectively to climate change	
Objectives	• A fair contribution to the global effort to achieve the stabilisation of GHG concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. • Effectively adapt to and manage unavoidable and potential damaging climate change impacts through interventions that build and sustain South Africa's social, economic and environmental resilience and emergency response capacity.
Goals	• Decrease GHG emissions to levels required by science/in line with Cabinet-approved targets – with particular emphasis on the energy sector, which accounts for over 70% of South Africa's emissions (GHG emissions to peak between 2020 and 2025 and decline from 2035). • Build resilience to climate change in communities. • Develop, implement and maintain a GHG emissions information management system in respect of the energy sector.
Intervention	• The use of incentives and disincentives, including regulation and the use of economic and fiscal measures, to promote behaviour change that would support the transition to a low-carbon society and economy. • Contributing towards the achievement of the renewable energy goals, energy security and the reduction of GHG emissions.

The Earth Summit Conference convened by the UN General Assembly in 1997 [234] and the Paris Agreement for sustainable development (2015) emphasized the urgent need for global action to address the negative impact of GHG emissions on climate change (*Appendix A*)

This research study strategically addresses the factors contributing to climate change. The proposed manufacturing of plastic-sand bricks offers an alternative approach that minimizes the lengthy baking and curing processes associated with traditional clay brick production. By using plastic waste in the production of plastic-sand bricks, the study promotes the retrieval of waste plastic from the environment, transforming it into a valuable resource and alternative binder material to be used in the construction industry. This approach helps mitigate gas emissions that would have otherwise been released into the atmosphere.

8.3 Limitation of this study

Many studies have documented the ongoing damages identified in many national, continental and global crises. Most of these research studies highlighted topics such child labour violence, gender-based violence, human trafficking, education, food and nutrition, health, the environment, social and political turmoil, security and droughts. It is tough to discuss all these crises. Therefore, this study focused on just the four crises (plastic pollution, unemployment, lack of affordable housing and climate change) that are intensifying at a shocking rate in South Africa and globally. This study proposes only one of the many opportunities of utilizing recycled plastic waste to produce alternative building material such as eco-friendly plastic-sand bricks.

8.4 Conclusion

This chapter culminates by showcasing how the developed composite material successfully achieves the research objectives set forth in the study. The traditional clay brick has been widely used as a common building material in masonry construction. However, with the increasing demand for bricks and the need to reduce plastic waste, researchers have explored incorporating different types of plastic waste into bricks. This innovative approach of creating plastic-sand bricks offers hope and potential for developing new civil engineering materials with promising applications in the construction industry [335] [230].

The study concludes that HDPE plastics have the potential to be incorporated into brick manufacturing that exhibit superior strength compared to traditional cement or burnt clay bricks. Furthermore, the addition of Kaolin Clay DSF enhances both the mechanical and environmental properties of the plastic-sand bricks. This suggests that the manufacturing process of plastic-sand bricks is environmentally friendly, offering a viable solution to tackle plastic waste, unemployment, escalating building costs, and climate change. Tulashie's research [336] has led to the conclusion that there is no singular combination of ratios suitable for producing sustainable and eco-friendly plastic-sand bricks. The study also revealed that choosing the right ratio often involves trade-offs among various factors, such as compressive strength, water absorption rates, impact resistance, and efflorescence. Despite these challenges, the study identified ideal ratios that show great promise for the effective production of plastic-sand bricks.

Moreover, this study aligns with the global calls made in various UN World Conferences to combat plastic pollution, preserve natural resources, generate job opportunities, promote affordable eco-friendly housing, and mitigate climate change. This study contributes to the National Strategy for Sustainable Development and Action Plan as well at a global level by incorporating HDPE as an alternative binder in brick production.

This study also ties up the National Development Plan of South Africa which is intricately linked to job creation, economic transformation, and affordable housing through its vision, goals, and strategies. Notably, plastic-sand brick manufacturing contributes immensely to build a more inclusive, prosperous, and sustainable future. Consequently, the introduction of eco-friendly plastic-sand bricks in the construction industry serves as a catalyst for sustainability promotion. By utilizing plastic-sand bricks, waste reduction is promoted, offering a valuable contribution to sustainable development and eco-conservation efforts simultaneously. This underscores the potential benefits and significance of using plastic-sand bricks in advancing environmentally conscious practices [158].

It emphasizes the urgency of addressing poor disposal practices and promoting plastic recycling to avoid detrimental impacts on all sectors of society, particularly in South Africa. The study emphasizes the vital imperative to prioritize sustainability and sustainable development as a pressing challenge [212].

8.5 Future research

Further research is proposed in the following areas:

- The inclusion of other additives to improve the environmental and mechanical properties of the composite material would be thought-provoking.

- Investigations into the use of alternative Nano fillers and additives of different particle sizes, shapes and concentration would be valuable.
- Finding alternative or cold casting/processing techniques would be recommended since it would avoid the use of heat.
- Recycling plastic waste to produce many other products could be looked into, more especially in untapped areas such as creating eco-friendly plastic tracks stadiums for runners and joggers. This type of athletics track is advantageous, compared to concrete and cement tracks.
- The creation of support structures in the building industry such as scaffold boards which can be produced from plastic waste which are strong, lightweight and durable. Scaffold boards with special interlocking features will be very useful in the building industry, compared to the conventional wood timber and steel structures which are extremely heavy to carry, time consuming to assemble and expensive to clean.
- Further investigation on the environmental aging of plastic sand bricks is essential for predicting their long-term performance, identifying potential challenges, and developing strategies to enhance their resistance to environmental factors. This research is crucial for ensuring the sustainable use of plastic sand bricks in construction and contributing to the development of resilient and eco-friendly building materials.

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Appendices

Appendix A: Emergence of the concept of sustainability

Appendix B: Laws that foster sustainability and sustainable development

Appendix C: Supplier's Information Sheet for Kaolin Clay DSF

Appendix D: Water contact angle images

Appendix E: Draft design of the innovative plastic-sand brick using Kaolin Clay

Appendix F: Draft design of the interlocking compressed fit plastic-sand bricks

Appendix A: Emergence of the concept of sustainability

1.0 The emergence of the sustainability concept

The conferences held from 1972 to 2022 presented the ever-evolving concept of sustainability. It all started from sustainability having an environmental focus and progressively other topics of national and global interest have been included which highlighted social and economic challenges. In order to continue with the sustainability agenda, the world leaders in sustainable development must work much harder and in the right direction. It definitely needs more world class leaders who subscribe to honesty and integrity. The world must be occupied, used and shared by all who live in it. It was also clear that the benefits of economic growth are not shared enough around the world more especially poorer nations. Yet developed and developing countries can extract raw material from poorer countries for their own purpose and profit. So, the question is what is the sustainability agenda and who drives it? Is the purpose of sustainability to eradicate poverty and inequality?

1.1 Sustainable development conferences (1972-2022)

The researcher commences with the topic on sustainable development which can be traced back to environmental concerns since 1972 [182]. This section has been intentionally included to form the basis and precursor to the emergence of the concept of sustainability and sustainable development. From the UN Environmental Programme literature on sustainable development, it has been noticed that the world's vision and commitment on this subject had been ever changing over the last 50 years. The researcher, therefore present the summary of the key focus of the various conferences held since 1972 and its links to this research study [183].

