STRUCTURAL PERFORMANCE ASSESSMENT OF WASTE PLASTIC INTERLOCKING BRICKS

Submitted By

HASSAN ALI SUBHANI

MS Structural Engineering (Fall 2020)

(Regn. # 00000328677)

Supervisor

Assistant Professor Dr. Sarmad Shakeel

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST), Islamabad, Pakistan

2023

Form TH-4

National University of Sciences and Technology

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our Supervision by: **(Student Name: Hassan Ali Subhani & Reg No. 00000328677)**

Titled: **Structural Performance Assessment of Waste Plastic Interlocking Bricks** be accepted in partial fulfillment of the requirements for the award of **Master of Science** degree with (A Grade).

Examination Committee Members

1. Name: Dr. Rao Arsalan Khushnood (co-Advisor) Signature:

2. Name: Dr. Junaid Ahmed Signature:

3. Name: Dr. Hammad Anis Khan Signature:

Supervisor's name: Dr. Sarmad Shakeel Signature:

Date: 27/11/2023

29/11/23

Dr. Muhammad Usman
Head of Department
Date:

HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

COUNTERSIGNED

Date: 04 DEC 2023

Principal & Dean

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

This is to certify that the

Thesis titled

STRUCTURAL PERFORMANCE ASSESSMENT OF WASTE PLASTIC INTERLOCKING BRICKS

Submitted by

HASSAN ALI SUBHANI

MS Structural Engineering (Fall 2020)

0000032677

has been accepted towards the partial fulfillment for the award of degree

Master in Structural Engineering

Dr. Sarmad Shakeel

Supervisor

Dr. Rao Arsalan Khushnood

Co-Supervisor

Dr. Hammad Anis

Committee Member

Dr. Junaid Ahmed

Committee Member

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS thesis written by Mr. Hassan Ali Subhani, Registration No. 00000328677, of MS Structural Engineering 2020 Batch (NICE), has been vetted by undersigned, found completed in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors and mistakes and is accepted as partial fulfillment for award of MS degree.

Signature: ______________ Assistant Professor NICE (SCEE), NUST

Name of Supervisor: Dr. Sarmad Shakeel

Date: ______________

Signature: ______________ HoD Structural Engineering NUST Institute of Civil Engineering School of Civil & Environmental Engineering National University of Sciences and Technology

Head of Department: Dr. Muhammad Usman

Date: 30-11-23

Signature: ______________

Principal & Dean SCEE: ______________ PROF DR MUHAMMAD IRFAN Principal & Dean SCEE, NUST

Date: 04 DEC 2023

II

DECLARATION

I certify that this research work titled "Structural Performance Assessment of Waste Plastic Interlocking Brick" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged /referred.

Signature of Student

Hassan Ali Subhani

00000328677

ACKNOWLEDGEMENTS

In the name of Allah, the most Beneficent, the most Merciful as well as peace and blessings upon Prophet Muhammad, His servant and final messenger.

I am first and foremost extremely grateful to Allah Almighty for enabling me to complete my research project and without Whose willingness I could not have imagined accomplishing such an enormous task.

The efforts and sacrifices that my parents and teachers have made over the course of my life to reach where I stand today are highly acknowledged. My siblings were a source of constant motivation and always stood by my side during tough times and I highly value their love and support.

I respect and appreciate the efforts put in by my supervisor Dr. Sarmad Shakeel, Assistant Professor Structural Engineering Department and my co-supervisor Dr. Rao Arsalan Khushnood, Ex- Head of Department Research SCEE. Throughout the research project their constant support and taking time out of their busy schedule for mentorship kept me proceeding forward. I would like to express gratitude to my GEC members, Assistant Professor Dr. Hammad Anis Khan and Assistant Professor Dr. Junaid Ahmed for facilitating my research.

I am also thankful to Mangla Metals Pvt. Ltd for providing waste foundry sand for my research work and also HoD Materials Engineering SCME and HoD Transportation NICE for allowing me to use their facility for experimental work. Efforts made by Lab. Technician Khawar Iqbal and Lab Engr. Hamza of Material Testing Lab SCME are highly acknowledged.

I am extremely grateful to entire Structural Engineering Lab Staff (Lab Engr. Isameel, Lab Engineer Mati Ullah, Lab Engr, Saif, Lab Technicians Mr. Riasat, Mr. Ghulam Rasool, Mr. Fawad, Mr. Zeeshan and Mr. Zareef) for assisting and mentoring regarding the tests. In addition, the support provided by Lab Technician Mr. Ahmed of Geotech Lab and Lab Technicians of Transportation Lab is also highly acknowledged.

Finally, I would extend my appreciation towards my friends (Jamal, Qasim, Wajid, Kaleem, Suleman, Amir, Fahad, Nabeel, Zaryab, Jahanzeb, Haseeb, Farhad, Atif, Ibrahim and Mariam Usman) and my wife Nazish, who kept encouraging me and provided necessary assistance in the completion of this research project.

Dedication

To

My late sister and brother like friend Usman Ali Arshad

Gone But Never Forgotten

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The climate crisis is brewing up worldwide and there is an urgent need to develop and adopt products with low carbon footprint. Although the drivers of pollution are numerous, the lack of solid waste management is a key contributor. To tackle this menace of increasing solid waste in the environment three R's of waste management are proposed which includes reduce, recycle, and reuse. In this research, an attempt has been made to reuse solid waste from different sources to fabricate a brick that conforms to the standards laid by international and local building codes. Plastic waste comprising of Polyethylene Terephthalate (PET), High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE) were utilized along with waste foundry sand from steel industry. Waste plastic brick with different dosages of PET, HDPE, and LDPE as well as waste foundry sand were manufactured. Its properties were later investigated and compared with control clay fired brick samples. Test results revealed that waste plastic brick formulation 50:50 i.e. (waste plastic: foundry sand) exhibited the optimal mechanical performance. Its compressive strength was 8.23 MPa which was comparable to second class clay fired brick. Its splitting tensile strength was 1.35 times and flexural strength was twice compared to second class clay fired brick. From durability perspective, waste plastic brick does not show any sign of efflorescence and has water absorption ten times less than conventional clay fired bricks. Waste plastic brick is a better thermal and electrical insulator than second class clay fired brick and also possesses adequate bond strength with mortar. From the test results it is evident that waste plastic brick formulation 50:50 has adequate structural performance and can serve as replacement of conventional clay fired bricks in masonry structures. Utilizing waste plastic brick in masonry structures would be a giant leap forward towards a sustainable construction sector while addressing environmental concerns simultaneously.

Keywords: Plastic waste, Masonry structures, Mechanical properties, Sustainable construction, Waste management

CHAPTER 1

INTRODUCTION

1.1 General

Increased pollution levels in the atmosphere pose a great environmental threat. Waste produced worldwide is 1.3 billion tons per year and is projected to increase to 2.2 billion tons by year 2025 [1]. Annual production rate of municipal solid waste is increasing at 2.4% per annum in Pakistan [2] due to population growth and urbanization [2] [3]. Plastic is a major component of global waste which is used widely because of numerous advantages such as lower production and processing cost [4], light weight, transformation into different shapes [3], durability and ease of usage [5]. However, plastic waste poses numerous environmental problems as it is non-biodegradable [5] [6]. Plastic waste persists for more than 500 years in the environment [6] resulting in microplastic pollution, loss in biodiversity, penetration into food chain and contaminating ground water [5]. Waste plastic either ends up in landfills or is recycled or is incinerated [5]. According to [7], around 51% of plastic waste is buried, 22% of it is recycled and 27% of it is incinerated [7]. Incineration is extremely unsafe way of disposing plastic as it produces toxic gases [8].

Construction industry is a leading greenhouse gas contributor and makes up for 40% of global energy demand [9]. Brick is one of the oldest construction materials with its use starting to date back in 6500 BCE [10]. About 1500 billion bricks are produced worldwide out of which 87% come from the developing countries [11]. In South Asian region, the residential construction comprises 62% of clay fired bricks [12]. Pakistan ranks 3rd in most bricks manufactured in South Asia with about 18000 brick kilns generating 45 billion bricks per year [13]. In conventional clay fired bricks coal is normally used as energy source to fire the bricks in brick kilns. About 24 million tons of coal per year is consumed worldwide to manufacture bricks and coal is considered to be one of the most polluting materials [11]. A brick kiln, depending on type of kiln and fuel used, typically releases 70 to 282 g of carbon dioxide, 0.29 to 5.78 g of carbon monoxide and 0.15 to 1.56 g of particulate matter per kilogram of brick fired [14].

Another construction material responsible for pollution is steel. About 105 million metric tons of steel is manufactured globally per annum [15]. Production of steel involves generation of waste foundry sand [15]. To cast 1 ton of steel about 0.6 tons of waste foundry sand is generated [15] which is a municipal solid waste that pollutes the environment.

Numerous research has been conducted to explore the feasibility of utilizing waste materials in the structures. The benefit of utilizing waste includes conservation of natural resources and disposal of waste in efficient and secure manner [16]. This research aims to utilize waste products; waste plastic and foundry sand, to manufacture a brick that has equivalent or enhanced structural performance as compared to conventional clay fired bricks. Utilizing waste material in construction industry can make it sustainable by transforming it from a linear economy to a circular economy. Moreover, this would check the pollution levels, ensuring a healthy environment for the future generations.

1.2 Problem Statement

Construction industry is a highly unsustainable sector that produces huge quantum of waste with little or no utilization of waste in construction products. Solid waste management is a growing challenge in developing countries which need serious efforts to reduce its generation as it pollutes the environment. In this research, an effort has been made to utilize plastic waste in masonry structures by formulation of waste plastic interlocking brick. The brick would satisfy the demands of the construction sector, conform to standards laid by different organizations, and also tackle the pollution challenges.

1.3 Research Objectives

Following objectives were identified for this research

1. Development of waste plastic brick comprising of recyclable materials
2. Formulating an interlocking brick which eliminates the use of mortar as adhesive in masonry construction
3. Assessing the structural performance of waste plastic bricks through ASTM testing protocols
4. Drawing comparison with conventional clay bricks to ascertain its feasibility in masonry construction

CHAPTER 2

LITERATURE REVIEW

2.1 Properties of clay fired bricks

Brick is an important masonry component. The production of brick involves seven steps [13]. In the first step the clay is prepared after its extraction from the earth. It is vital to investigate the properties of clay as various defects in brick such as cracking, bloating, lime popping, and efflorescence are caused by using substandard clay [17].

Next step involves mixing clay with water to form a mixture that is poured into molds of desired shape. Later bricks are sun dried after which they are placed in the kiln for the firing process. The firing temperatures vary from 1000 to 1500 degree Celsius [13]. When the bricks are fired the moisture inside the mixture evaporates and vitrification of aluminosilicates present in the clay takes place that later results in hard ceramic product [17].

The firing process imparts firmness and compactness to the brick that contributes to its strength [17]. However, firing bricks at elevated temperatures often results in uneven brick surface and reduction in the unit height of the brick by a few millimeters [18].

The permissible variations in dimensions as specified by ASTM C62 [19] are mentioned in the Table 1.

Specified dimension, in. (mm)	Maximum Permissible Variations from Specified Dimension, plus or minus, in. (mm)
Up to 3 (76), incl	3/32 (2.4)
Over 3 to 4 (76 to 102), incl	1/8 (3.2)
Over 4 to 6 (102 to 152), incl	3/16 (4.8)
Over 6 to 8 (152 to 203), incl	¼ (6.4)
Over 8 to 12 (203 to 305), incl	5/16 (7.9)
Over 12 to 16 (305 to 406), incl	3/8 (9.5)

Table 1: Permissible variations in the specified dimensions of the brick

After firing process is completed, unpacking of bricks takes place wherein bricks are cooled so it reaches an ambient temperature [17].

The major advantage offered by bricks is its reduced thermal conductivity [20] that results in cooling effect in summer and warmth in winters [6]. Moreover, clay fired bricks are noncombustible and poor conductor [20] of both heat and current.

Bricks can be classified into three categories based on its resistance to freeze and thaw [19]; Grade SW (Severe Weathering), Grade MW (Moderate Weathering) and Grade NW (Negligible Weathering).

The compressive strength and water absorption requirements for individual bricks are specified in the Table 2 below [19].

Designation	Minimum Compressive Strength gross area, psi (MPa)	Minimum Water Absorption by 5-h Boiling, %
Grade SW	2500 (17.2)	20.0
Grade MW	2200 (15.2)	25.0
Grade NW	1250 (8.6)	No limit

Table 2: Compressive strength and water absorption requirements for individual bricks

One of the problems associated with clay bricks is susceptibility to produce efflorescence. Efflorescence can occur at the beginning during masonry work as a result of the presence of CaO [12]. It can also take place after many years, a phenomenon known as gypsum efflorescence [21]. Both masonry components, brick, and mortar, are reported to source of gypsum efflorescence [21]. Presence of anhydrite in the brick and carbonation of masonry joint contributes towards gypsum efflorescence [21].

2.2 Properties of masonry

The mechanical properties of masonry are influenced by many factors. According to [10], type of mortar (both composition and quantity), nature of material, workmanship and bonding between masonry unit and mortar are main factors contributing to mechanical properties of masonry.

As per the sensitivity analysis carried out in [10], the most governing parameter regarding masonry compressive strength is the compressive strength of masonry unit (brick) followed by mortar thickness. Thinner mortar layers have increased bond strength between mortar joint and masonry unit, therefore enhances the strength of masonry [10]. The least contributing factor towards masonry compressive strength is the mortar compressive strength [10]. However, high strength mortar yields more brittle failure of masonry as compared to low strength mortar [10].

During the earthquake, the structure is exposed to in-plane and out of plane loadings due to multi-directional ground motions [22]. The structure in return tries to absorb and release kinetic energy as it has elastic and fracture capability [22]. It has been established from experimentation that masonry structures have low resistance in tension and shear [10]. These structures tend to fail as a result of diagonal shear due to in-plane load and cracking because of out of plane bending [10].

The most repetitive damage recorded in post-earthquake surveys of unreinforced masonry structures is out of plane damage to the peripheral walls [22]. This damage occurs at low seismic levels as compared to require for in-plane damage [22]. Bricks normally have flat surfaces and friction between these flat surfaces in addition to binding agent (mortar) adds to the resistance of masonry against out of plane loading [12].

Utilization of waste in masonry

Numerous efforts have been made in the past to utilize industrial and agricultural waste in masonry. This research can be categorized into three types based on the production method employed to cast the masonry unit: firing, cementing and geo-polymerization [23]. Firing involves the use of a traditional brick kiln to fire raw materials at elevated temperatures. Cementing utilizes binding agents such as cement to produce bricks. Whereas geo-polymerization involves chemical reaction that converts amorphous silica and alumina solids to amorphous aluminosilicate geopolymer at ambient or slightly high temperatures [23]. But most research is concentrated on utilizing organic and inorganic waste in burnt bricks.

Manufacturing of burnt bricks containing organic waste

In one of the studies, degraded municipal solid waste was used to produce bricks but a drastic (up to 78%) loss in compressive strength was reported [1]. Cigarette butts were used in different dosages to manufacture burnt bricks in another research study. However, compressive strength was reduced by 88% and flexural strength by 50% [1].

Likewise, sugarcane bagasse ash and rice husk ash were used in replacement with clay by weight at different proportions. Compressive and flexural strengths as well as thermal conductivity reduced with increasing dosages of sugarcane bagasse ash and rice husk ash [1].

In another study, fly ash was utilized in the manufacturing of clay fired brick but a decrease in compressive strength along with flexural strength was reported by the researcher [1].

The research findings have been summarized in Table 3 below.

Organic Waste Material	Replacement	Compressive strength	Flexural Strength	Density
Degraded municipal solid waste	5%-20%	reduction up to 78%		reduced mass density
Cigarette Butt	2.5%, 5%, 7.5% and 7.5%	reduction by 88%	reduction by 50%	decreased by 30%
Sugarcane bagasse ash and rice husk ash	5%, 10% and 15%	decreased up to 5.53 MPa	reduced up to 0.83 MPa	
Fly Ash	0-25%	reduced by 50%	reduced by 50%	decreased up to 18%

Table 3: Mechanical properties of burnt bricks containing different organic waste

Manufacturing of burnt brick incorporating inorganic waste material

One researcher investigated the use of waste glass sludge in different replacement percentages by weight of clay to produce clay fired bricks. Increase in compressive strength by 23% was recorded due to the replacement with waste glass sludge as a result of reduction in porosity of brick [1]. Similarly, waste glass was used by replacing clay by up to 10% in the manufacturing of bricks. The addition of waste glass enhanced the compressive strength of the masonry unit [1].