1.2 UN Environment conference and sustainable development (1972)

The 1972 United Nation's first Environment Conference and Sustainable Development [184] was held in Stockholm which focussed on the environment as an area of most concern. This was the first world conference to make the environment a major issue. The delegates adopted 26 principles in keeping with the management of environmental concerns at the centre of international discussion, to start a dialogue on the industrialized and developing countries on what was the link between economic growth, land, air and sea pollution and not forgetting the general well-being of people throughout the world.

1.3 Rio De Janerio earth summit and sustainable development (1992)

Twenty years after the Stockholm Conference, the 12 days United Nations Global Conference on Environment and Development (UNCED) [185], which was called the 'Earth Summit', was convened in Rio de Janeiro, Brazil, to focussed primarily on the impact of human socio-economic activities on the environment. The conference emphasised that the social, economic and environmental factors were actually interdependent and can evolve together at the same time. It also emphasised that the success in one factor, for example, on the environment was certainly dependent on the pro- active actions implemented by the other two factors: social and economic factors. The Earth Summit had a positive outlook for all people on two fronts: *firstly*, that the concept of sustainable development was possible at any local, national or international level. *Secondly,* that the environment, social and economic factors must be integrated and balanced to meet the needs of society to help sustain human life on this planet. The central message of the conference was to persuade international leaders to rethink economic development and its corresponding challenges as well as provide workable solution to prevent irreparable damage to our natural resources and the ever-increasing pollution of our planet.

1.4 A five-year review of progress on agenda 21, New York (1997)

It was agreed in 1992 that a five-year review of progress made since the Earth Summit would be held in 1997 by the UN General Assembly in a special session on 23-27 June 1997, New York [186]. The focus was to think of ways to resolve the challenges faced by socio-economic development on the environment. The world delegates had signed the UN Convention on Climate Change which acknowledged that the earth's changing climate with its negative impact was a common concern of all people. The delegates were concerned that many of people's behaviour and work activities have been increasing GHG emissions and negatively affecting our natural ecosystems and humankind themselves. The delegates also approved and adopted the Rio Declaration which placed people at the centre and that they are entitled to a peaceful, healthy and productive lifestyle in synchrony with nature. Four sections namely: social and economic dimensions, conservation and management of resources for development, strengthening the role of major groups and means of implementation were adopted as Agenda 21.

1.5 Millennium summit and sustainable development conference (2000)

This three-day conference was held in NY, United States of America (USA) on 6-8 September 2000 [187] to discuss what role the UN would play at the beginning of the 21st century. The conference focussed on assisting the poorest of the poor countries by trying to provide a better life for all people by 2015. The summit concluded with the adoption of the Millennium Declaration which highlighted global issues and were summarised as follows:

- Eradicate extreme poverty and hunger;
- Achieve universal primary education;

- Promote gender equality and empower women;
- Reduce child mortality;
- Improve maternal health;
- Combat HIV/AIDS, malaria and other diseases;
- Ensure environmental sustainability;
- Develop a global partnership for development.

1.6 Johannesburg conference on sustainable development (2002)

The Conference which was held in Johannesburg, South Africa on 26 August to 4 September 2002 [188] focussed on assisting the people to change their lives, protect and preserve our natural resources and ways to deal with global problems such as increased demand for food and water. The conference also pledged to commit themselves to build a just and humane, a more equitable, developing a more caring society and ensuring the dignity for all people is maintained. But, 30 years ago, a similar gathering in Stockholm was held where the delegates agreed to put in place measures to reduce and prevent the deterioration of the environment. Also 10 years ago, at the UNCED, which was convened in Rio de Janeiro, the delegates concluded that the protection of three factors namely, the environment and social and economic development are crucial and paramount to sustainable development. While the Johannesburg conference has made strides in influencing the global community delegates towards a partnership approach for the benefit of all the people. It still reiterated that the issues of poverty eradication were of major concern, the need to have different consumption and production patterns and focussing on the protection and careful management of all the natural resources for economic and social development must be addressed for sustainable development. It is sad to indicate that whilst the conference at Johannesburg concluded on a positive note and an optimistic view, the global environmental issues still continues to deteriorate.

1.7 New York world summit on sustainable development (2005)

(General Assembly UN.: General 21 March 2005)

The NY Summit concluded several resolutions which were adopted by the General Assembly on 16 September 2005 [189]. It focussed on concrete ways to fight poverty and different forms of terrorism, giving reassurance of their willingness to assist in the protection of all people from all types of crimes destroying humanity such as genocide or war crimes. There was a call for Heads of African States to tackle these problems with renewed energy and stronger determination. The summit has adopted more robust stance to achieve the Millennium Development Goals (MDGs) by 2015.

The summit still kept their focus on the greatest environmental and development challenges. The main question was on how to control, cope and manage with increased climate change. The majority of stakeholders following the subject of sustainable development now fully agree that all human behaviour and living patterns is making a detrimental impact on the environment. This was clearly noticeable from the boom of the industrial revolution that greenhouse gases have increased drastically and was a major concern. The earth had indicated an increased level of temperature and the ocean levels have moved to higher levels. It was also concluded that the major efforts to tackle and reduce poverty and to pursue sustainable development will be fruitless if the environment is continually being damaged and natural resources continue to be depleted. An interesting point to mention is that within a country level, it is vital that government make investments to improve the management of the environment and ensure that structural changes are being made so that environmental sustainability can be a reality. The sad scenario is that much of Africa, more especially South of the Sahara continues to experience violence, extreme poverty and multiple disease.

1.8 High-level meeting on the Millennium Development goals, 22-25 September 2008, New York (2008)

The UN Secretary-General and the President of the General Assembly convened a high-level meeting to check the progress on achieving the MDGs [190]. This high-level meeting was convened to also allow delegates review their progress, record and close any possible gaps as well as show full support in making and taking definite steps towards sustainability.

1.9 Millennium development goals summit, 20-22 September 2010, New York (2010)

The Millennium Development summit [191] concluded by adopting an action agenda which was entitled “Keeping the Promise: United to achieve the MDGs and as well as all the internationally agreed goals.” The world leaders from various civic movements, different business enterprises were also expected to make plans and promises to fast track activities in respect of sustainable development. The summit also outlined various initiatives that were needed to be completed in order to eradicate poverty, constant hunger and everlasting diseases.

1.10 Rio20 and the United Nations conference on sustainable conference (2012)

Still, 20 years after the Earth Summit, the United Nations Conference on Sustainable Development (UNCSD) held in Rio de Janerio, 2012 [192], which was also known as Rio+20, concluded on a comprehensive document which presented a transparent and practical way how sustainable development can be made successful. The delegates at the conference developed a set of SDGs which were built on the foundations of the MDGs were concluded in 2000 in the NY Conference. One of the main focus of these goals was to enhance and promote sustainable development in a more systematic, integrated and a global way. The conference also adopted creative ways, policies on promoting a green economy and also highlighted strategies to increase financial support for sustainable development.

1.11 President of the general assembly's special event towards achieving the millennium development goals, 25 September 2013, New York (2013)

The President of the UN General Assembly convened a special meeting event [193] to fulfil the MDGs by 2015. At this meeting, the delegates reconfirmed their support towards achieving the goals and also decided to schedule a summit in September 2015 to agree and to adopt the proposals for the new goals which in effect will build on the MDGs as well as on any other future challenges. The new goals were aimed at bringing about a balance of the three components of sustainable development namely, providing economic growth and transformation, promoting a just society, protecting the environment and presenting an opportunity for people to be rescued from poverty.

1.12 COP21 and the Paris agreement for sustainable development (2015)

The delegates to the UN Framework on the Climate Change reached an historic agreement where they agreed together in one global voice to fast-track and intensify their efforts and financial support which was required to ensure that carbon emissions be reduced to an all-time low. It was noteworthy that for the very first time, the Paris Agreement [183] was able to cause nations to fight a united common cause on all aspects of climate change. Great efforts were being made to at least keep the global temperature below 2°C. One of the aims of the Paris Agreement is to develop the capacity of nations so that they will be able to identify and tackle the negative impact of climate change.

1.13 New York & the new sustainable development goals (SDGS), New York (2015)

It was the initial good news when the 193 member UN General Assembly adopted the 2030 Agenda for Sustainable Development [194]. This agenda speaks to pathways for people to follow so that they will be able to engage in an environment that is peaceful, a society that is caring and in an economy that is prosperous. The issue of poverty was discussed at length announcing it to be one of the largest global challenge. The delegates appealed to all institutions, stakeholders and nations to join hands to ensure that the new agenda was implemented.

i) Transforming our world: the 2030 agenda for sustainable development

The UN [195] indicates that the high delegation meeting held at the UN headquarters at NY, 25- 27 September 2015 have agreed on the new global sustainable development goals. This historic decision reaffirms the commitment of all participating heads of states in governments and high representatives towards working tirelessly to achieve the SDG agenda by 2030. They have placed their full might towards eradicating poverty at all costs which they recognized is the major global challenge and is the first and foremost challenge for sustainable development. Adopting this universal, transformational goals and targets means that the delegates have committed themselves towards accomplishing sustainable development in three dimensions: economic, social and environmental in a balanced, interlocked and integrated way. The SDGs is a global ambitious call to bring about an end to poverty, protect and save our planet as well as ensure that all of people enjoy a life of peace and prosperity.

1.14 UN Environment assembly, Nairobi, 02 March 2022

The delegates from the various Heads of State, Ministers of Environment and experts from 175 nations of the world had endorsed one of the most important resolutions during the UN Environment Assembly at Nairobi [196]. This was due to plastic pollution which has now grown into a global monster. The resolution took cognisance of the entire lifecycle of plastic from its production until it is discarded as waste material. The meeting established an Intergovernmental Negotiating Committee (INC) that would commence their full-scale work in 2022 to craft together a draft global legally binding document which is hoped to be completed by the end of 2024. One of the key aspects to this binding agreement is the presentation of the various alternatives to relook at the full lifecycle of plastics due its negative impact on society, the potential of reusable and recyclable products for the future. Inger Andersen, Executive Director of the UN Environment Programme (UNEP), indicated that the agreement was the most important international multilateral environmental deal since the Paris climate accord.

Appendix B: Laws that foster sustainability and sustainable development

1.0 Laws are needed to make sustainability development a reality

The United Nations Economic Commission for Europe (UNECE) is one of the five regional commissions under the jurisdiction of the UN Economic and Social Council, that warns of three important statistics namely: the annual global extraction of materials has more than trebled from 27 to 92 billion tons since 1970, the world's population during the same period has rocketed to more than doubled and the global CO_2 emissions increased by approximately 90%. As a result, pressure on natural resources, most of which are not renewable, continues to grow, bringing negative impacts in terms of pollution, ecosystem degradation, biodiversity loss, and climate change. This implies that the world's natural resources are used at a faster rate as compared to the rate at which they are replenished. Hence, Dernbach and Mintz [211] outlines that sustainable development provides a structure for people to live and work together and at the same time be in synchrony with nature instead of the living and consuming resources with disregard to nature for decades. Therefore, sustainability needs to have a supportive accountable legal framework, despite of there being so many environmental and natural resource laws that have been enacted. If we want to make substantial progress towards sustainability and sustainable development, then we must develop and implement laws and have legal institutions if some of them do not exist. They conclude that we need to use laws and policies to protect our planet and promote sustainability. They strongly believe that laws can enforce the goals and requirements for achieving sustainability.

It is imperative to take cognisance and be aware of the various environmental, social and economic challenges that policies need to be implemented to achieve sustainability and sustainable development. Ashford and Hall [337] in their similar arguments state that companies need to foresee, develop, and implement policies in such that they would concurrently accomplish the goals of social, environmental, and economic dimensions. They further added that policy interventions are essential to develop capacity and willingness, present opportunities to people to change their institution to a more sustainable enterprise.

Abbott and Marchant [338] argue that institutions alone cannot promote sustainability. One of the prerequisites of sustainability would be to institutionalise sustainability across all government structures and the operations of the legal system. Failure to this, sustainability is likely to be weak or will become a technical exercise.

Framework for Assessing and Improving Law for Sustainability [339] highlights that laws play a key role and is part of the answer to sustainability problems of the world. Whilst it may not be the complete answer to a complex situation in respect of all the processes, relationships and challenges that exist within the social, economic and political systems, it is one of the integral components that cannot be left out to resolve sustainability challenges. It is contended that for sustainability goals to be accomplished, it must be relevant, effective and be systematically implemented within legal frameworks and carefully designed tools must be available and effective. It is concluded that laws itself are simply not enough even if they are implemented. The crucial factor is that laws that are crafted must be able to achieve it intended purpose.

Adler [340] also emphasises that not enough attention is focussed on the aspect of laws which could make a huge difference on the practices and policies as well as how it would have a positive or negative effect on sustainability. This implies that having laws in place and making sure that they are implemented, would prevent for example droughts which has been caused through climate change and atmospheric conditions. Hence, there is a positive relationship between laws and sustainability

Dernbach and Mintz [211] argue that it is simply not good enough to use laws to resolve problems. However, laws are a statutory requirement to be skilfully drafted and promulgated so that it achieves the desired outcome one is looking for. But, the important thing is that these laws must be formally evaluated after its implementation to actually make sure that they made a change or produced the outcome showing sustainability development. For this to happen, there must be credible and appropriate assessment tools must be made available.

Governments representatives within a country and at a global level must be held accountable and must play a key role in achieving the sustainable development goals and targets. Schillemans et al. [341] argues that the concept accountability is when people have the right to know and understand what government's plans are and how they are going to achieve them, the cost of delivering the goals of the plans, whether the goals have been realised and whether it was completed with the budget.

Romzek and Dubnick [342] highlights four types of accountability namely legal, political, bureaucratic, and professional. Professional accountability deals with all employees being required to be fully accountable for their conduct and actions and perform their job to the best of their ability. If they fail to meet their job performance they can be fired. Political accountability deals with the constituency the employee represents and how well they respond to their priorities and needs. Bureaucratic accountability systems deal with the superior and subordinate relationship based on following orders to get the tasks completed. Legal accountability deals with control measures that is applied to public administration activities. Here, the outside agency made up of an individual or a group would be able to apply the law on any matter.