Likewise, clay replacement with waste marble powder by about 35% was carried out to produce clay fired bricks. Although, density of brick reduced but so did the compressive strength [1].

The Table 4 below summarizes research results incorporating inorganic waste materials.

Inorganic Waste Material	Replacement	Compressive strength	Flexural Strength	Density
Waste Glass Sludge	5%-25%	increased by 23%	increased by 100%	

Waste Glass	0-10%	ranged between 19.3 and 24.65 MPa		increase in bulk density
Waste Marble Powder	0-35%	decreased to 8.3 MPa		decrease in bulk density

Table 4: Mechanical properties of burnt bricks containing various inorganic waste

Manufacturing of microbial induced bio-bricks

Microbial induced bio bricks have numerous advantages over cement such a low carbon footprint, low viscosity and more sustainable [24]. Addition of synthetic and natural fibers in bio-brick matrix increases compressive strength by 70% [24]. Moreover, water absorption was similar to that of traditional red bricks [24].

Limitation of utilizing waste products in masonry

Numerous factors have been quoted in [23], that hinder use of agro-industrial waste in masonry. Waste materials are often contaminated that require mechanical or chemical treatment before use [23]. Moreover, there is reluctance from construction sector and public in adopting waste incorporated bricks [23].

Properties of waste plastic

Plastic constitutes a large proportion of worldwide waste, that can either be recycled mechanically, chemically, or thermally [3]. In mechanical recycling the plastic waste is shredded which results in physical degradation of plastic waste but is rather an inefficient mode of recycling [3]. Chemical recycling involves chemical breakdown of plastic into monomers which in turn can then be used to produce new plastic [3].

In thermal recycling the plastic waste is heated at high temperatures, so it melts, and the molten product is then used to produce new plastic products [3]. Extrusion is reported to be the oldest and easiest method of processing the plastic waste [7]. Extrusion involves converting plastic from solid to liquid and back again to solid without compromising its properties.

Plastics can be divided into two types: thermosetting plastic and thermoplastics [25]. During the processing, the thermos-setting plastic achieves a cross linked structure which modifies its properties and makes it thermally stable [25]. The mechanical properties of thermos-setting plastic are superior to thermoplastic, however as its non-recyclable it creates an environmental problem [25].

Thermoplastic, on the other hand, can be recycled multiple times and molded into different shapes [6] [25] without any alteration in its properties [25]. Thermoplastic is widely used globally because of its low processing cost, durability, and strength [6].

There are many types of thermoplastics including polyethylene terephthalate (PET), High-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP) and polyvinyl chloride (PVC) to name a few. When HDPE is blended with LDPE in 1:1 the average melt strength will be maximum as macromolecular chain structure will generate some type of spatial structure [26].

Properties of waste foundry sand

Waste foundry sand is generated at the foundries during the casting operation of steel. To produce molds and cores in foundries a binder material, usually bentonite, is utilized which deactivates at temperature of about 1400 degree Celsius [27]. Since these binders form loose bound deposits on sand grains, they no longer are able to be utilized further [27].

The quality of waste foundry sand depends on numerous factors such as the casting process and source from which it was obtained [15]. Chemically waste foundry sand is composed of about 60% SiO_2 and the rest consist of compounds like Al_2O_3, Fe_2O_3, Cr_2O_3 and CaO [11]. Morphologically, waste foundry sand consists of rough, angular, and spherical particles and since it is rich in silica so it hydrophilic in nature and attracts more water to its surface [15].

Use of plastic in construction

Plastic has been utilized in the construction sector both in concrete and masonry. According to [5], when plastic pellets were added to concrete mix, there was a decrease in fresh density as well as reduction in compressive strength. Several factors contributed to this decrease in strength such as hydrophobic characteristic of plastic which resulted in restriction of hydration process of cement, as well as generation of voids from waste plastic as it adheres poorly with cement due to low surface energy of plastic [5].

It has also been reported in [5] that addition of plastic aggregates to concrete had resulted in decrease in flexural strength due to weak interfacial zone generated between cement paste and plastic aggregate.

In one of studies [3] carried out on fiber reinforced concrete incorporating plastic waste PET concluded that addition of PET did not affect the failure mode of concrete but at the same time improved mechanical behavior by increasing strength and first cracking load. Another researcher [25] added different shapes of plastic waste into self-compacting concrete. Compressive strength in this case increased up to 15% with the addition of 1.5% to 3% of plastic waste.

Plastic waste has also been used in the production of bricks. In one of the research studies [14], PET plastic waste and crushed glass was used to manufacture bricks. The density of resultant brick exhibited reduced porosity. The compressive and tensile strength increased by three times compared to controlled clay brick [14]. Another researcher [4], utilized plastic waste as binding material to produce cement-less paver blocks. The manufactured block had reduced water absorption (0.6% for 50% of plastic waste addition) as a result of dense bond between melted plastic waste and fine aggregates. The block also had lower bulk density which improved its handling and transportation.

It has documented in [5], that with increase in plastic content in bricks the water absorption reduced drastically in bricks.

In another study [25], sand bricks incorporating sand, sand dust, cement, and water in ratio of 9:9:4:2 was developed. Later, different dosages of plastic were added to the sand bricks and the results showed that with the increase in plastic waste content the compressive strength reduced along with workability and water absorption. The reason behind it was the lack of bonding between plastic and sand.

Another researcher [25], manufactured brick composed of laterite quarry waste, bitumen, and PET. The optimum PET content in brick was found out to be 70% resulting in compressive strength of 8.16 MPa [25]. With increase in plastic content water absorption was reported to decrease [25].

Plastic waste has also been used as aggregate in asphalt which improved the skid and crack resistance of the pavement as reported in [3]. The optimum content of plastic was worked to be 5% without affecting viscosity of asphalt mixtures [3].

Shape of the brick

Conventional masonry structures perform inadequately against seismic and impact loadings [18]. Interlocking masonry structures are gaining popularity in both load bearing and non-load bearing structures as it presents numerous advantages such as requirement of less skilled workers thus reducing cost of structure [28]. As per [18], the production rate by employing interlocking brick can be 2.5 to 5 times greater than conventional brick [29] [18] and can reduce labor cost by 60 to 80% [18].

Interlocking brick has grooves and protrusions which makes them easier to lay and reduce construction time [30]. The interlocking bricks are held together by kinematic restraint that permits certain degree of relative movement of building elements [31].

Interlocking dry stacking masonry involves masonry units which are laid without the use of mortar [32]. Mortarless interlocking brick does not encounter issue of shrinkage damage which increases the construction speed [29]. Moreover, physical, chemical, and mechanical degradation of mortar layer occurs as evident from the inspection of old building thus results in loss of structural integrity of the building [18]. According to a research study [18], the contact behavior at the interface of the interlocking blocks is governed by its surface roughness.

The structural performance of interlocking masonry system depends on the shape of interlocking brick [31]. The protrusions or the interlocking key enable the masonry system to resist axial, lateral and flexural loads [32]. Interlocking keys can be provided in vertical, horizontal, or even in both directions [18]. The interlocking mechanism as a result of shape of the brick significantly affect the distribution of stress within the brick due to applied load [32].

Current design practices of interlocking brick have a distinct feature of providing small shear keys to facilitate construction [18]. However, due to the lower projection area of interlocking key shear resistance between interlocking bricks is not enhanced significantly [18].

Numerical Analysis of Interlocking Bricks

Failure of conventional masonry comprising of masonry unit and mortar, occurs at masonry unit and mortar interface due to low tensile and shear strength of mortar [5] [18]. Since interlocking bricks do not have a mortar layer, therefore there is no tensile strength provided for the constructed brick [5].

In interlocking brick system, the masonry unit has the tendency to move slightly as interlocking keys do not fit properly in the grooves especially in case of in-plane loading [5] [18]. This movement then aids in dissipation of energy of masonry system [5] [18]. In dry-stacking interlocking brick system the contact behavior between masonry unit depends upon numerous factors such as cohesion, contact pressure and friction [18]. This contact behavior as result of joint imperfection in turn determines the ultimate load carrying capacity of masonry system [18].

In one of the studies as reported in [12], the compressive strength of interlocking masonry panel depends directly on the compressive strength of masonry unit [12]. The compressive strength of masonry prism depends on the number of masonry units utilized. Compressive capacity of masonry prism decreases with increasing number of masonry units [18].

One researcher studied the effect of compressive load on masonry prism comprising of three masonry units and concluded that a high concentration zone is present at the web-shell [5]. This high concentration zone occurs due to contact mechanism between masonry prism which reduces the compressive strength of interlocking masonry prisms [5]. As a result of this contact mechanism, vertical cracks are developed, and web splitting failure occurs which happens to be a common failure mechanism in interlocking masonry system [5].

In one of the research studies [18], interlocking masonry prisms were modelled in ABAQUS using a concrete damaged plasticity model. To simulate the contact behavior at joints of interlocking masonry bricks, three modelling methods were adopted: perfect contact, imperfect contact, and cohesive element contact [18]. It was found that for ultimate load carrying capacity of interlocking brick prisms both perfect and imperfect contact provided fairly accurate results which were experimentally verified [18]. There were limitations to the model as well, initially the interlocking bricks filled the gaps between them a phenomenon known as seating [18]. This large initial displacement could not be captured by the model. Moreover, the post peak behavior of interlocking prism could not also be modelled accurately as the model less residual capacity compared to the laboratory test results [18].

In another research [12], interlocking burnt clay masonry wall panels were constructed and its structural performance was evaluated. Compared to conventional brick wall panels, the interlocking clay brick panels had 43% increased out of plane load carrying capacity [12]. In addition, interlocking masonry brick panels have higher energy absorption capacity as compared to conventional wall panels [12].

It is reported in [12] that the interlocking wall panel have 25% more out of plane load carrying capacity than its in-plane load carrying capacity. Also, interlocking wall panels generally exhibited 40% increase in its lateral capacity compared to wall panel constructed with traditional bricks and also developed diagonal shear cracking when exposed to out of plane loading [12].

In another study [28], axial compressive behavior of rubberized interlocking wall was investigated. High initial axial deformation at lower loads was observed which again was due seating effect in which gaps in construction of rubberized interlocking masonry wall are first filled [28].

Environmental Impact Assessment

Masonry structures are expensive to construct as extraction of raw material and the manufacturing process are cost-intensive and have a lot of environmental issues associated with it [33]. Quarrying operations to obtain clay require a lot of energy and also alter the landscape resulting in production of a huge quantity of waste [23].

To construct an energy efficient building, it is imperative to improve the thermal performance of the walls and bricks are usually used as masonry unit in wall [34]. Usually, bricks have high carbon footprint as they are usually manufactured from clay fired kilns or cement and contain high embodied energy [23].

Plastic waste is generated in large number out of which only 7% is recycled, 8% is incinerated and rest is disposed in the landfills [3]. About 22% to 43% of plastic waste generated globally ends up in landfills [5]. Mismanagement of plastic waste results in ending up in marine environment that are consumed by fishes and ultimately enters our food chain [3]. Plastic waste is subjected to degradation via photodegradation, weathering and biodegradation resulting in microplastics that is polluting the environment [5].

Plastic waste can clog the drainage system resulting in accumulation of water on the surface which acts as breeding ground for mosquitos and other water borne diseases [5].

Foundries consume a huge amount of energy in production of steel and generate a huge quantum of waste in form of sand and sludge which is usually disposed in open spaces or water bodies as they are not usable for further applications [27].

Environmental impact of conventional brick and interlocking brick was conducted as per ISO 14040-44 guidelines in one study [29]. Conventional brick had 28% to 73% greater environmental impact as compared to interlocking bricks [29].

CHAPTER 3

METHODOLOGY

The casting of waste plastic brick involves melting of PET/HDPE/LDPE blends. The ratio of PET, HDPE, and LDPE waste plastic to be used in casting of waste plastic brick was evaluated using compressive strength test as per ASTM C579. Later the compressive strength, water absorption, efflorescence, and modulus of rupture of the manufactured waste plastic bricks and control clay fired bricks was determined in accordance with ASTM C67. Similarly, splitting tensile test was conducted on waste plastic brick formulations as per guidelines laid in ASTM C1006. Moreover, the bond strength between waste plastic brick and mortar was also investigated in accordance with ASTM C1072. In order to analyse the microstructure of waste plastic brick Scanning Electron Microscopy was performed. Thermal performance of bricks is necessary to be investigated as it must conform to insulation requirements laid by various buildings codes worldwide to ensure liveable environment for the inhabitants. To determine the melting point of waste plastic brick DSC was conducted and thermal conductance test was performed in order to determine the insulation capability of waste plastic brick in comparison with traditional fired clay bricks. Electrical resistance was also measured through a resistivity meter. Tests were also conducted on brick prisms to determine the compressive strength as per ASTM C1314-03b and shear strength as per BS EN 1052. In addition, the tensile property of the waste plastic brick for different formulations were also investigated as per JSCE guidelines. Friction and wear resistance using pin in disk apparatus was also found for the waste plastic brick as per ASTM G99.

The Table 5 below represents the test matrix adopted for this research.

Phase	Material/Formulation	Test	Standard
Phase1: Casting optimal Strength Plastic Brick	Foundry Sand	SEM	-
		XRF	-
		Sieve Analysis	ASTM C136
		Water Absorption	ASTM C128
	Plastic (LDPE, HDPE & PET)	DSC	-
	Plastic Ratios (7 formulations)	Compressive Strength Test	ASTM C579-B

Phase 2: Determining Mechanical Properties of Waste Plastic Brick	Waste Plastic Bricks (5 Formulations) + Control Clay Fired Bricks (2 formulation)	Compressive Strength Test	ASTM C67-05
		Water Absorption	ASTM C67-05
		Flexure/Modulus of Rupture	ASTM C67-05
		Split Tensile Test	ASTM C1006-84
		Efflorescence	ASTM C67-05
	Waste Plastic Brick (2 Formulations)	Tensile Strength Test	JSCE
		Friction Coefficient	ASTM G99
	Micro-structure Analysis	SEM	-
	Waste Plastic Brick (2 Formulations) + Control Clay Fired Brick	Thermal Conductance	-
		Electrical Resistance	-
		DSC	-
Phase 3: Performance Evaluation of Interlocking Brick	Masonry Prism (3 Formulations)	Masonry Compressive strength	ASTM C1314-03b
		Bond Wrench (Flexural Tensile Strength)	ASTM C1072
		Triplet Shear Test	BS EN 1052

Table 5: Detailed experimental program for the research

The test numbers for casting different formulations consisting of various sizes are mentioned in the Table 6 below. The total number of samples casted for entire experimental work was **277**.