There were many previous laws in South Africa pre 1994 which aimed to restrict the vast majority of people to progress or advance in their own separate areas which created an unjust and inhumane society in so many different ways. The researcher's intention is to highlight that the amended laws that were promulgated during post 1994 in South Africa are linked towards promoting sustainability and sustainable development. The changes to the laws are a positive sign of reawakening our souls to transit towards a hope of achieving sustainability, to resolve the greatest of our current challenges being poverty and inequality across our nation. Some of the laws, regulatory legislations and frameworks that had to be promulgated post 1994 to ensure sustainability.

2. Laws, policies and frameworks required to promote sustainability in South Africa

2.1 Environmental laws

There are environmental legislation and the regulatory authorities that assist to reduce and prevent pollution and ecological degradation, encourage, promote and enforce nature conservation and set out procedures of how to use natural resources while promoting these in a justified manner. One of the supreme law of the land is the Constitution of the Republic of South Africa 1996 [90]. Section 24 of the Constitution sets out the right to an environment that is not detrimental to health, safety and wellbeing of all persons, and calls on the government to take legislative and other actions to ensure the individuals, companies or institutions to adhere and promote sustainability and sustainable development.

In line with the South African Constitution, a number of key pieces of legislation and specific regulations and frameworks have been promulgated that are relevant to this research study are indicated below:

- The Hazardous Substances Amendment Act 53 of 1992
- Environment Conservation Amendment Act, 1993
- Dumping at Sea Control Amendment Act, 1995

- National Environmental Management Act No. 107 of 1998 (NEMA)
- Mineral and Petroleum Resources Development Act No. 28 of 2002 (MPRDA)
- National Environmental Management: Protected Areas Act No. 57 of 2003 (NEM: PAA)
- National Environmental Management: Biodiversity Act No. 10 of 2004 (NEM:BA)
- National Environmental Management: Air Quality Act No. 39 of 2004 (NEM: AQA)
- National Environmental Management: Waste Act No. 59 of 2008 (NEM: WA)
- National Environmental Management Amendment Act, 2008 (Act No. 62 of 2008)
- National Environmental Management Laws Amendment Act, 2014 (Amendment Act No. 25 of 2014 (NEMLA)
- National Environmental Management: Air Quality Amendment Act, 2014. Act No. 20 of 2014:
- National Environmental Management: Integrated Coastal Management Amendment Act, 2014 (Act No. 36 of 2014)
- Second National Action Programme for South Africa to Combat Desertification, Land Degradation and the effects of Droughts

2.2 Social laws

1. Reconstruction and Development Programme, 1994 (RDP)
2. Housing Act, 1997 (Act No. 107, 1997)
3. Welfare Law Amendment Act, 1997 (Act 106 of 1997)
4. White Paper for Social Welfare Service (1997)
5. White Paper on Population for South Africa (1998)
6. Housing Consumer Protection Act No. 95 of 1998
7. The Child Support Grant (CSG) was introduced in 1998
8. Social Assistance Act, 2004 (Act 13 of 2004)

9. South African Social Security Agency Act, 2004 (Act 9 of 2004) (SASSAA)

10. Foster Child Grant in 2010

2.3 Economic laws

- Broad-based black economic empowerment (BEE) 2013 (As amended)
- The National Policy Development Framework, 2020 seeks to entrench good public policy- making practices in South Africa.
- The jobs Summit South Africa hosted the Jobs Summit on 4 and 5 October 2018, at Gallagher Convention Centre in Johannesburg to discuss the status of employment and the creation of jobs in South Africa.
- The Youth Employment Service was launched in 2018. (YES)
- The Amavulandlela Funding Scheme plays a vital role for funding entrepreneurs with disabilities.
- The Public-Private Growth Initiative (PPGI) is one of the major drives towards investing R840 billion in 43 projects spanning over 19 sectors. The aim of this initiative is to create employment for 155 000 people by 2024.
- Expanded Public Works Programme (EPWP) aimed at providing poverty and income relief through the provision of contract and temporary work for the unemployed.
- Another Basic Education initiative called the Presidential Youth Employment Initiative (PYEI) was extended for its third phase in 1 April 2022. It is now promising that more than 280,000 young people have the job extended in the third phase within primary and secondary schools in South Africa.

3.0 Active policies and specialised programmes needed to promote sustainability

Banerjee et al. [85] has cited that in a national survey which was conducted pre-transition 1994 that the rate of unemployment was 13% and thereafter had rocketed to more than 30% after 10 years. He cited three reasons why unemployment has remained in an all-time high. *Firstly*, the search for jobs has been less effective for the disadvantaged communities due to business centres being located far away from settlements and the low-cost housing areas. Furthermore, the lack of cheap public transport has further contributed to the problem of job searches. *Secondly,* the informal sector being situated at the outskirts of urban centres were unable to absorb the possible job seekers. The informal sector has shown very little growth and unemployment has automatically increased. High crime rate and initial start-up costs for small businesses had compounded the problem. *Lastly*, the further increase in the unemployment rate was the result of structural changes in the labour market which was brought about by the restructuring of the new government. Banerjee et al. [85] argues that active policy is compulsory to fuel employment and change since the problem of unemployment is not self-correcting.

Gradin [343] in his article argues that sustainability can be achieved but it requires new laws and some amendments to existing laws. He warns that it is less likely that sustainability will be achieved through a process of simply using existing laws to solve new challenging problems or having this notion of making adjustments and small changes to existing laws. However, existing laws might somewhat be supported with several other different approaches. These new policy approaches can be seen by convening a job summit in 2008 and youth programmes and services that have been put into action in South Africa.

This research study promotes employment for waste pickers within the plastic manufacturing industry. Mkhize et al. [344] in their Informal longitudinal Economy Monitoring Study (IEMS) explains the urban informal economy during two periods, 2012 and 2015, in 10 major cities around the world namely Accra, Ghana; Ahmedabad, India; Bangkok, Thailand; Belo Horizonte, Brazil; Bogota, Colombia; Durban, South Africa; Lahore, Pakistan; Lima, Peru; Nakuru, Kenya; and Pune. In India, most waste pickers engage in selling of their items or form part of the formal economy. This means that waste pickers sell their collected waste to formal business enterprises and other recycling centres. The respondents in the above study highlighted their economic contribution by doing work as waste pickers where they can generate income for their households, creating employment and job opportunities since the rate of unemployment in South Africa is extremely high.

Figure A1 indicates that the ages of the waste pickers in the survey ranged from 15 to 69 years. It was noted that 61% of all the waste pickers were relatively young, between the age of 24-35.

It is interesting to note that the introduction of waste pickers is certainly providing a growing sector in providing jobs for the unemployed and the youth.