<table>
<tr><th>Phase</th><th>Material/Formulation</th><th>Test</th><th>Casting Numbers per Formulation</th><th>Total</th></tr>
<tr><td rowspan="6">Phase1:
Casting optimal Strength Plastic Brick</td><td rowspan="4">Foundry Sand</td><td>SEM</td><td>-</td><td>-</td></tr>
<tr><td>XRF</td><td>-</td><td>-</td></tr>
<tr><td>Sieve Analysis</td><td>-</td><td>-</td></tr>
<tr><td>Water Absorption</td><td>-</td><td>-</td></tr>
<tr><td>Plastic (LDPE, HDPE & PET)</td><td>DSC</td><td>-</td><td>-</td></tr>
<tr><td>Plastic Ratios
(7 formulations)</td><td>Compressive Strength Test</td><td>6 (2 inches cubes)</td><td>42</td></tr>
<tr><td rowspan="11">Phase 2:
Determining Mechanical Properties of Waste Plastic Brick</td><td rowspan="5">Waste Plastic Bricks
(5 Formulations)
+
Control Clay Fired Bricks
(2 formulation)</td><td>Compressive Strength Test</td><td>5 (half size brick)</td><td rowspan="2">25</td></tr>
<tr><td>Water Absorption</td><td>5(half size brick)</td></tr>
<tr><td>Flexure/Modulus of Rupture</td><td>5 (full size brick)</td><td rowspan="2">50</td></tr>
<tr><td>Split Tensile Test</td><td>5(full size brick)</td></tr>
<tr><td>Efflorescence</td><td>10 (full size brick)</td><td>-</td></tr>
<tr><td rowspan="2">Waste Plastic Brick
(2 Formulations)</td><td>Tensile Strength Test</td><td>5 (dogbone shape)</td><td>10</td></tr>
<tr><td>Friction Coefficient</td><td>5 (50 in dia hollow disc)</td><td>10</td></tr>
<tr><td>Micro-structure Analysis</td><td>SEM</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Waste Plastic Brick
(2 Formulations)
+
Control Clay Fired Brick</td><td>Thermal Conductance</td><td>3 (50 mm dia disc)</td><td>6</td></tr>
<tr><td>Electrical Resistance</td><td>1 (half size brick)</td><td>2</td></tr>
<tr><td>DSC</td><td>Powdered Form</td><td>-</td></tr>
<tr><td rowspan="4">Phase 3:
Performance Evaluation of Interlocking Brick</td><td rowspan="4">Masonry Prism
(3 Formulations)
+
Masonry Wallets
(3 Formulations)</td><td>Masonry Compressive strength</td><td>9 (3 brick prism)</td><td>18</td></tr>
<tr><td>Bond Wrench
(Flexural Tensile Strength)</td><td>6 (2 brick prism)</td><td>12</td></tr>
<tr><td>Diagonal Shear Strength</td><td>1 (27 x 27 in wallet)</td><td>48</td></tr>
<tr><td>Triplet Shear Test</td><td>27 (3 brick prism</td><td>54</td></tr>
</table>

Table 6: Detailed casting regime adopted for the research

CHAPTER 4

RESULTS AND DISCUSSION

Raw Materials

In this research, waste plastic was utilized comprising of polyethylene terephthalate (PET), high density polyethylene (HDPE) and low-density polyethylene (LDPE) along with waste foundry sand WFS. Waste plastic was obtained from waste collection point in Islamabad whereas the waste foundry sand was collected from a steel mill located at Mirpur District, Azad Kashmir, Pakistan. For control samples, first class and second class clay fired bricks were utilized which were procured from a local brick kiln located at Islamabad, Pakistan.

Characterization

2.1 Waste Foundry Sand

Material characterization of waste foundry sand was carried out at both macro and microscopic levels to evaluate its physical and chemical properties. To examine the particle size distribution of WFS, sieve analysis was carried out as per ASTM C136 [35]**.** The particle size distribution of WFS in terms of percentage passing is shown in Figure 1 below having a fineness modulus of 2.56.

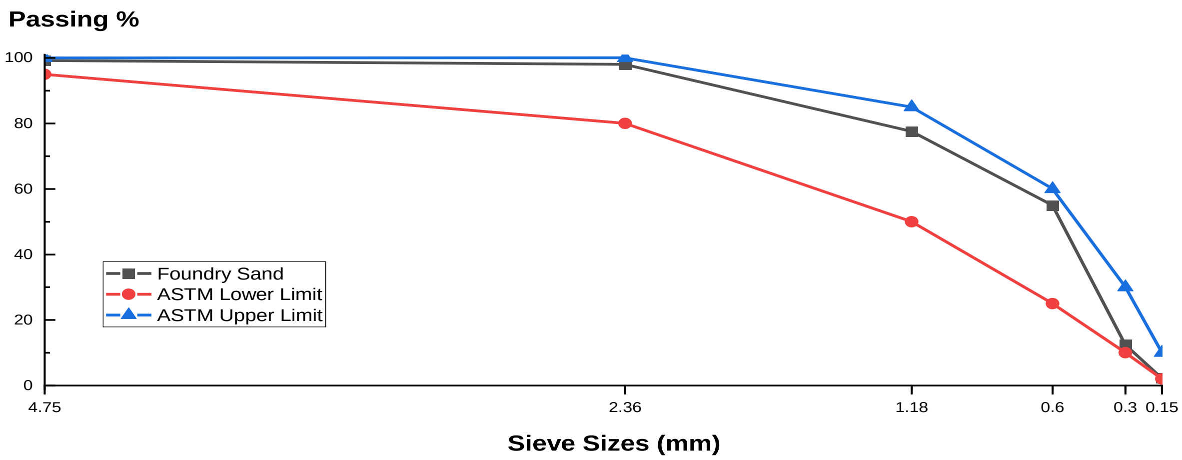


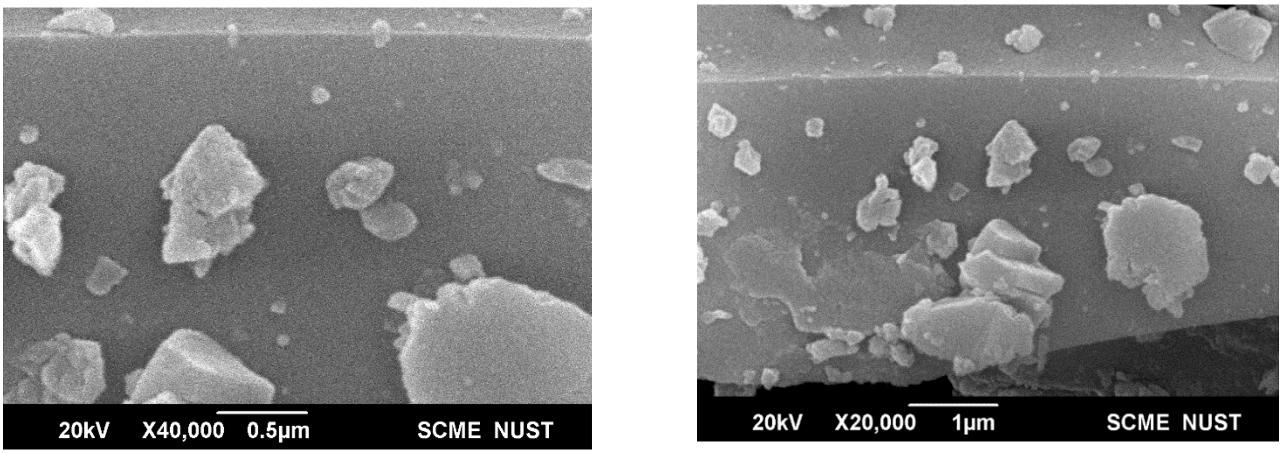
Figure 1: Particle size distribution of WFS

The oxide composition of WFS was determined through X-ray fluorescence and its composition summarized in Table 7 below.

Oxide Composition	Percentage
SiO_2	87.59
Al_2O_3	2.45
Fe_2O_3	6.72
CaO	2.11
MgO	0.32
SO_3	0.24
K_2O	0.57

Table 7: Oxide composition of WFS

It is evident from XRF result that main oxides in WFS were SiO_2 and Fe_2O_3 accounting for 94.31% cumulatively. The high quantity of Fe_2O_3 is attributed to traces of Fe being incorporated in the sand during the process of casting of steel. According to [11], average dry mass of SiO_2 in waste foundry sand is 60%. However, as per [15] the quality of waste foundry sand depends upon numerous factors such as the casting process, the material manufactured in the industry and the origin of the material from which WFS is formed. This explains the reason for the presence of high quantity of SiO_2 in WFS. Similarly, water absorption test was conducted on WFS in accordance with ASTM C128 [36]. The gravimetric method was adopted to calculate water absorption which turned out to be 0.8%. In order to investigate particle morphology, scanning electron microscopy (SEM) was performed on WFS as illustrated in Figure 2 below.



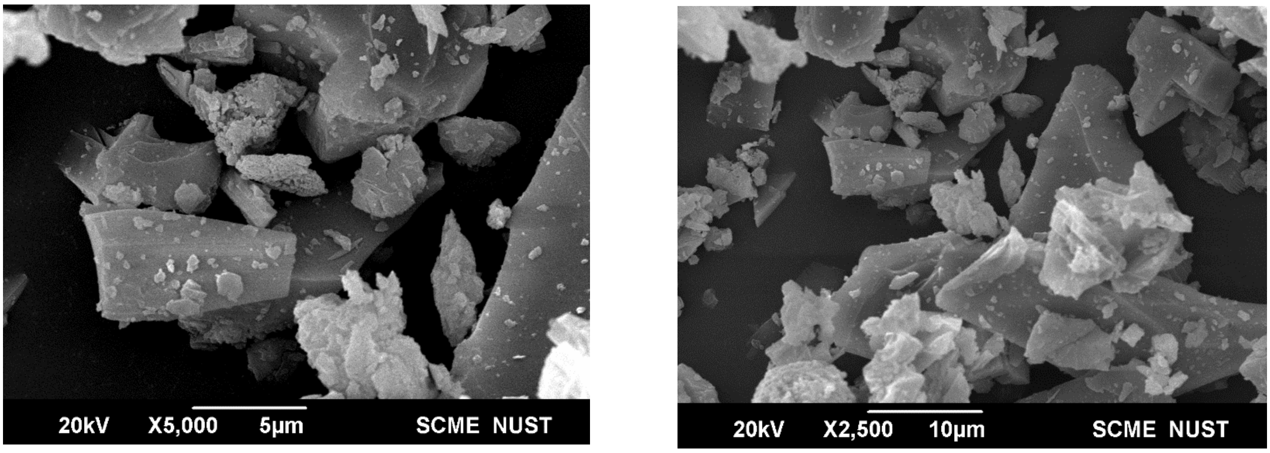


Figure 2: SEM of WFS highlighting particle morphology

According to SEM at various resolutions, WFS particle morphology is predominantly angular and irregular particles with presence of a few spherical particles as well. According to [15], WFS particles possesses rough, angular, and spherical particles.

Waste Plastic

Plastics can be categorized into two groups: thermoplastic and thermosetting plastic. Thermosetting plastic achieves a cross linked structure during its processing that makes it stable and provides resistance to heat at high temperatures [25]. Thermoplastic on the other hand is manufactured by heating and molded into different shapes but at the same time can be recycled and still retain its properties [25]. Although mechanical properties of thermosetting plastic are superior to thermoplastic but since it cannot be recycled it creates an environmental issue [25].

There are three ways to recycle waste plastic: mechanically, chemically, or thermal treatment [3]. Mechanical recycling involves shredding the plastic waste whereas in chemical treatment the polymers of waste plastic are converted into monomers and in this way new plastic is manufactured [3]. In thermal treatment waste plastic is melted at high temperature and then reused by casting it into new products [3].

In this research, PET/HDPE/LDPE is utilized which belongs to thermoplastic category. PET/HDPE/LDPE waste blend is first recycled mechanically and then thermally treated. The primitive way of recycling plastic waste is extrusion in which plastic is converted from solid to liquid and back again to solid without compromising its properties [7]. Out of the three waste plastic PET has the highest melting point. To determine this melting point, a differential scanning calorimetry (DSC) test was performed on PET.

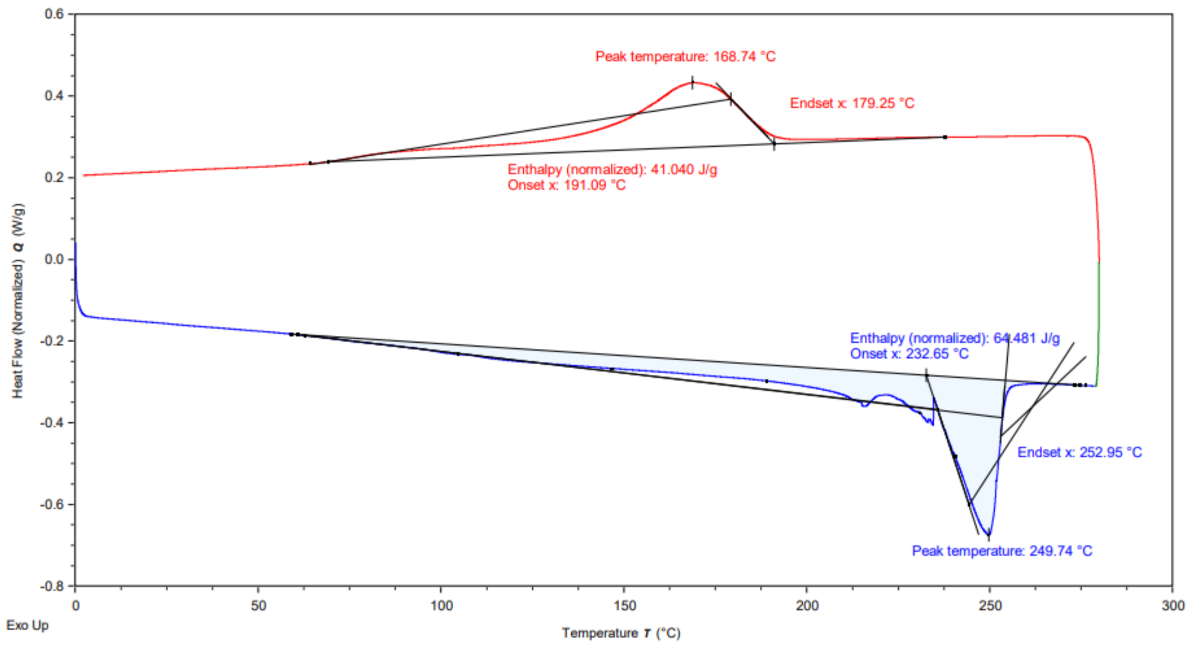


Figure 3: DSC of PET

According to the DSC plot as shown in Figure 3 above, the first heating cycle (represented by blue line) denoting an endothermic process provides the melting point of PET which is 249.74 ^{o}C. The energy associated with this transition is 64.481 J/g represented by the area under the curve. The top curve (represented by red line) corresponds to controlled cooling of PET which essentially is an exothermic process and gives insights to re-solidifying of PET. The peak on the top curve denotes the recrystallization temperature which is 168.74 ^{o}C.

Casting of Waste Plastic Brick

Firstly, waste plastic was segregated at the waste collection point. PET was obtained by extracting water bottles from the garbage. Household articles like plastic dishes and containers are the source for HDPE. Plastic shopping bags are composed of LDPE. After the waste was segregated from the waste collection point, it was then air dried for 4 days. This step was conducted to ensure the removal of excess moisture that may impede the shredding process. The shredding was done in two ways, for PET and HDPE mechanical shredders were used but for LDPE shopping bags were shredded via scissors as it could not be shredded using mechanical shredders.

After the completion of shredding process, the waste plastic was melted at 249 ^{o}C until a slurry was formed. Once the slurry was formed, WFS was added gradually and stirred continuously to achieve a molten paste which was then poured into mold. The mold had a dimension of 9 x

4.5 x 3 inches. The molten brick paste was then allowed to cool for 5 hours till it solidifies and also reaches the ambient temperature for handling. At last, the brick is de-molded and ready for investigating its mechanical properties. The schematic diagram as shown in Figure 4 below illustrates the whole manufacturing process of waste plastic brick.