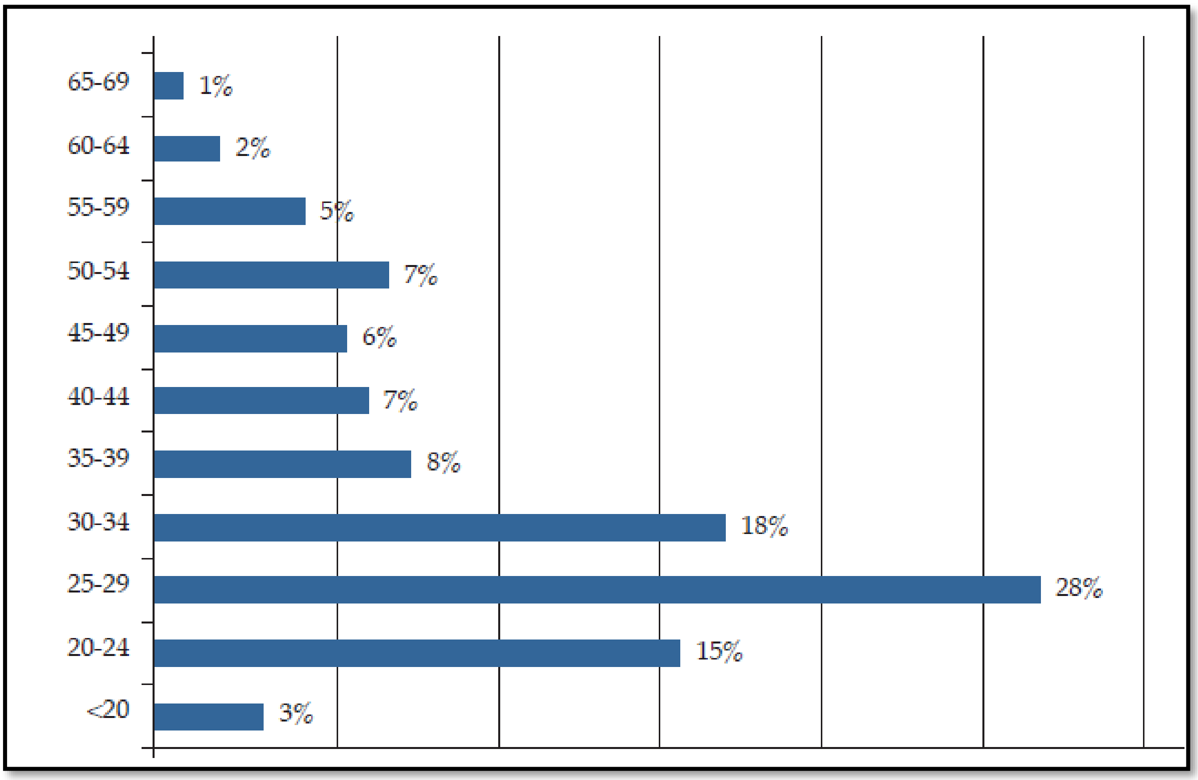


Figure A 1: Age range of waste pickers [344]

Rogan 2012, as cited in Mkhize et al. [344] indicated that the amendments to legislation made a paradigm shift towards becoming more progressive since 1990. But after 1994, the amended and new national legislation with other council initiatives and programmes implemented in Durban, has resulted in Durban being the forerunner in WM as compared to other cities in South Africa. This was due to its enormous research and positive approach towards understanding informal work and the important role they play towards economic growth and development. One of the historic policy events that took place was when the municipality's Informal Economy Policy (IEP), was discussed and approved in 2000. This made the city of Durban to be the first municipality to have taken the initiative towards introducing a policy that benefitted the waste pickers and others in the informal economy and the city as a whole.

Whilst the manufacturing of plastic-sand brick is one of the many solutions to reducing plastic pollution, promoting job creation, building of affordable houses and the reduction of GHG emissions, it will not take place naturally. The recent attention is given to how waste pickers can be incorporated into the WM system and into the formal industry in South Africa. This inclusion and transformation will have great imputes towards contributing positively towards the four crises. Godfrey and Oelofse [56] in their study projected that there will be about 215 000 waste pickers in 2017 and this number is still increasing. The South African Government, industry and various other stakeholders from academia, research, business have recognized the positive role played by waste pickers in diverting the discarded plastic waste from landfill towards recycling, reuse and recovery [345].

There have been many studies that supported the inclusion of waste pickers into a formal regulatory framework. This was needed since the waste pickers suffered poor working conditions, discrimination, inclement weather, low income, received minimal cash for their valuable waste products and were forces to spent many hours on dumpsites when they worked for waste agencies. Velis et al. [346] recommended that it was necessary to integrate waste pickers from their informal sector to a more controlled environment such as regulatory framework and also link their work back to the recycling value chain. It is also contended that the framework should have a way to transform the informal industry through facilitation within the organisation and provide advocacy and training of the waste pickers raising their dignity and respect within all communities. Samson [347] emphasises that waste pickers contribute substantially to the recycling industry due to their recovery of valuable waste products. She argues strongly that an organized and incorporated approach of waste pickers into a framework that is systematically managed and monitored is obligatory.

The informal sector in Pakistan is responsible for the recycling of waste. Masood and Barlow [348] believes that it is beneficial to integrate this informal sector with the formal sector. Hence, this transformative thinking has made it possible to draw up a framework that made it possible to facilitate the incorporation of both the informal and formal WM sectors in such a way that it would boost all spheres (social, economic and environmental). They were certain that such an integration will assist government, all municipalities, society and as well as change the outlook of the informal waste sector. Dias [349] presented the outline of the legal framework regarding how the integration of informal waste pickers in SWM in Brazil would operate. Lately, Brazil endorsed the passing of legislation for incorporation of waste pickers into the formal sector. This new legislation gave waste pickers much more prominence in public and due recognition for their input in the economy. Brazil has become one of the first countries that integrated waste pickers into their country's policies.

South Africa, drawing on the experiences of Brazil and other countries had followed a similar way regarding the inclusion of waste pickers. Molewa [350]**,** previous Minister of the Environment in South Africa, in her parliamentary speech alerted everyone that there was a rise in the recycling of plastic waste throughout the country. She categorically indicated that waste pickers played a pivotal role in redirecting the waste from landfills and playing a vital role in the recycling economy of South Africa. He promoted the idea of strategic interventions to offer economic opportunities which could be realised by promoting business activities that would include the waste pickers into a well-managed and caring sector.

In the study conducted by the Department of Environment, Forestry and Fisheries Department of Science and Innovation [345] the involvement of the South African government, industry and civil society was important to officially integrate waste pickers into the formal sector by planning guidelines to identify the significant role played by waste pickers in rescuing resources that were dumped in landfill. This evidence-based guideline was compulsory to design policy measures to enhance the activities this developing sector. Mazhandu et al. [351] in their study outlined the role of government and various associations to register all waste pickers by 2022 and their drive towards zero waste to landfill by 2030. This new regulatory framework will provide numerous advantages for all industries in South Africa.

4.0 National Framework for Green Building in South Africa

The South African Government adopted a National Framework for Green Building in South Africa (NFGBSA) in November 2011 [352]. This official policy provided a paradigm shift toward green building construction in the country. The NFGBSA supports the Government in meeting its sustainable development commitments. All eco-friendly material, technologies and products supports the green building framework. Hence, this research study is in line with one of the components of the green building criteria that is the construction of buildings using preferable eco-friendly environmentally materials.

Appendix C: Supplier's Information Sheet for Kaolin Clay DSF kaolin-group

south africa

PRELIMINARY DATA SHEET

Kaolin DSF

Kaolin DSF is a dry-separated, raw kaolin clay powder, which has been micronized to mean particle size of 2 micron. It is used in its raw or further refined form as an additive for a variety of building materials ranging from paint, to castings and specialty plasters and specialist applications of these, as well as a mineral filler for various industrial applications, including polymer compounds.

PROVISIONAL VALUES AND ANALYSIS

Chemical composition:

SiO_2	60,3%
Al_2O_2	23,5%
K_2O	2.3%
TiO_2	0.7%
Fe_2O_3	1.1%

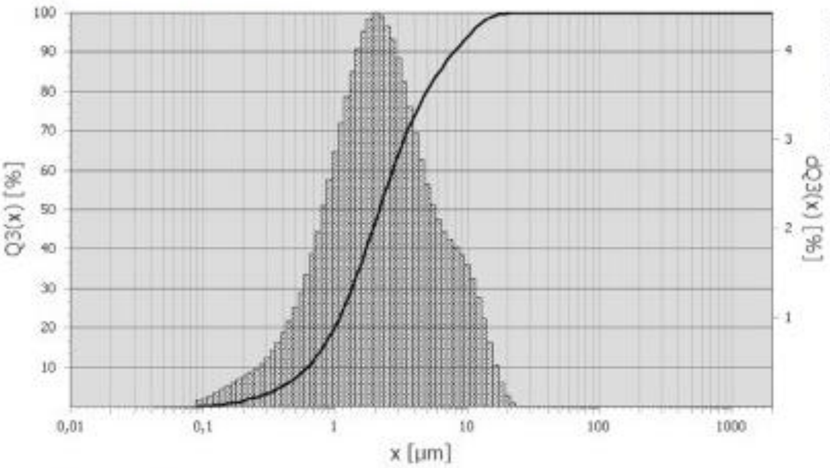
CAS Numbers and description

1332-58-7	Kaolin
14808-60-7	Quartz (SiO_2)

Physical analysis:

Colour	Off-white
Whiteness	± 70%
Aerated powder density	650kg/m³
Tapped powder density	750kg/m³
Loss on Ignition (LOI) @ 1000°C	7.4%
PH value:	8
Mean Particle size:	d50 = 2,2µm

Particle size distribution:



Q3(x) [%]	x [µm]
5	0,4
10	0,6
25	1,2
50	2,2
75	4,1
90	7,9
95	10,6
99	15,3

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Appendix D: Water contact angle images