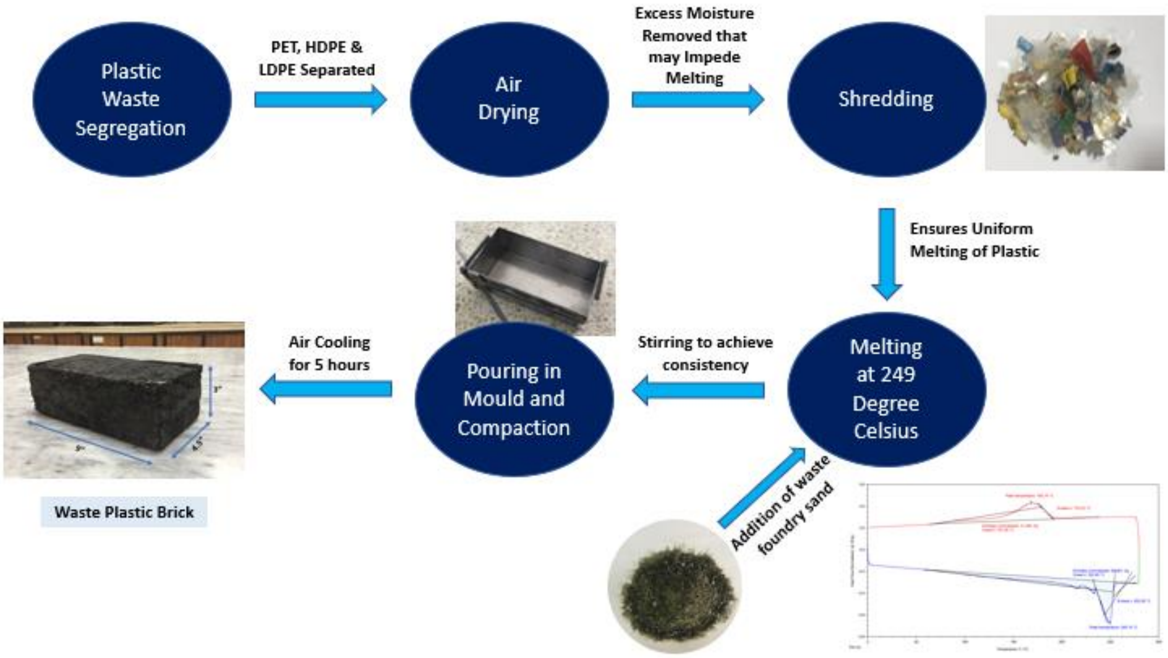


Figure 4: Schematic diagram illustrating the casting procedure of waste plastic brick

In this research, 4 different formulations of PET/HDPE/LDPE blend were utilized to determine the optimum ratio of the blend to cast waste plastic brick incorporating WFS. The details of the formulation of PET/HDPE/LDPE are listed in Table 8 below.

Nomenclature	PET (% by volume)	HDPE (% by volume)	LDPE (% by volume)
50:25:25	50	25	25
60:20:20	60	20	20
70:15:15	70	15	15
80:10:10	80	10	10

Table 8: Nomenclature of different dosages of waste plastic used in casting

To formulate an optimal strength waste plastic brick incorporating WFS, different ratios of waste plastic i.e., PET/HDPE/LDPE and WFS were investigated. Table 9 below summarizes different quantities of waste plastic and WFS used in manufacturing of waste plastic brick.

Nomenclature	PET	HDPE	LDPE	WFS
100:0	50	25	25	-
30:70	15	7.5	7.5	70
40:60	20	10	10	60
50:50	25	12.5	12.5	50
60:40	30	15	15	40

Table 9: Nomenclature of different formulation of waste plastic brick

Discussion of Physical and Mechanical Properties

4.1 Melt Strength of Waste Plastic

The casting of waste plastic brick involves melting of PET/HDPE/LDPE blend. It is imperative to know the melting strength of waste plastic and the ratio of PET/HDPE/LDPE that would produce the maximum strength waste plastic brick. In order to come up with the correct combination of PET/HDPE/LDPE blend, PET, HDPE and LDPE were melted and their melt strength was evaluated by performing compressive strength test as depicted in Figure 5 below.

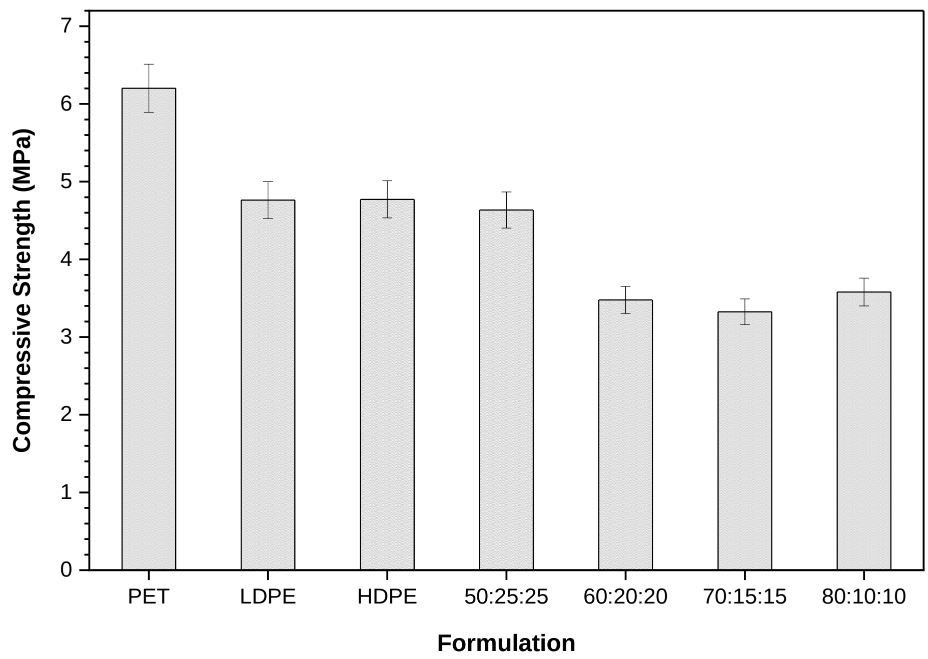


Figure 5: Compressive strength of different dosages of waste plastic to be used in manufacturing of waste plastic brick

To perform the compressive strength test 2 inches cubes were cast by melting different formulations of PET, HDPE, and LDPE. The loading rate was kept at 6.25 mm/min as prescribed in ASTM C579**.** From the test results, it can be inferred that PET has the highest compressive strength of 6.2 MPa among PET/HDPE/LDPE blend. The compressive strength for HDPE and LDPE is identical with compressive strengths of 4.77 and 4.76 MPa respectively. Since PET has the highest compressive strength its ratio in PET/HDPE/LDPE blend, therefore PET proportion was kept higher in deciding the remaining PET/HDPE/LDPE formulations whereas HDPE and LDPE content was kept same as the compressive strength was almost equal. According to [26], doping HDPE with LDPE improves the melt strength as macromolecular chains develop a spatial structure. When HDPE and LDPE are utilized in 1:1, the average melt strength is reported to be maximum whereas its maximum stretching ratio is low [26].

The stress strain response of different PET/HDPE/LDPE blends were examined and are shown in Figures 6 and 7 below.

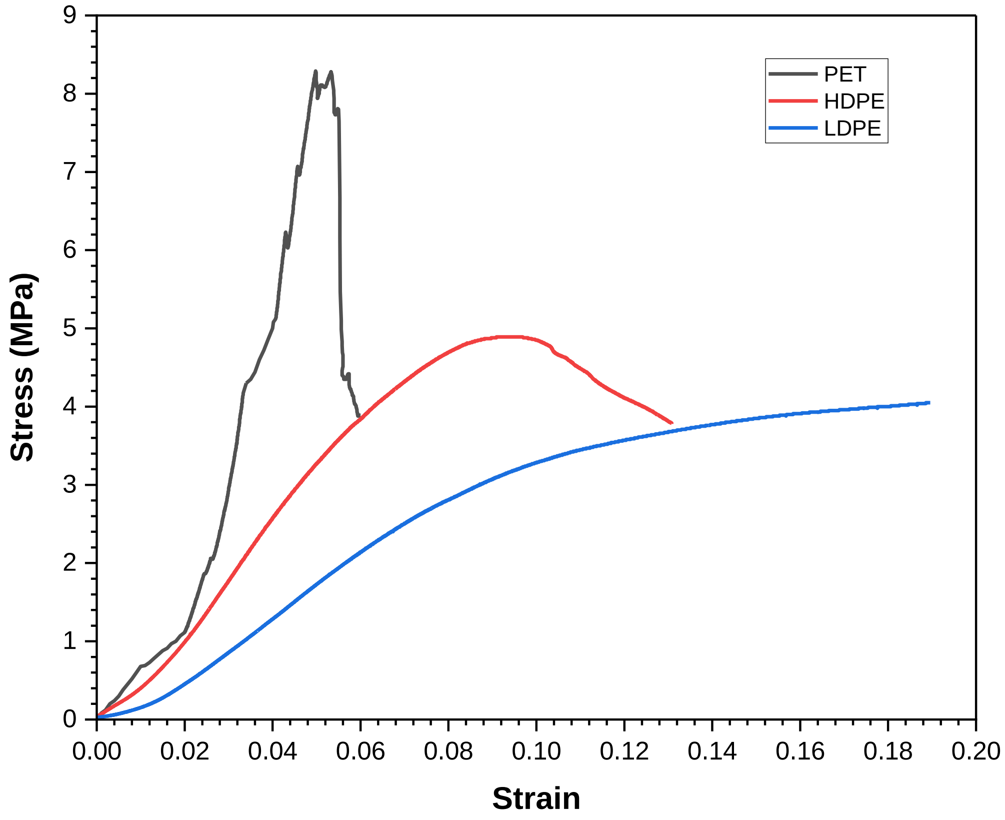


Figure 6: Stress strain plot of PET, HDPE & LDPE

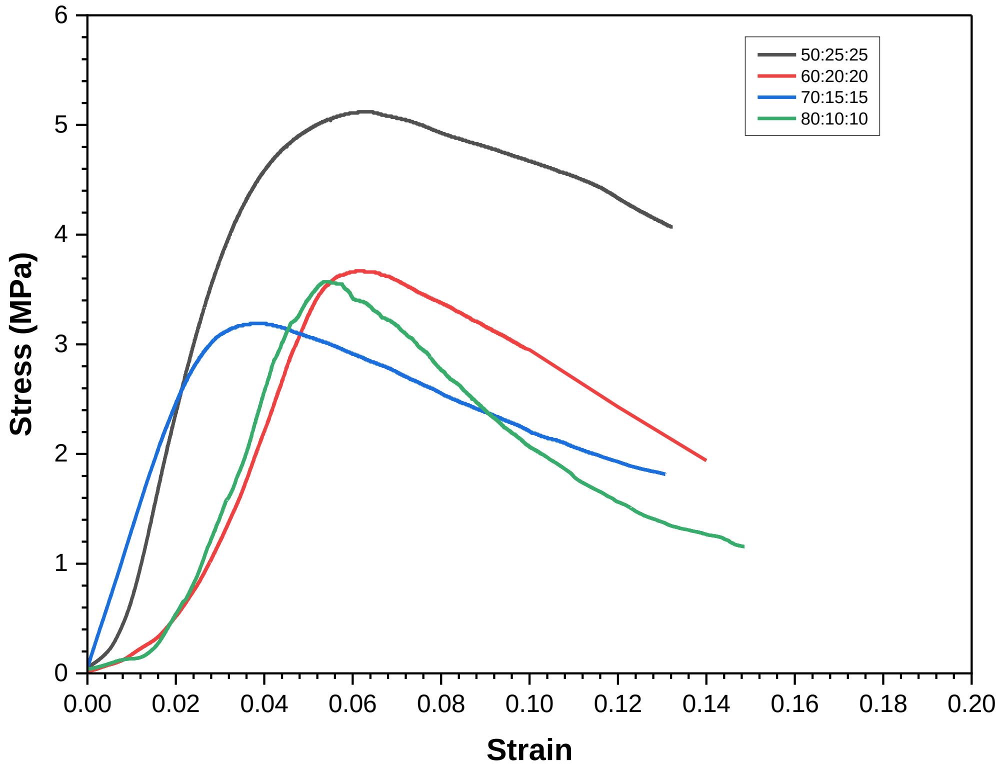


Figure 7: Stress Strain plot for various PET/HDPE/LDPE blends

Compressive Strength of Bricks

Compressive strength of the brick is one of the most important parameters in evaluating the performance of masonry structures. The figure below shows the results for waste plastic brick forged from different dosages of plastic waste and WFS as enlisted in Table 9. The test was performed conforming to the guidelines laid in ASTM C67 [37]. Half brick samples were used with loading rate kept as 1 mm/min.

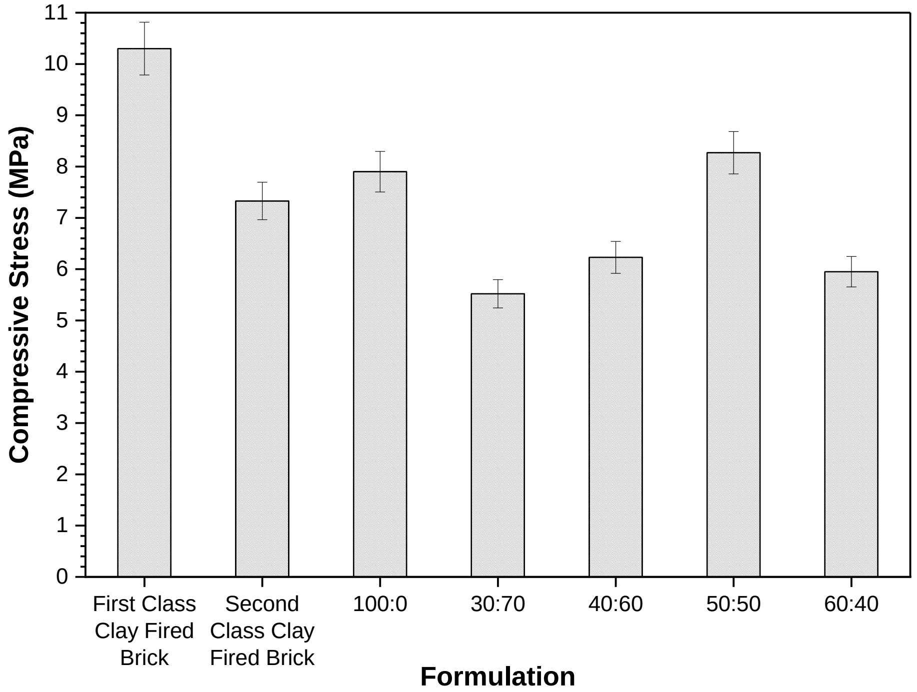
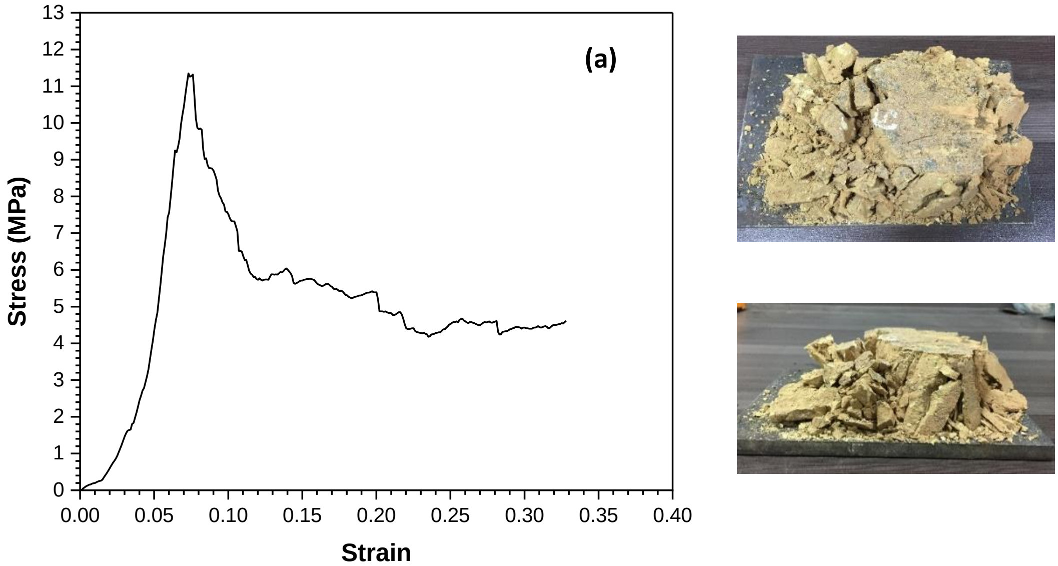
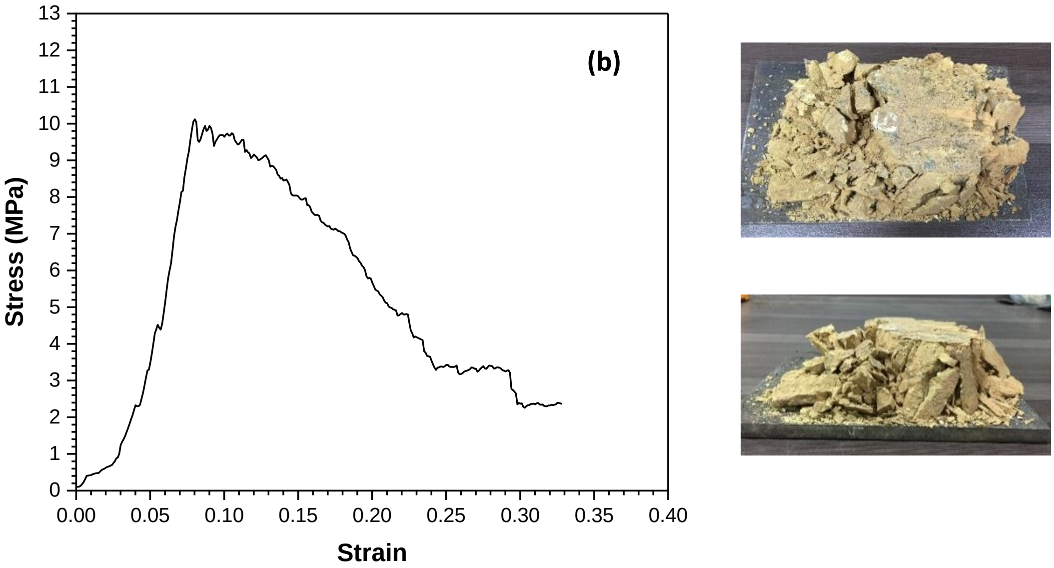


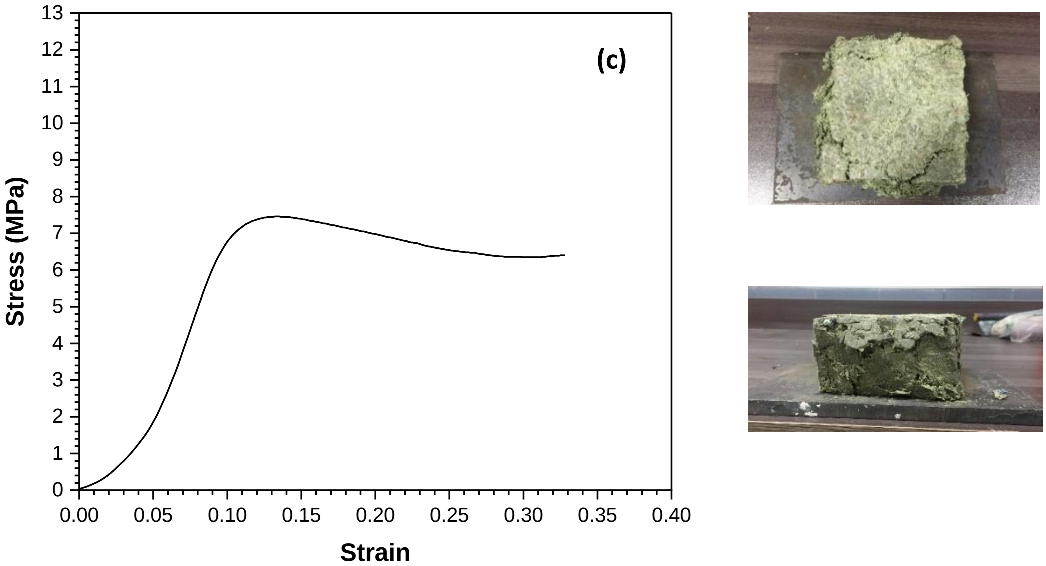
Figure 8: Compressive strength test for control and waste plastic brick formulations

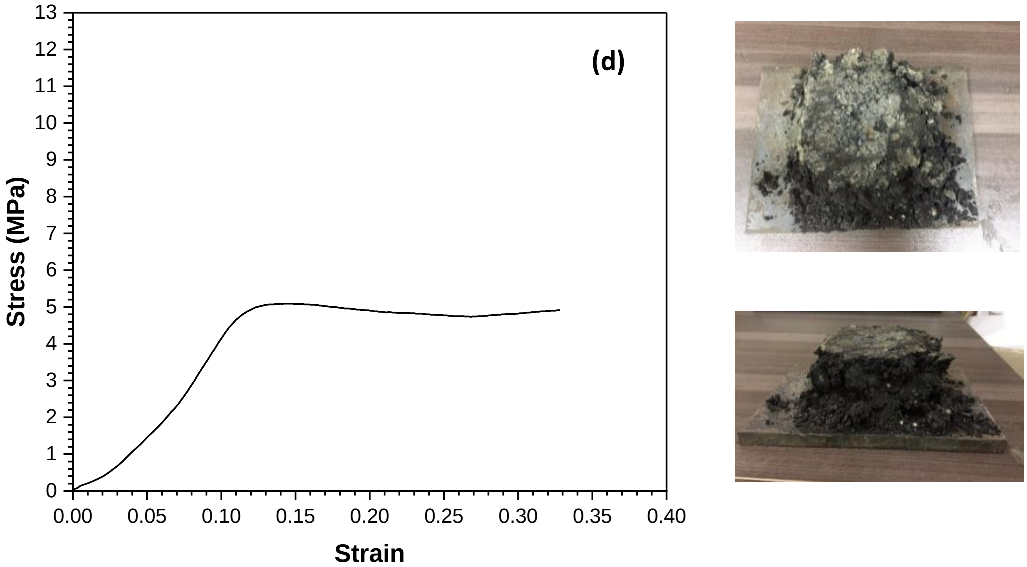
According to the test results, formulation 50:50 produced the maximum compressive strength of 8.23 MPa amongst waste plastic brick formulations. This strength is comparable to second class brick used for non-load bearing structures. Formulation 30:70 yielded the least compressive strength of 5.52 MPa due to lesser quantity of melted plastic that acts as a binder with WFS. Compressive strength increased for 40:60 formulation reaching a maximum compressive strength for 50:50 which had optimum quantity of melted waste plastic and WFS.

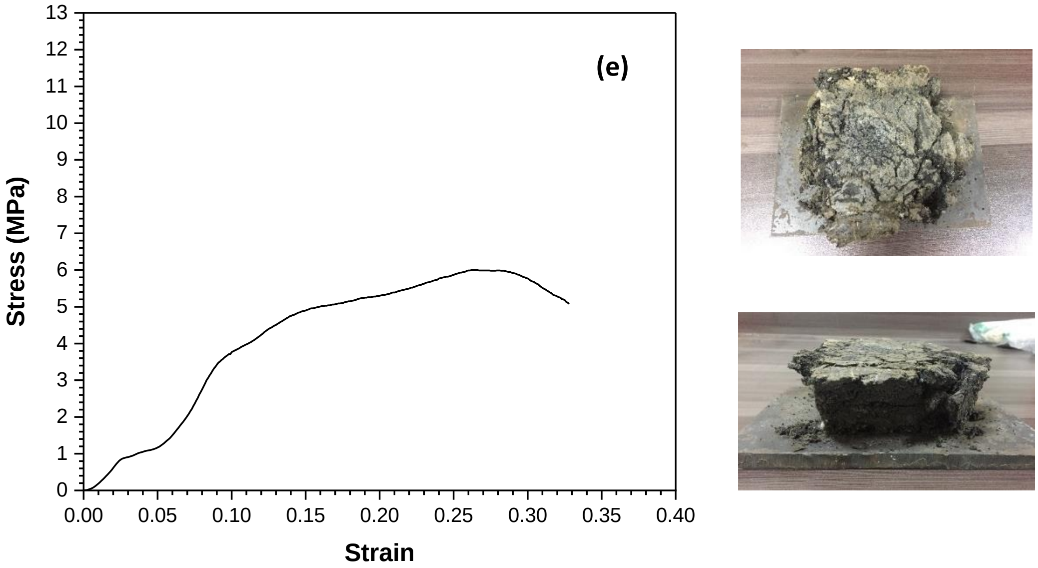
The stress strain responses of different formulations and control samples have been presented in Figures 9 and 10 below.

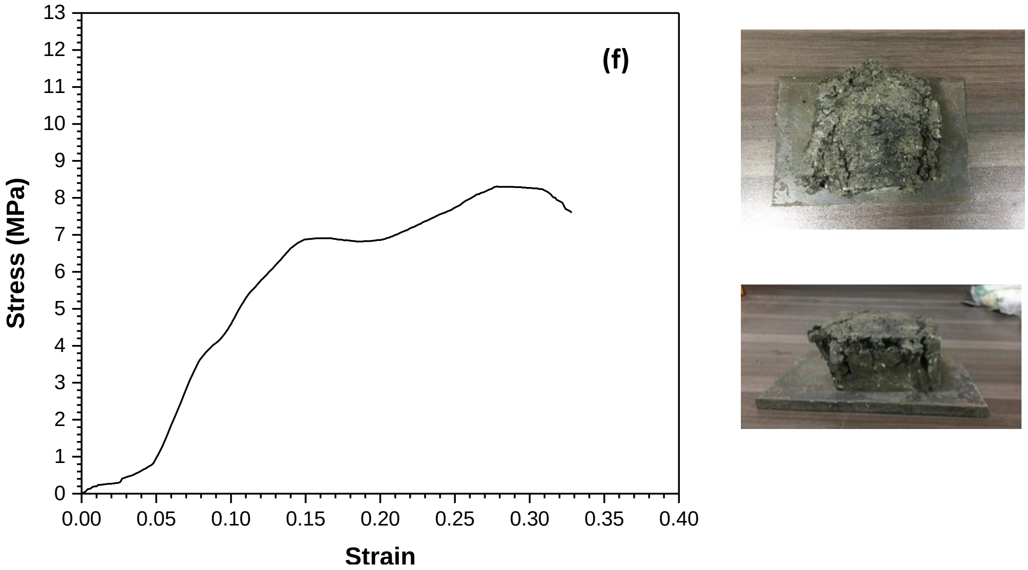



(b)
Stress (MPa)
Strain
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
0 1 2 3 4 5 6 7 8 9 10 11 12 13


(c)
Stress (MPa)
Strain
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
0 1 2 3 4 5 6 7 8 9 10 11 12 13


(d)
Stress (MPa)
Strain
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
0 1 2 3 4 5 6 7 8 9 10 11 12 13





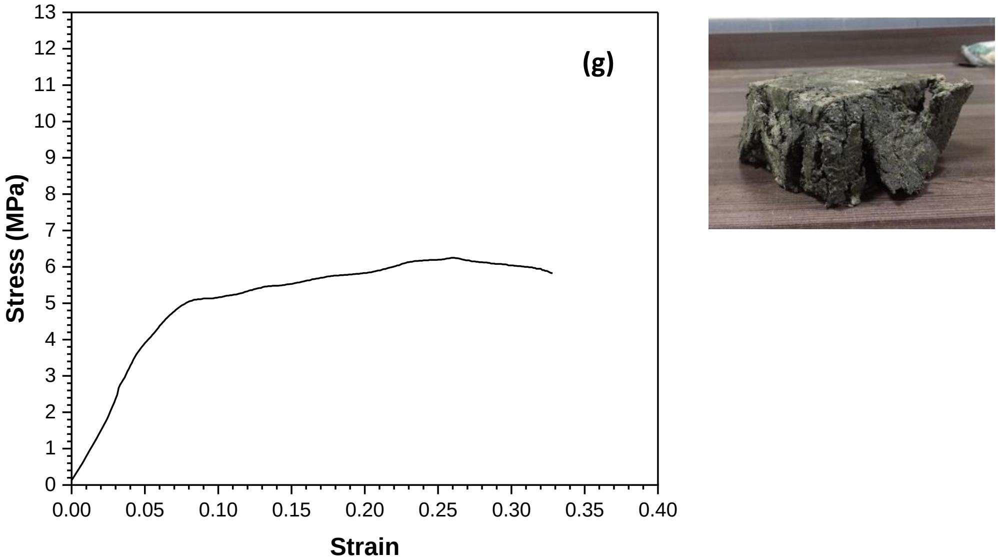


Figure 9: Stress strain plot and damage occurred on top and sides of the sample (a) first class brick (b) second class brick (c) 100:0 (d) 30:70 (e) 40:60 (f) 50:50 (g) 60:40

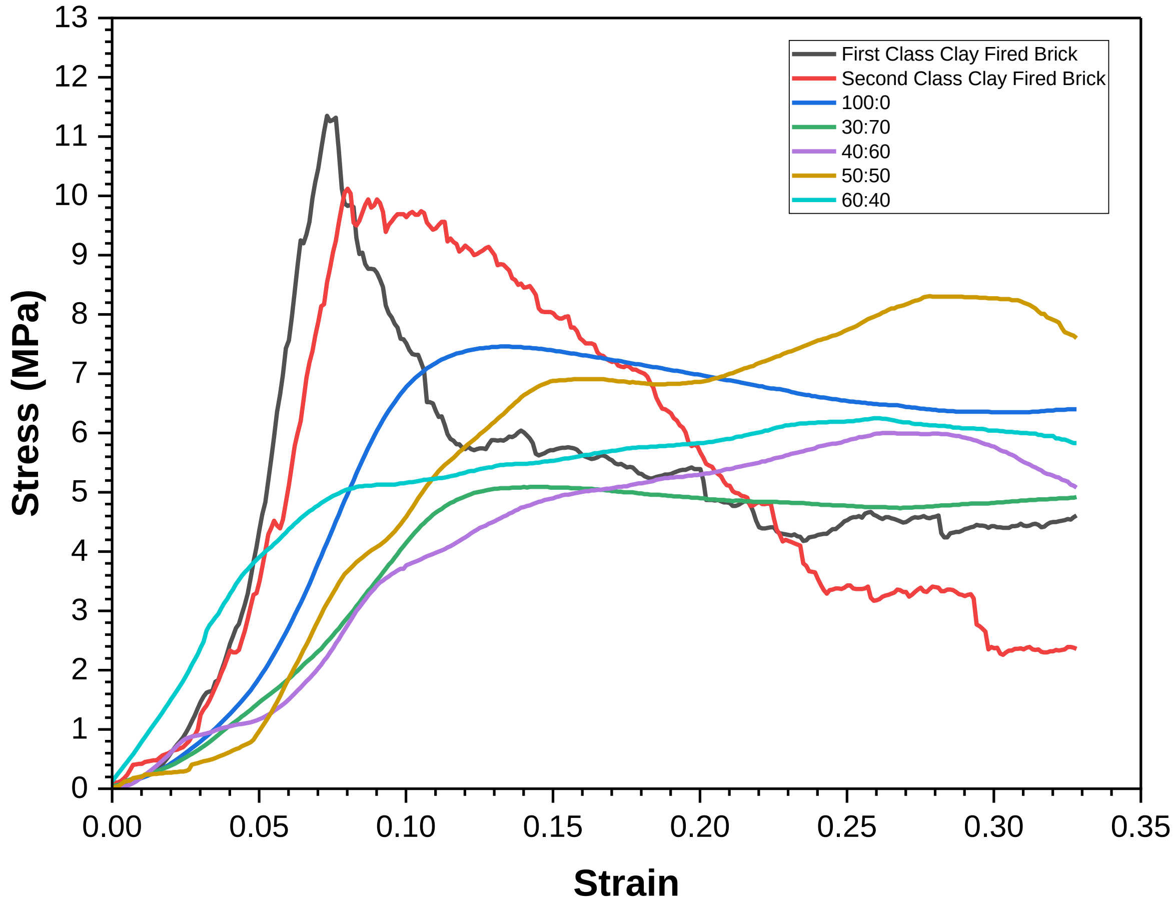


Figure 10: Stress strain of various formulations of control and waste plastic brick

According to [38], the satisfactory failures in bricks are defined as ones exhibiting approximately equal cracking on the four outer faces having minimal damage on the face in contact with the platens. From the figures above, it can be seen that all samples underwent satisfactory failure.

Water Absorption

Water absorption is an important parameter that determines the durability of the masonry structure. According to [4], durability of materials depends on its water absorption. Excessive moisture absorption can lead to dampness on the exterior finishes on the wall and result in deterioration of the finishes and reveals an unaesthetic façade. Water absorption test on control samples and waste plastic brick formulations was conducted as per ASTM C67 [37]. Half brick samples were submerged in water for 24 hours for computing the water absorption for the results are summarized in Figure 11 below.