	B- 65:35			
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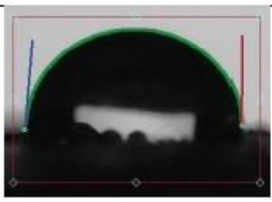
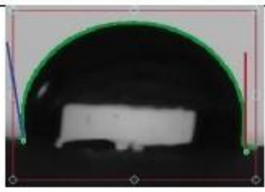
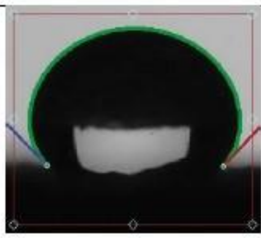
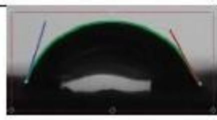
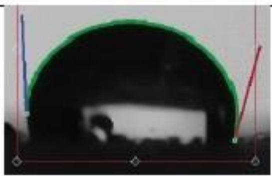
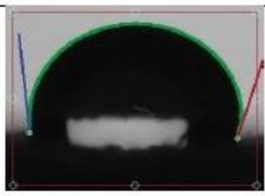
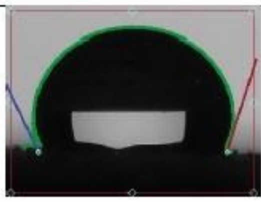
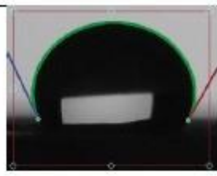
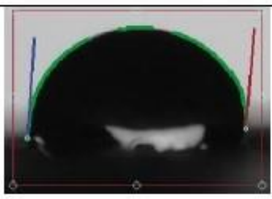
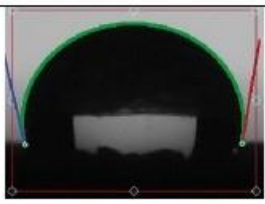
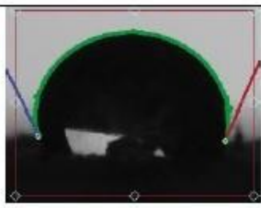
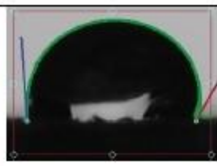
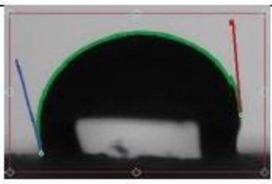
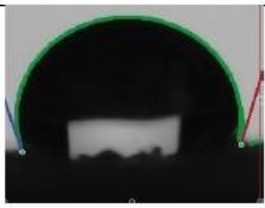
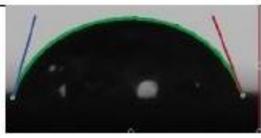
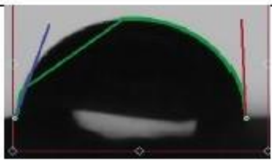
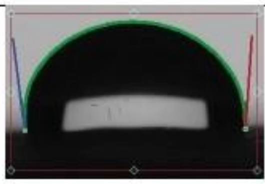
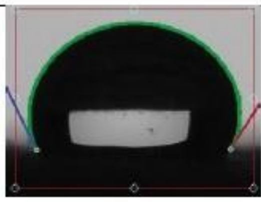
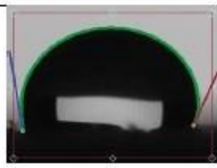
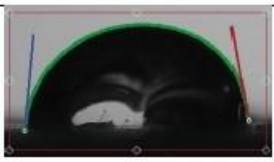
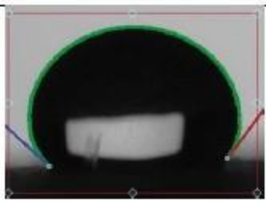
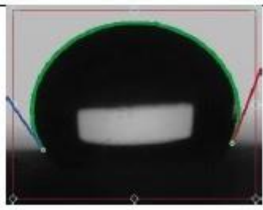
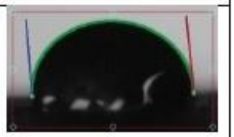
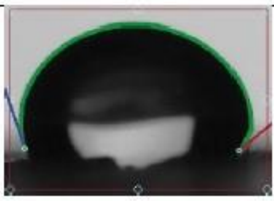
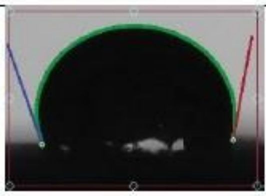
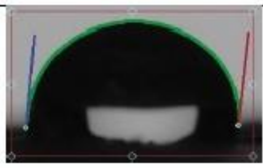
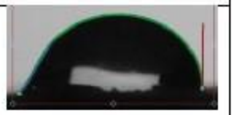
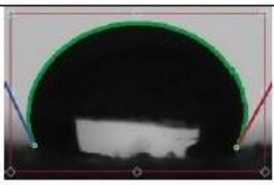
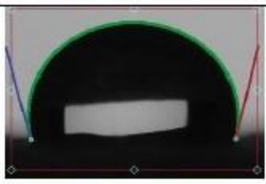
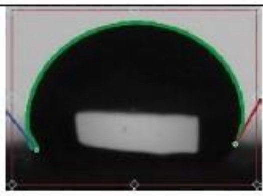
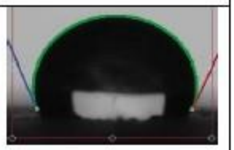
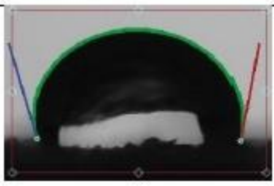
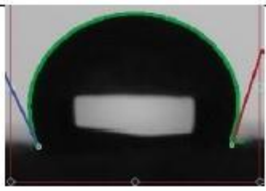
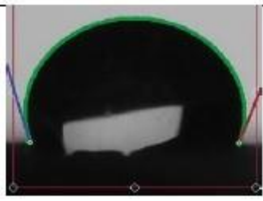
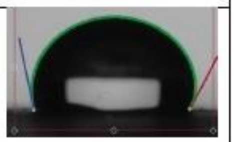
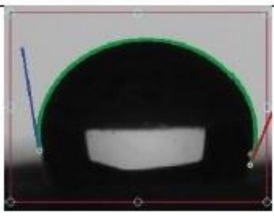
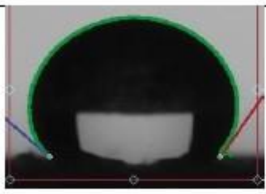
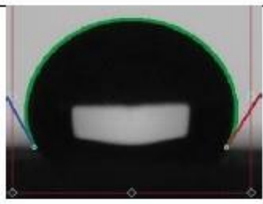
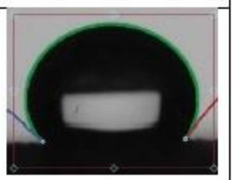
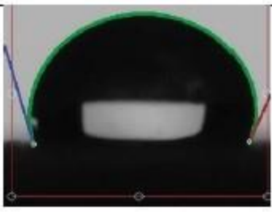
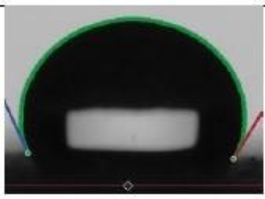
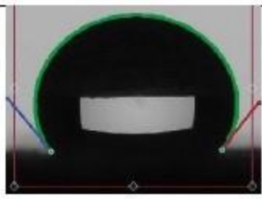
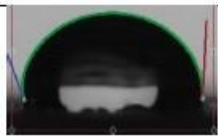
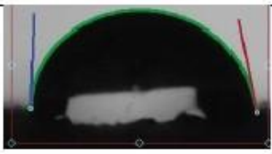
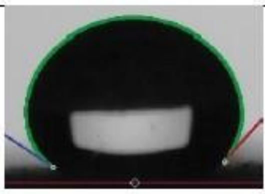
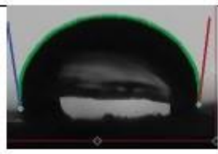
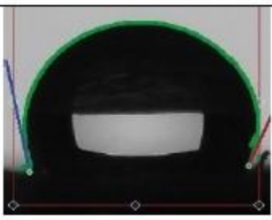
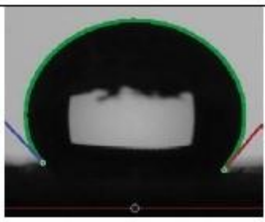
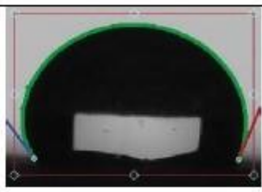
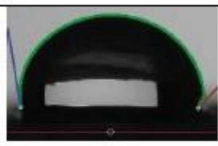
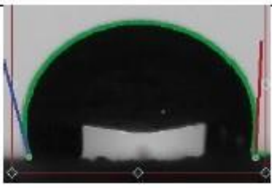
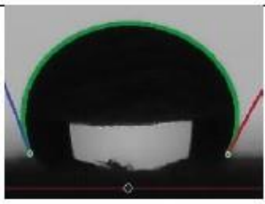
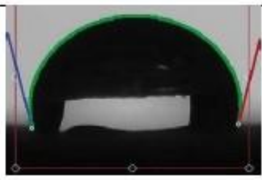
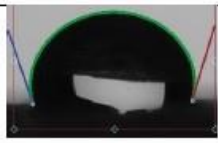
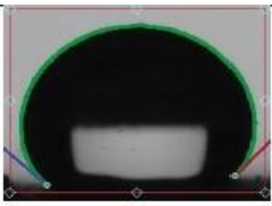
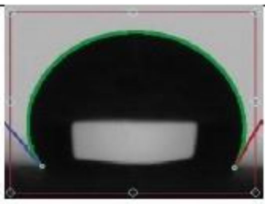
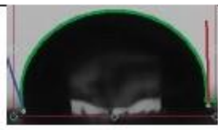
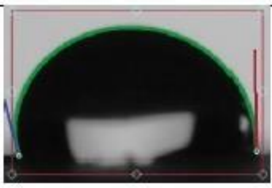
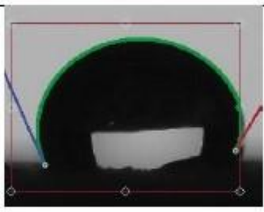
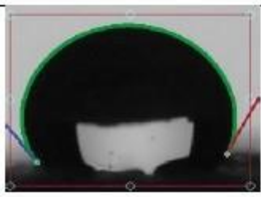
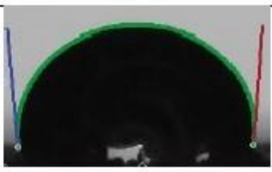
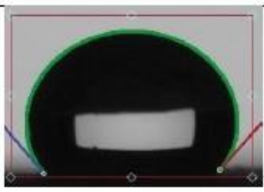
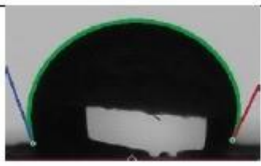
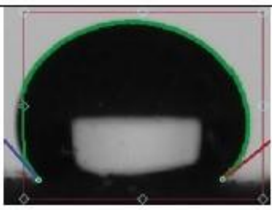
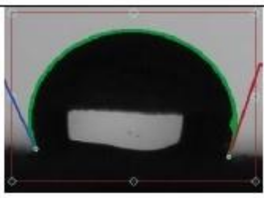
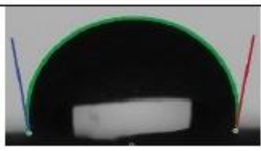
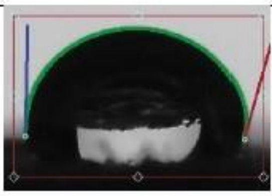
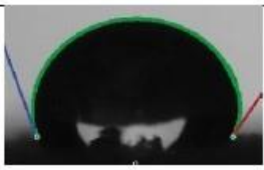
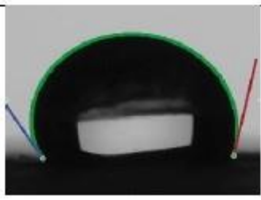
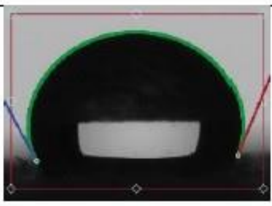
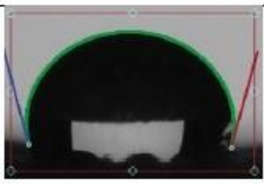
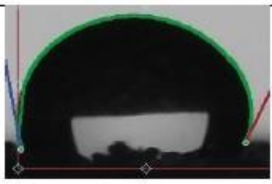
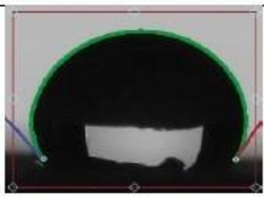
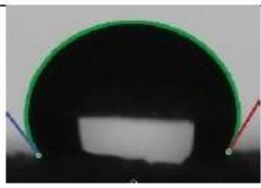
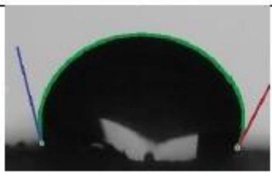
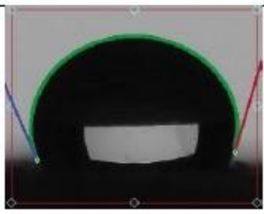
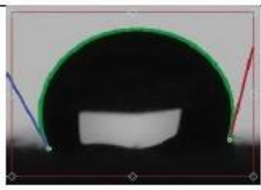
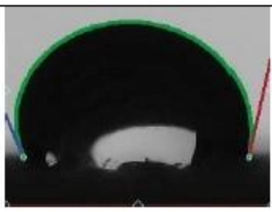
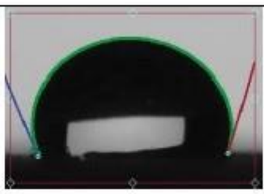
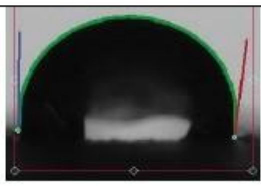
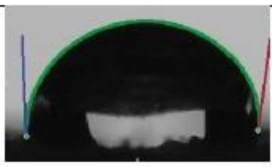
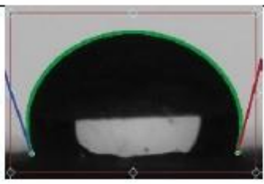
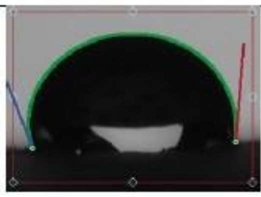
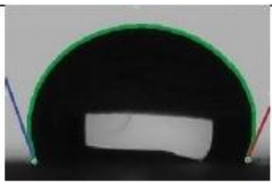
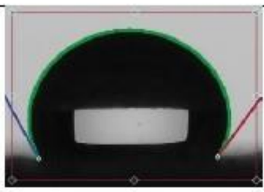
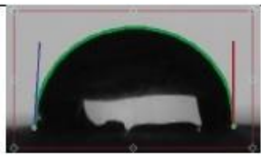
1				
2				
3				
4				
5				

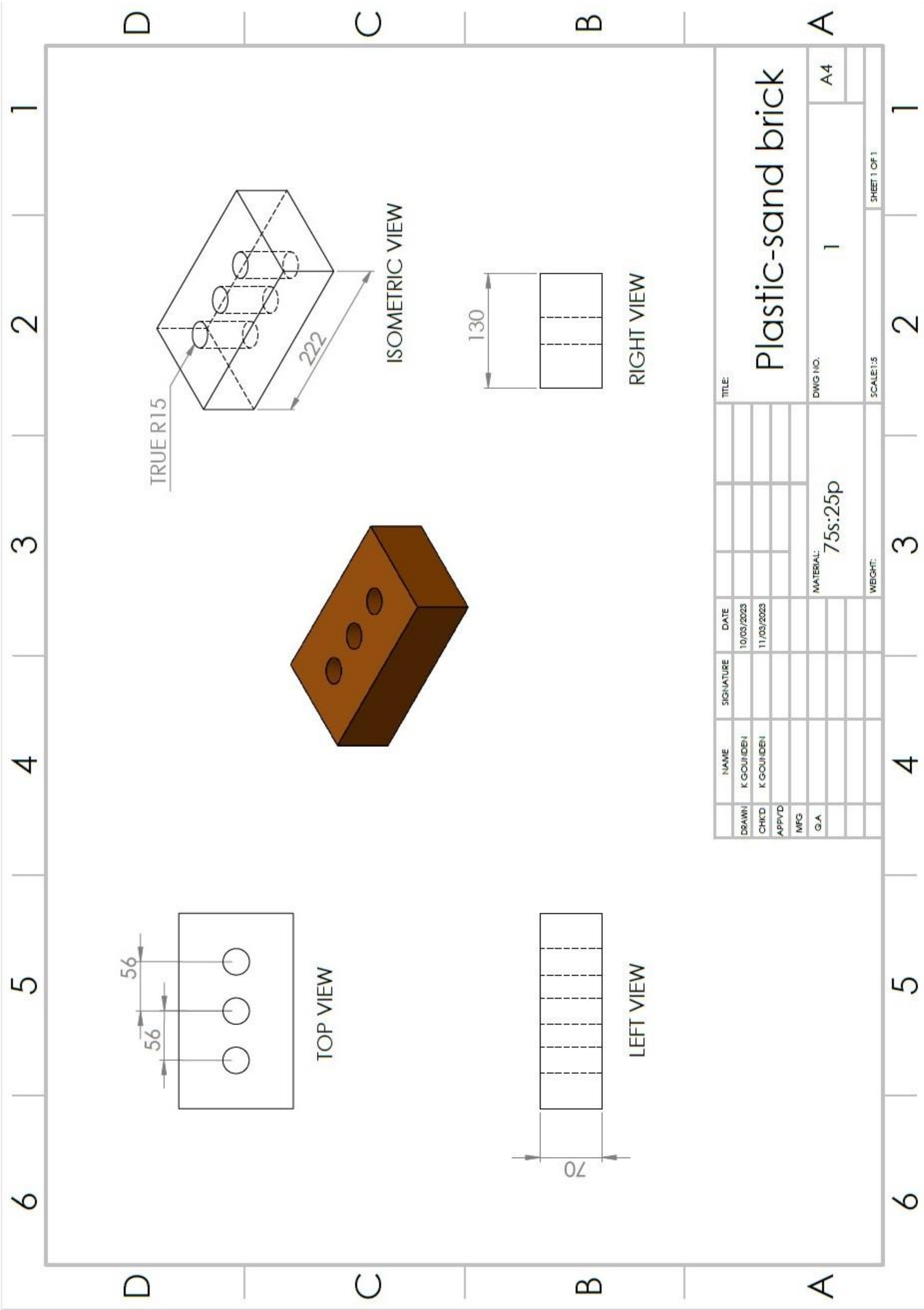
	C- 70:30			
Sample No.	0% Kaolin Clay	1% Kaolin Clay	5% Kaolin Clay	10% Kaolin Clay
1				
2				
3				
4				
5				

	D- 75:25			
Sample No.	0% Kaolin Clay	1% Kaolin Clay	5% Kaolin Clay	10% Kaolin Clay
1				
2				
3				
4				
5				

	E- 80:20			
Sample No.	0% Kaolin Clay	1% Kaolin Clay	5% Kaolin Clay	10% Kaolin Clay
1				-
2				-
3				-
4				-
5				-

	F- 85:15			
Sample No.	0% Kaolin Clay	1% Kaolin Clay	5% Kaolin Clay	10% Kaolin Clay
1				-
2				-
3				-
4				-
5				-

Appendix E: Draft design of the innovative plastic-sand brick using Kaolin Clay



Appendix F: Draft design of the interlocking compressed fit plastic-sand bricks