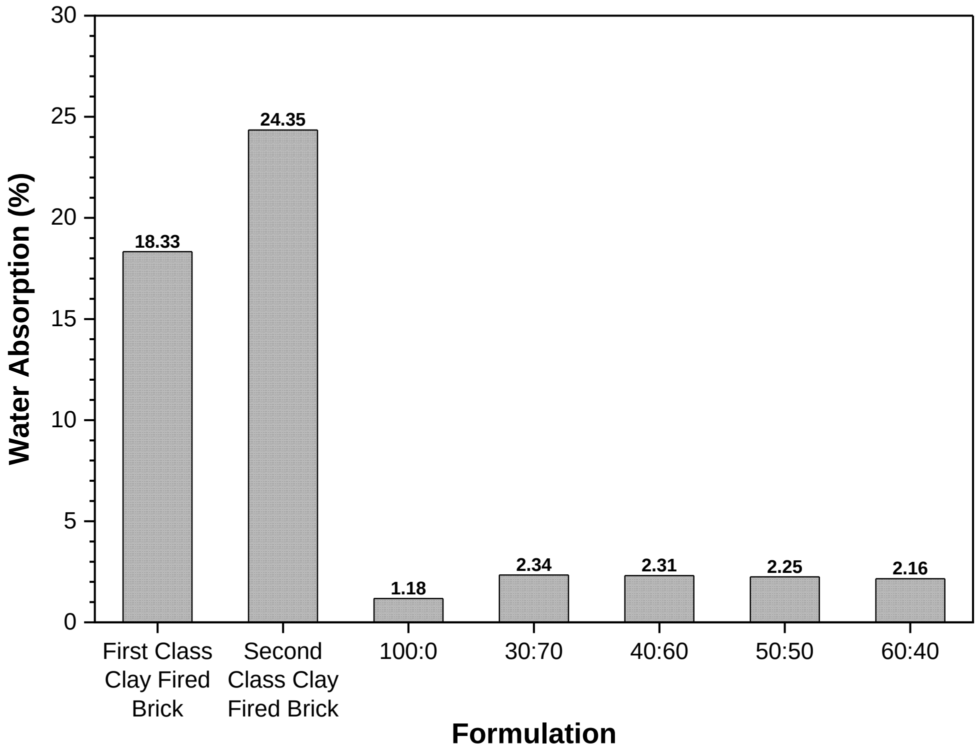


Figure 11: Water absorption for different formulations of control and waste plastic brick

Water absorption of waste plastic bricks was significantly less than control clay fired brick samples. According to [5], plastic has hydrophobic property which repels water at its surface. Another factor accounting for low water absorption of waste plastic brick is the low water absorption of WFS. Although water absorption was observed to decrease with an increase in plastic waste content, this increase was insignificant.

Efflorescence

Efflorescence is deposition of white residue on the surface of the brick. According to [12], CaO is major cause of efflorescence. According to [39], the efflorescence product is composed mostly of $CaCO_3$, $CaSO_4$ and Na_2CO_3. To investigate the efflorescence phenomenon in waste plastic brick and control brick samples efflorescence test as per ASTM C67 [37] was performed. Firstly, 10 full size bricks were sorted into 5 pairs based on their appearance. After scraping dirt from the bricks, one brick from each pair was immersed in water to a depth of 1 inch for a period of 7 days. Other brick from the pair was wrapped in plastic sheet to avoid contact with moisture for the same period. After 7 days, the pairs were oven dried for 24 hours. At last, the pairs were examined visually from a distance of 10 feet to observe for any traces of efflorescence. The test results are shown in Figures 12 and 13 below.

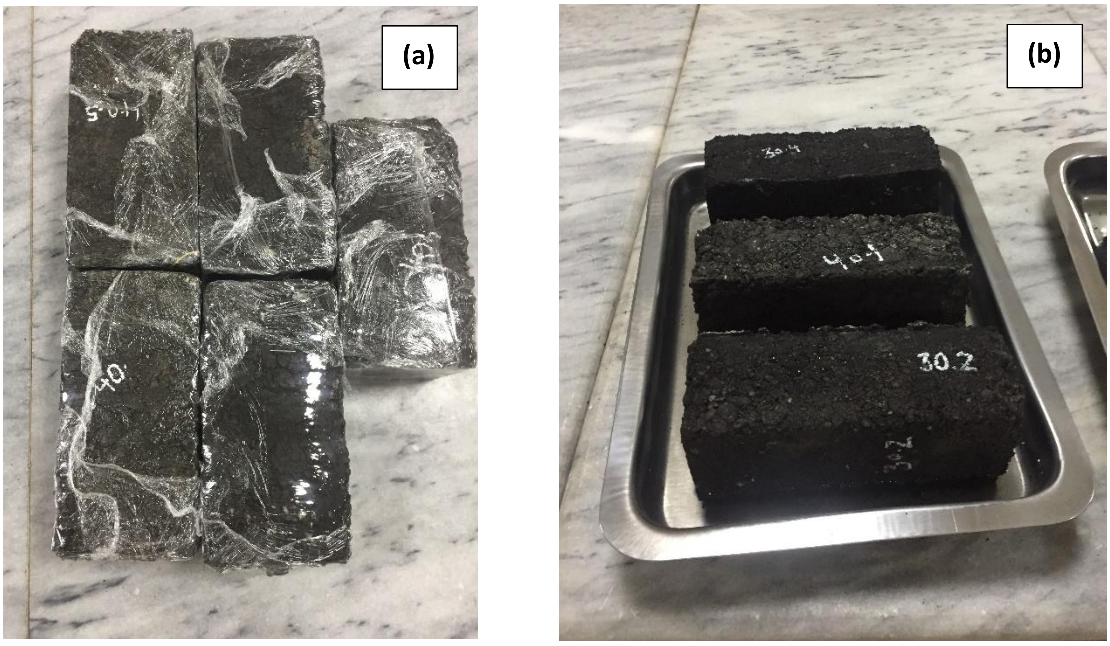


Figure 12: Efflorescence test procedure for bricks in (a) dry state (b) immersed in 1 in depth of water

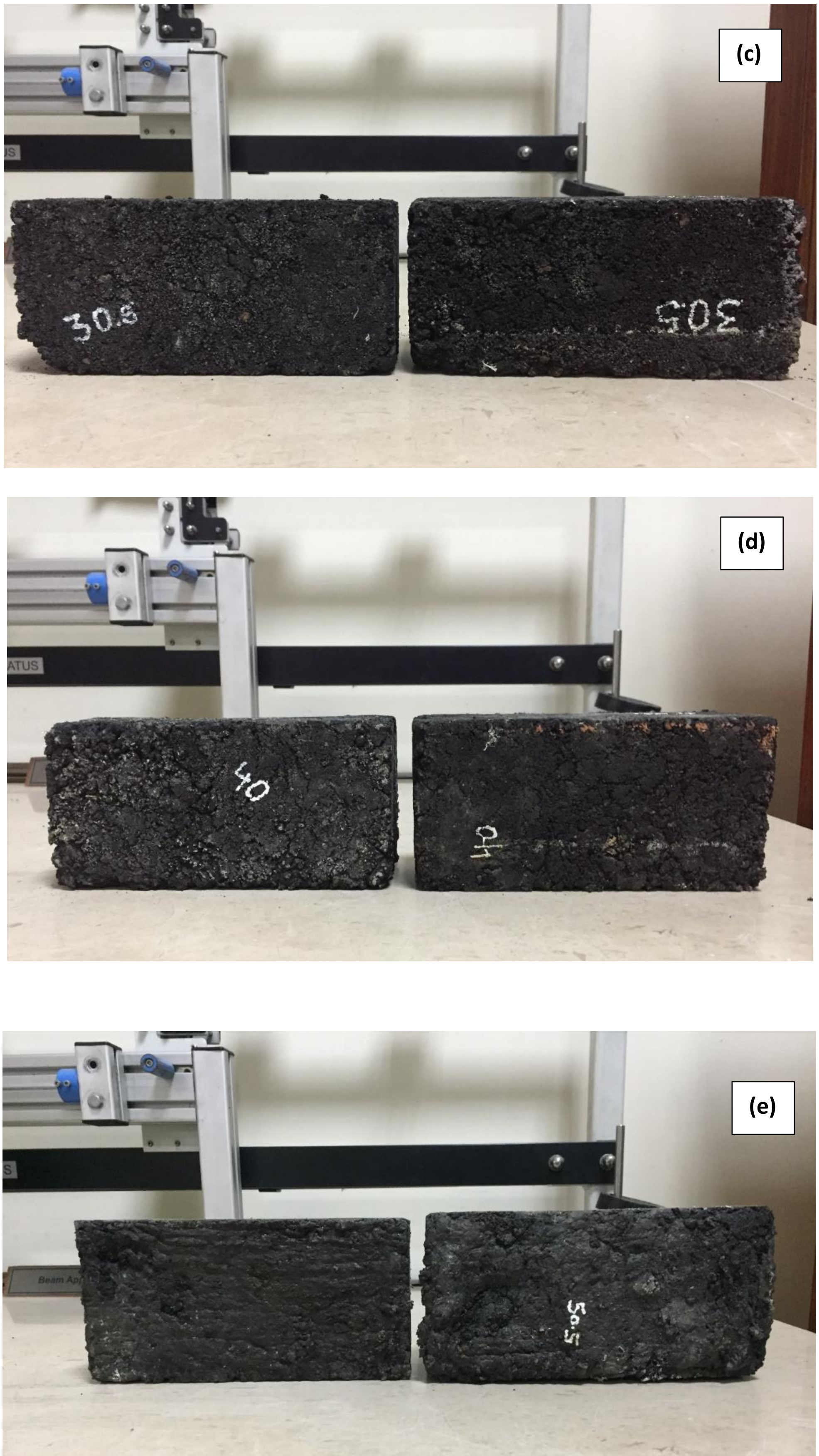

(c)
(d)
(e)

Figure 13: Efflorescence test results for (a) second class brick (b) 100:0 (c) 30:70 (d) 40:60 (e) 50:50 (f) 60:40

The bricks on the left correspond to plastic wrapped bricks whereas on the right are the ones immersed in water. From the test results, as summarized in Table 10 below, formulations second class clay fired brick, 30:70 and 40:60 was effloresced, whereas formulations 100:0, 50:50 and 60:40 did not show any sign of efflorescence. This was because with increasing plastic content, WFS content decreased in waste plastic brick as a result water absorption decreased and so did CaO content in waste plastic brick formulations thus preventing occurrence of efflorescence.

SAMPLE	**Second Class Clay Fired Brick**	**100:0**	**30:70**	**40:60**	**50:50**	**60:40**
RATING	Effloresced	**Not Effloresced**	Effloresced	Effloresced	**Not Effloresced**	**Not Effloresced**

Table 10: Efflorescence rating for control and different brick formulations

Density

Density of the brick plays a crucial role in the overall weight of the structure. As per [34], lightweight bricks decrease the structural load and are much suited to construction in seismically active areas. The density of the waste plastic brick formulation and the control brick samples are presented in Figure 14 below.

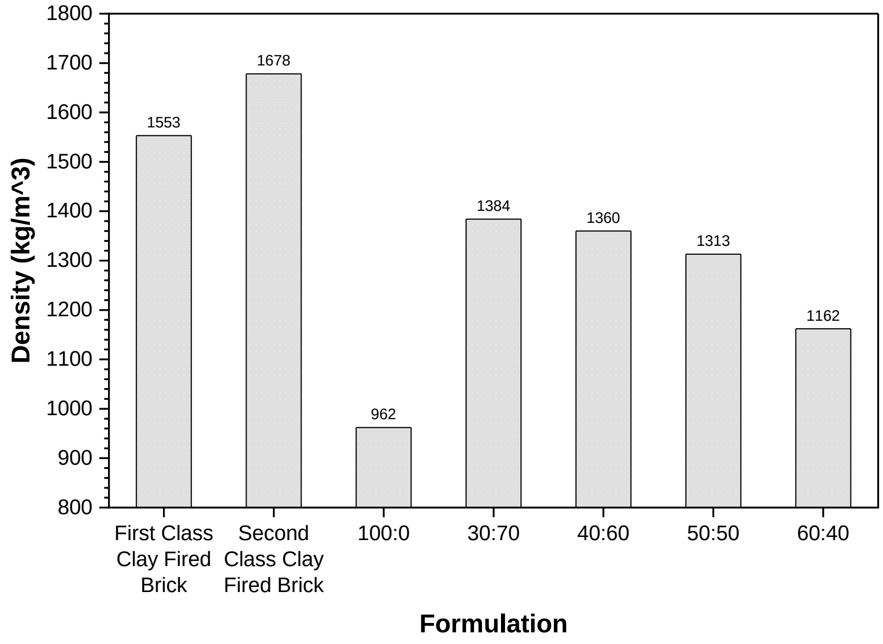


Figure 14: Density for control and different waste plastic brick formulations

According to the test results, waste plastic brick formulations have lesser density as compared to control clay brick samples. Waste plastic is considered to be incredibly light weight thus 100:0 ratio resulted in least density brick among all formulations. With the introduction of WFS, the density of waste plastic brick increased. The density of optimum waste plastic brick formulation 50:50 is 21.8% lesser as compared to second class clay fired brick.

Modulus of Rupture (Flexural Strength)

Flexural strength is defined as the ability of a material to resist bending forces before it yields. Modulus of rupture test was conducted as per ASTM C67 [37] on various plastic brick formulations and control second class clay fired brick sample. Upper span was kept 100 mm and lower span was fixed at 200 mm. Rate of loading was kept 0.15 kN/sec and the test results are shown in Figure 15 below.

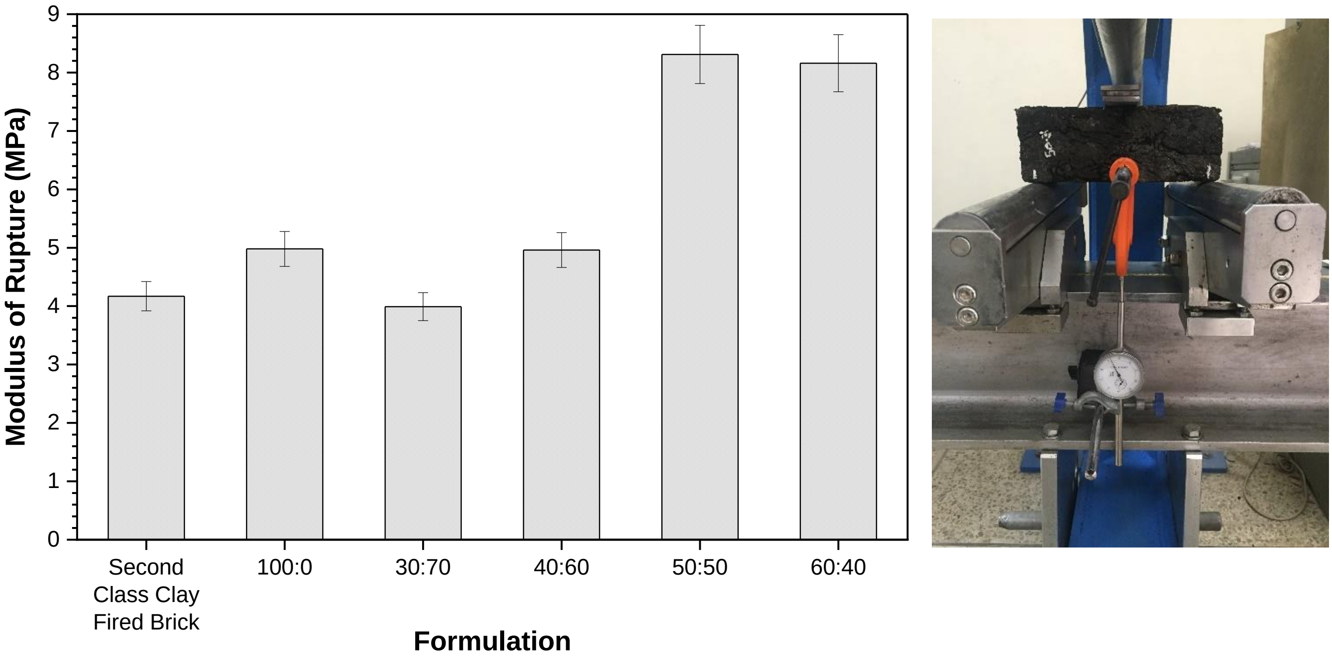


Figure 15: Modulus of rupture for control and different waste plastic brick formulations

From the test results it can be inferred that second class clay fired brick and waste plastic brick formulation 30:70 have identical flexural strength of nearly 4 MPa and so did waste plastic brick formulation 100:0 and 40:60 bearing a flexural strength of approximately 5 MPa. With the increase in waste plastic content and decreasing dosage of WFS, an increase in flexural strength was observed. The flexural strength for waste plastic brick formulation 50:50 was twice compared to second class clay fired brick.

Flexural strength is a crucial factor in determining the suitability of brick for use in floors. According to ASTM C410 [40], the minimum modulus of rupture required for Type T and Type H individual industrial floor brick is 5.2 MPa. Waste plastic brick formulations 50:50 and 60:40 fulfill the requirement and can be used for industrial floors.

The load deflection response for modulus of rupture test is shown in Figure 16 below.

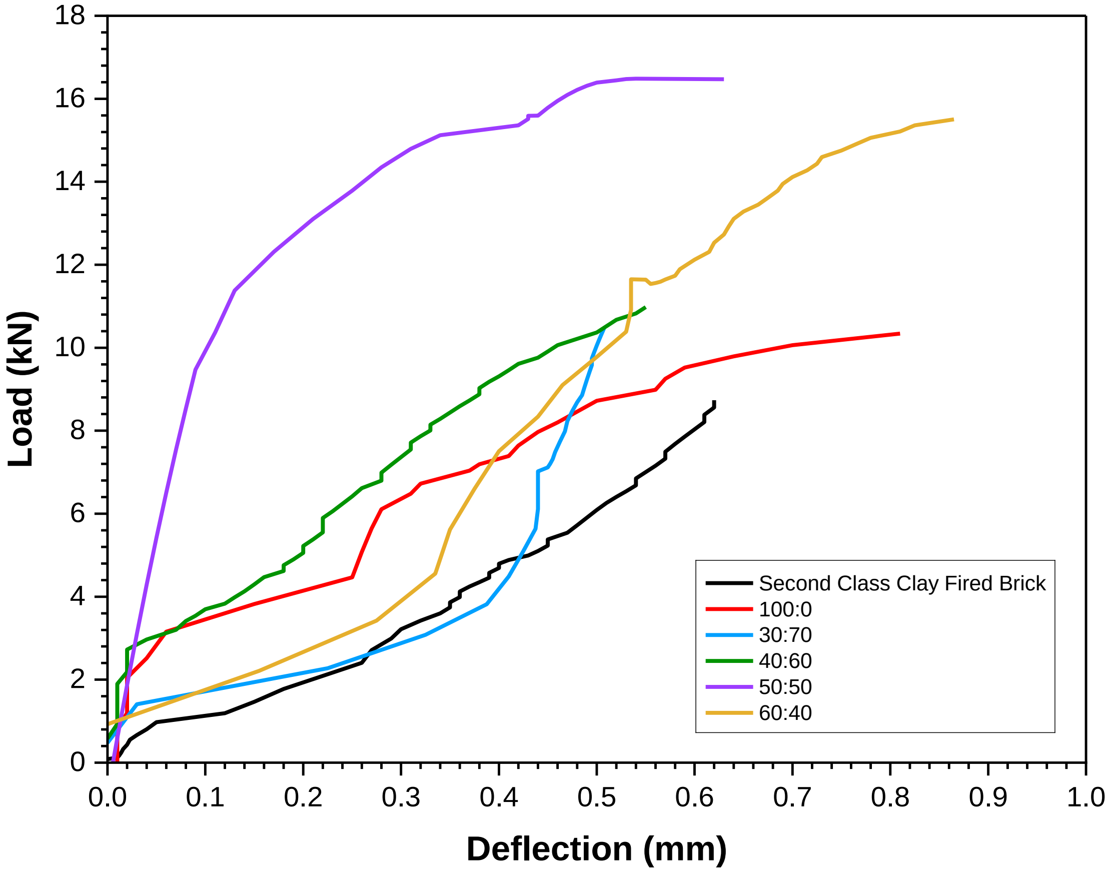


Figure 16: load deflection curves for control and waste plastic brick formulations

Splitting Tensile Test

Bricks standalone and in masonry walls in conjunction with mortar fail commonly in tension when exposed to compression loads. According to ASTM C1006 [41], differences in modulus of elasticity and Poisson's ratio between brick and mortar lead to generation of tensile stresses. Moreover, when grout is poured in between the brick it can also lead to formation of tensile stresses because of aforementioned reasons and resulting in a splitting failure. To investigate the splitting tensile strength of control clay fired brick sample and waste plastic brick formulations, splitting tensile strength test as per ASTM C1006 [41] guidelines were performed. The loading rate for the test was kept 148 N/sec and Figure 17 below summarizes the test results.

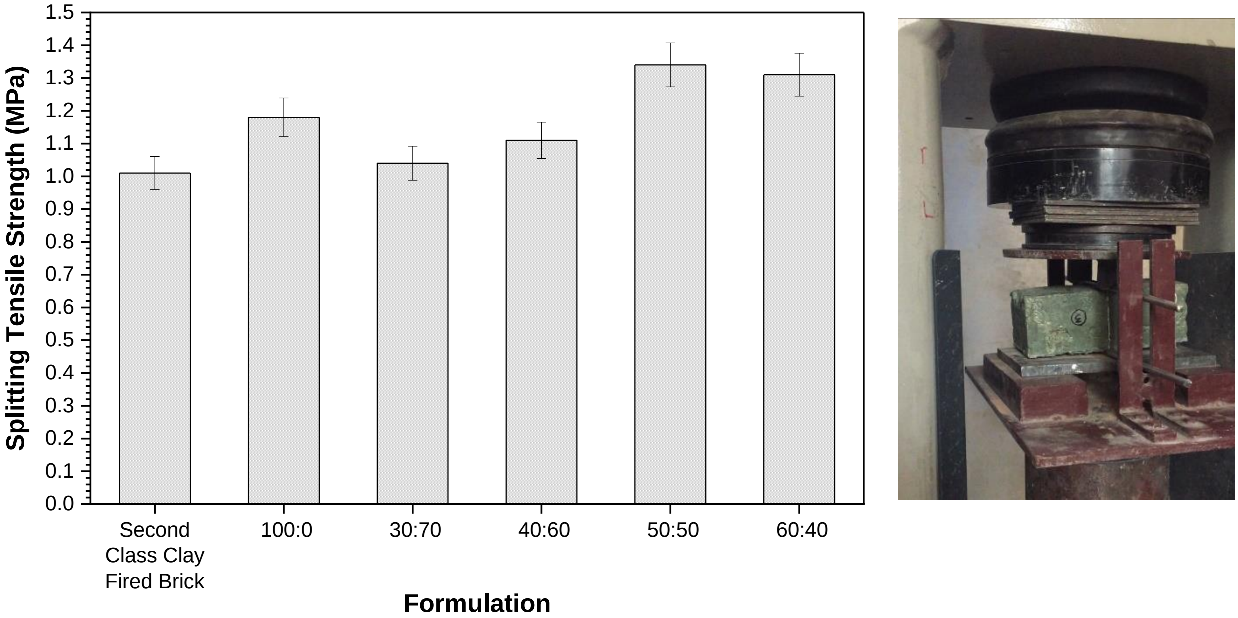


Figure 17: Splitting tensile strength of control and waste plastic brick formulations

From the test results it can be inferred that second class clay fired bricks have the least splitting tensile strength which is attributed to its brittle nature during compression test. Waste plastic brick formulations have a ductile response under compression, so it resulted in greater splitting tensile strength. It can be deduced that with increasing waste plastic content and decreasing WFS resulted in an increase in splitting tensile strength. Maximum splitting tensile strength was observed in case 50:50 formulation which is 1.35 times higher than control second class clay fired brick.

Masonry Flexural Bond Strength

Construction of a wall involves laying bricks with mortar, so it is imperative to investigate the bond strength between the masonry unit and mortar which in turn determines the compatibility of both masonry elements. For this purpose, masonry flexural bond strength test was conducted as per ASTM C1072 [42]. The mortar used had a composition of 1:2.75 cement sand as prescribed by ASTM C109 [43]. Compressive strength was conducted on 50 mm cube samples after 28 days of curing. The compressive strength of mortar was 30.28 MPa with loading rate kept as 1.8 kN/sec. Similarly, flexural strength of mortar was performed on mortar prism bearing dimension of 160mm x 40mm x 40mm and cured for 28 days. The flexural strength of the mortar prism was 5.72 MPa with loading rate for the test kept 0.05 kN/sec.

For the masonry flexural bond strength test, two masonry units were used with mortar layer sandwiched between masonry units. For the test, second class clay fired control sample and optimum waste plastic brick formulation 50:50 both flat and interlocking shape was utilized. The test apparatus along with the test results are shown in Figure 18 below.

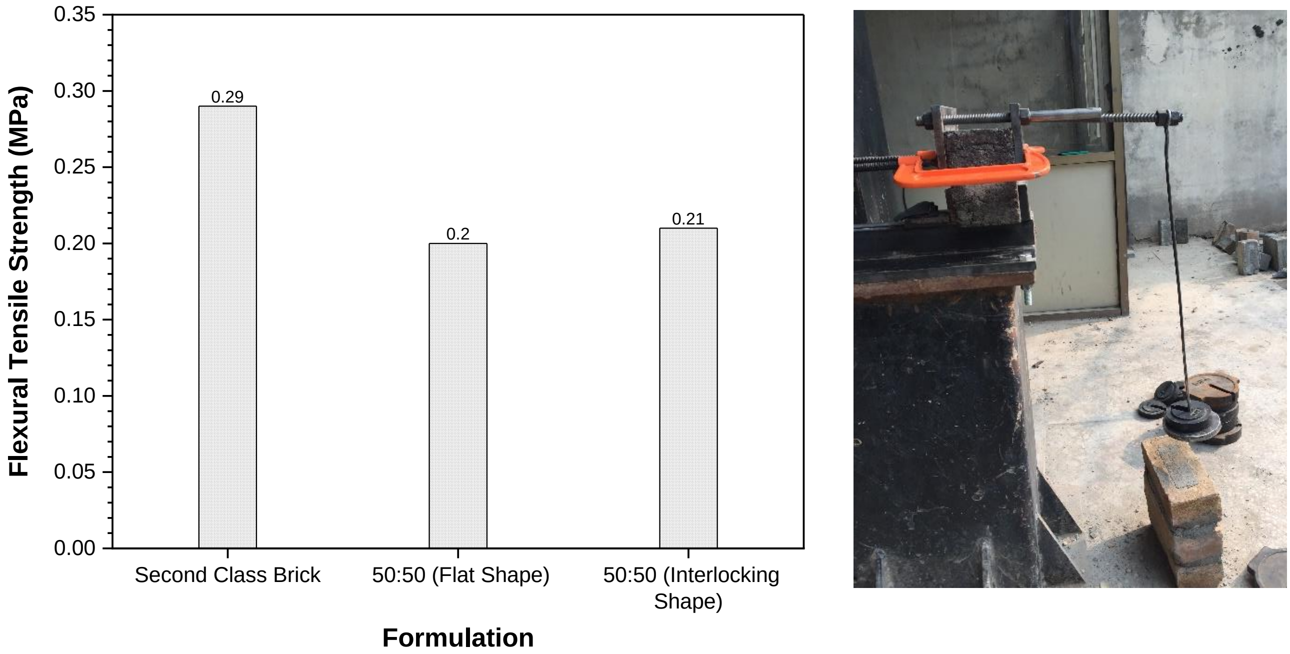


Figure 18: Flexural Tensile Strength of second class brick, waste plastic brick 50:50 flat shape and interlocking shape

From the test results, it is evident that second class brick has better bonding with mortar with a flexural tensile strength of 0.29 MPa. Flat waste Plastic brick formulation 50:50 has flexural tensile strength of 0.20 MPa which is 69% of strength achieved by second class clay fired brick. Interlocking waste plastic brick improves the flexural tensile strength slightly around 4.76 % as compared to flat waste plastic brick formulation 50:50. Hence, it can be established that waste plastic brick has adequate adhesion with mortar and does not require any special bonding agent to lay the bricks during the construction of the wall.

Microstructural Analysis

From the test results it is evident that waste plastic brick formulation 50:50 is the yields the optimum mechanical properties. This is directly related to bonding between melted plastic and

WFS particles. To examine this, scanning electron microscopy (SEM) was conducted on the aforementioned sample. The test results have been demonstrated in Figures 19 below.

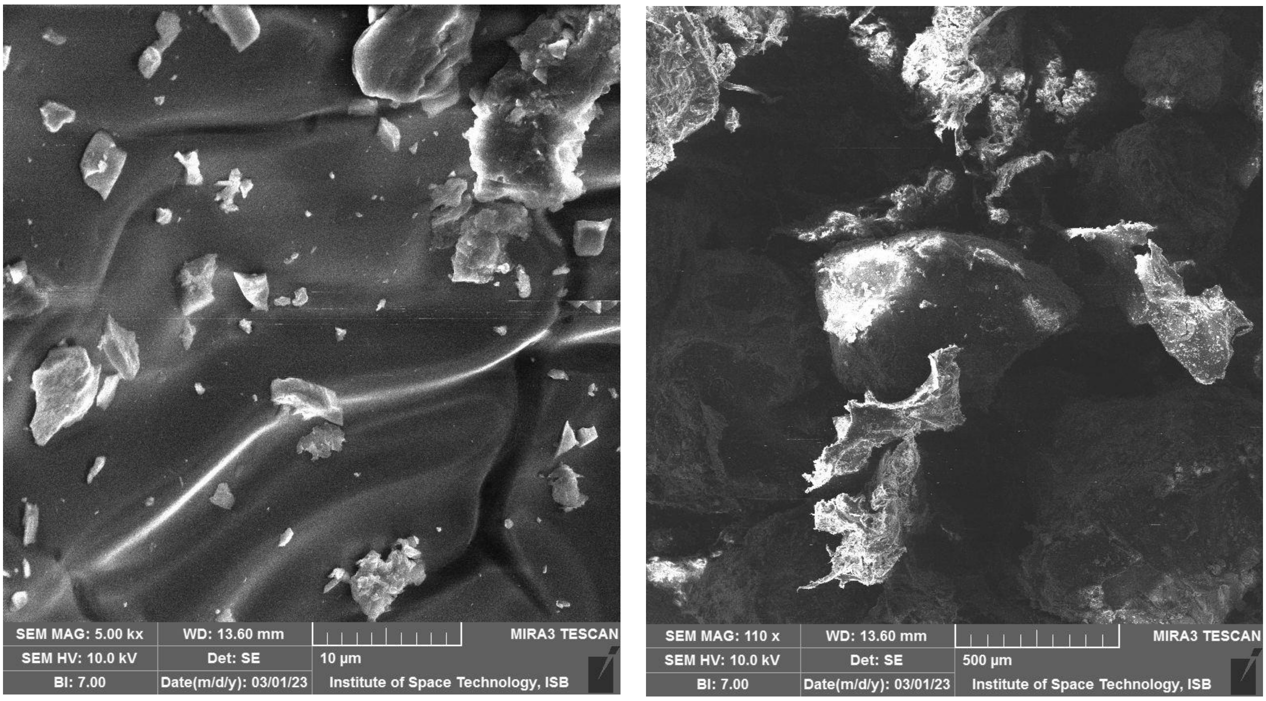


Figure 19: SEM image of waste plastic brick formulation 50:50

As evident from the test result, angular and irregular WFS particles appear to adhere well with melted plastic. Figure 20 below shows the presence of C and Si elements in abundance within the sample. C corresponds to melted waste plastic as PET/HDPE/LDPE comprises of hydrocarbons. Si is the most common oxide element in the WFS and its traces on SEM reflect the presence of WFS.

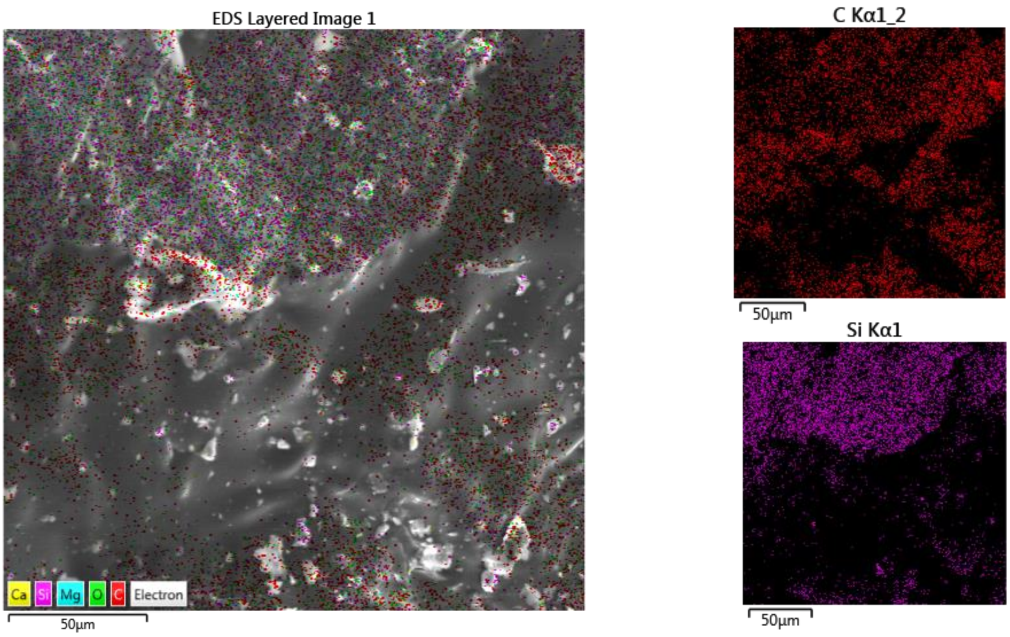
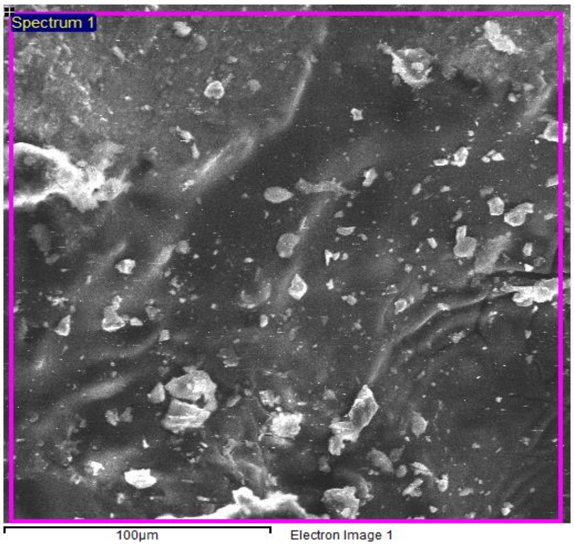


Figure 20: EDS mapping of waste plastic brick 50:50

Energy dispersive spectroscopy (EDS) was performed to analyze the elemental composition of waste plastic brick formulation 50:50. The test results reveal, as summarized in Table 11 and Figure 21 below, presence of 50% by weight carbon which predominantly comes from hydrocarbon chains present in waste plastic PET/HDPE/LDPE. The rest of the elements correspond to the WFS, which is also confirmed by XRF test results discussed earlier.



EDS		
Element	Weight %	Atomic %
C K	50.66	60.65
O K	38.15	34.29
Mg K	1.75	1.04
Al K	0.55	0.29
Si K	5.02	2.57
Ca K	1.63	0.58
Fe K	2.24	0.58

Table 11: Elemental composition of waste plastic brick formulation 50:50

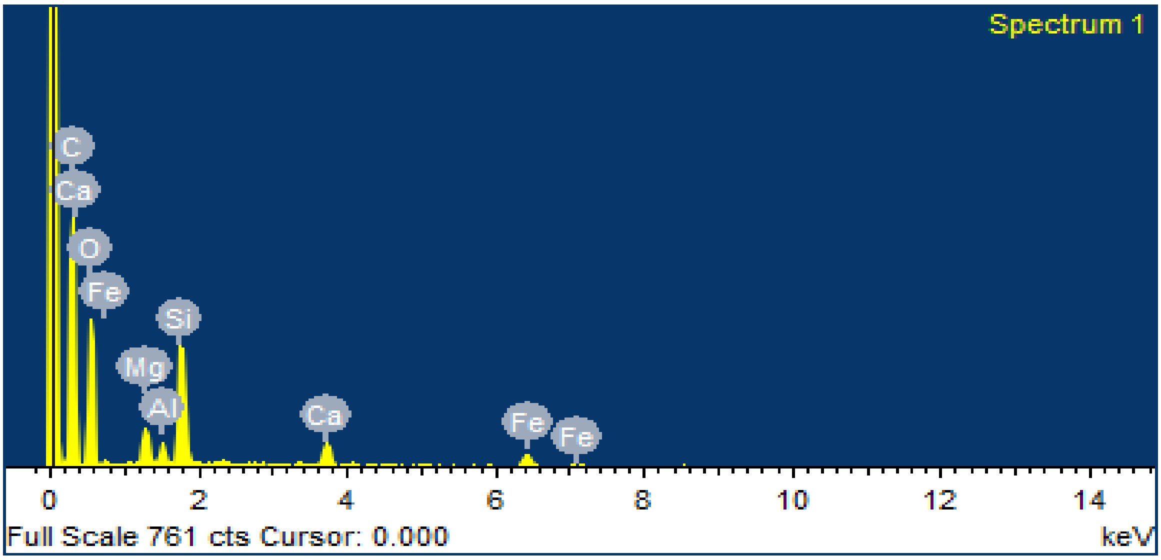


Figure 21: EDS spectrum of waste plastic brick formulation 50:50

1.2 Thermal Conductance

Thermal conductivity of the brick is an important factor determining the overall energy efficiency of the building. As per [44], thermal conductivity of the brick is influenced by several factors such as volume fraction of the voids, microstructural alignment or water content and manufacturing process parameters. Thermal conductivity test was performed on waste plastic brick formulations 50:50 and 100:0 to assess the thermal performance of waste plastic brick. The results were then compared with traditional fired red brick as reported in [44]. The test results are summarized in Table 12 and Figure 22 below.

Sample	Temperature (C)			
	25	30	45	60
100:00	0.242	0.239	0.221	0.226
50:50	0.675	0.688	0.673	0.66
Traditional Fired Red Brick [40]	-	0.769	0.78	0.8

Table 12: Thermal conductivity for various brick formulations and at different temperatures

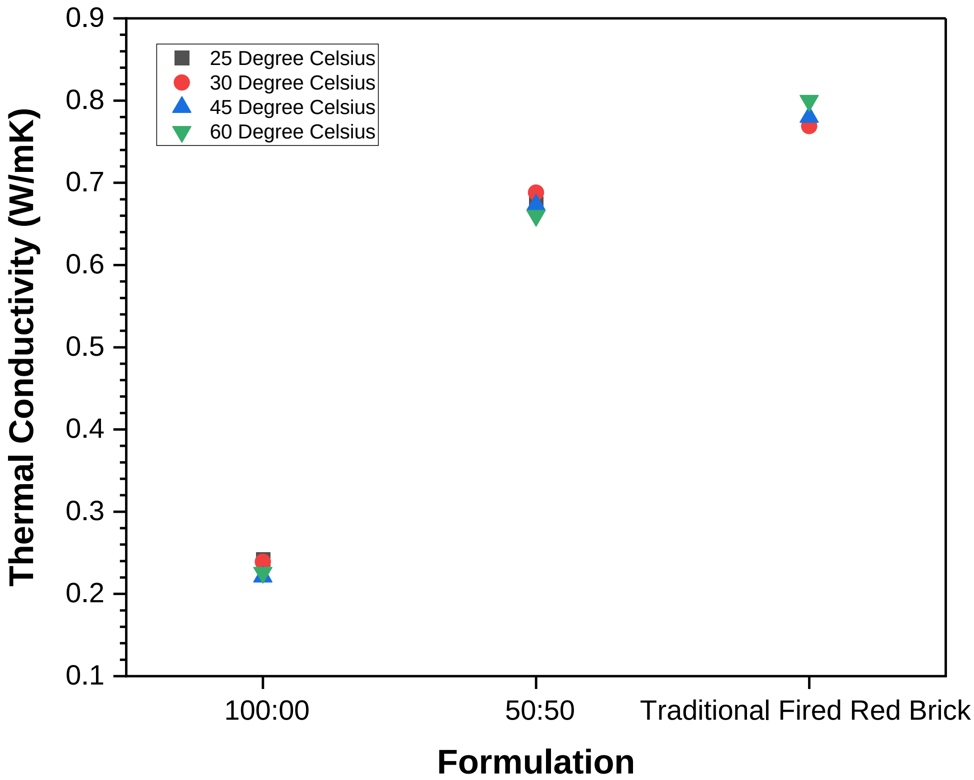


Figure 22: Thermal conductivity for different brick formulations

From the test results, it is evident that waste plastic brick formulations have lower thermal conductivity than traditional fired red brick. This implies that the waste plastic brick formulations have a better insulation property as compared to traditional fired red brick. From the test result, it can also be inferred that with the addition of WFS thermal conductivity increased drastically.

Differential Scanning Calorimetry

The melting point of brick is important to assess thermal performance of masonry structure. According to [45], international building code require minimum 1 hour rating for exterior wall. Eurocode has laid three specific requirements for fire safety of wall: temperature insulation, structural integrity, and structural adequacy [45]. Temperature insulation has been discussed in the previous section. Structural integrity refers to ensuring bond between masonry unit and mortar remains intact. In case of melting of masonry unit, the bond weakens resulting in failure of structure. DSC was conducted on optimum waste plastic brick formulation 50:50 to find the melting point of the brick. The test result has been summarized in Figure 23 below.

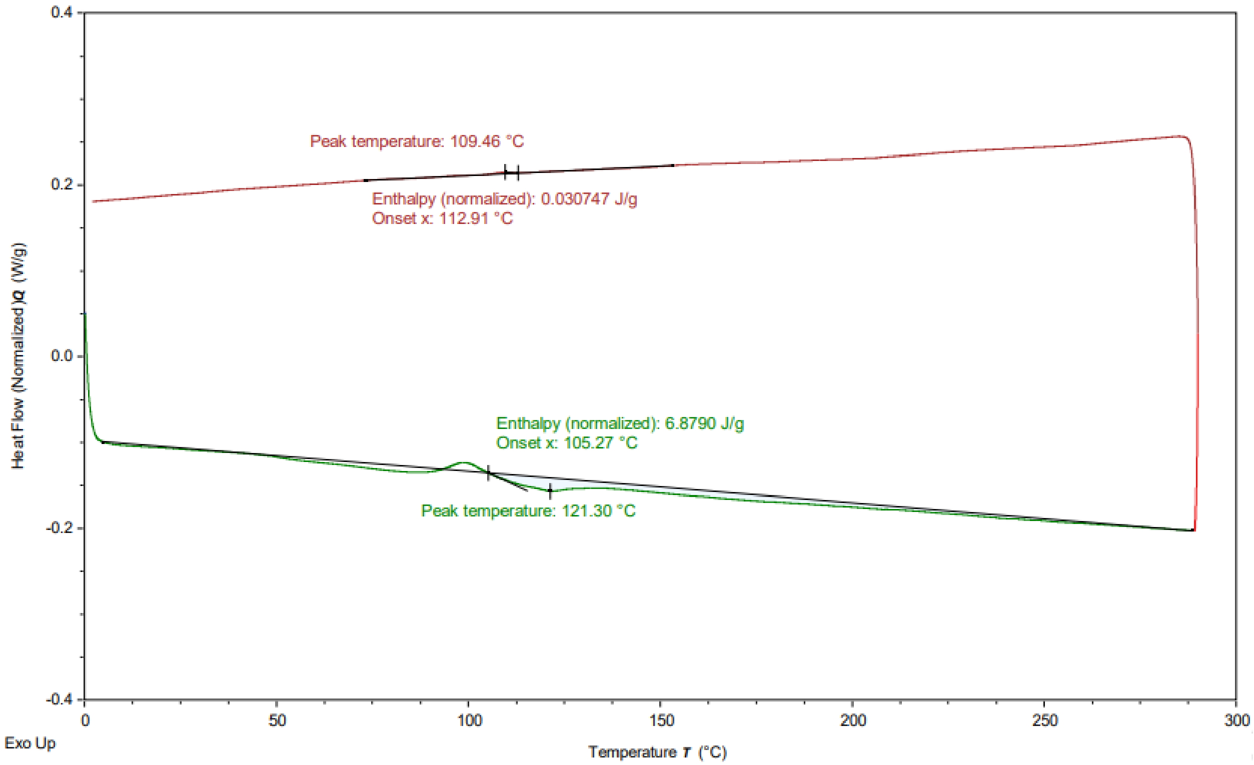


Figure 23: DSC of waste plastic brick formulation 50:50

From the test result, the melting point of waste plastic brick formulation 50:50 was 121.30 ^{o}C as depicted on the heating curve with an enthalpy of 6.879 J/g. The recrystallization temperature of the said brick was 112.91 ^{o}C as marked on the cooling curve.

Electrical Resistance

Electrical resistance provides information regarding electrical insulation of the building. To investigate the electrical resistance of the waste plastic brick, an electrical resistance test was conducted with the aid of resistivity meter. The test results are shown in Figure 24 below.

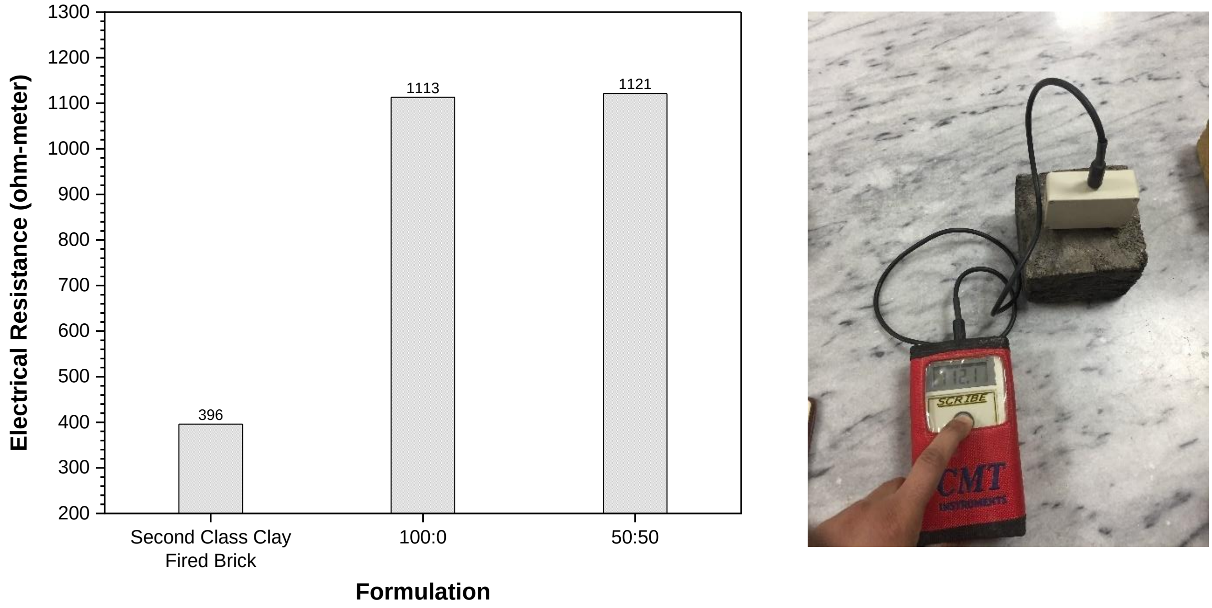


Figure 24: Electrical resistance of different brick formulations

According to Ohm law, current is directly proportional to voltage and inversely proportional to resistance provided the temperature remains constant. The test was conducted at room temperature. From the test results, it can be inferred that the control sample second class clay fired brick has least electrical resistance which implies that it is a better conductor of electric current as compared to waste plastic brick formulation 100:0 and 50:50. It can also evident that there is no significant difference in electrical resistance of waste plastic brick formulations, which means addition of WFS did not impact the electrical resistance of the waste plastic brick.

Mortar characteristics

Compressive strength

The compressive strength of the mortar cube having a dimension of 50 mm was determined via universal testing machine at a loading rate of 1.8 kN/sec. The average compressive strength of the mortar specimen, cured for a period of 28 days, turned out to be 30.28 MPa and the Figure 25 below shows the stress strain plot of the cube.

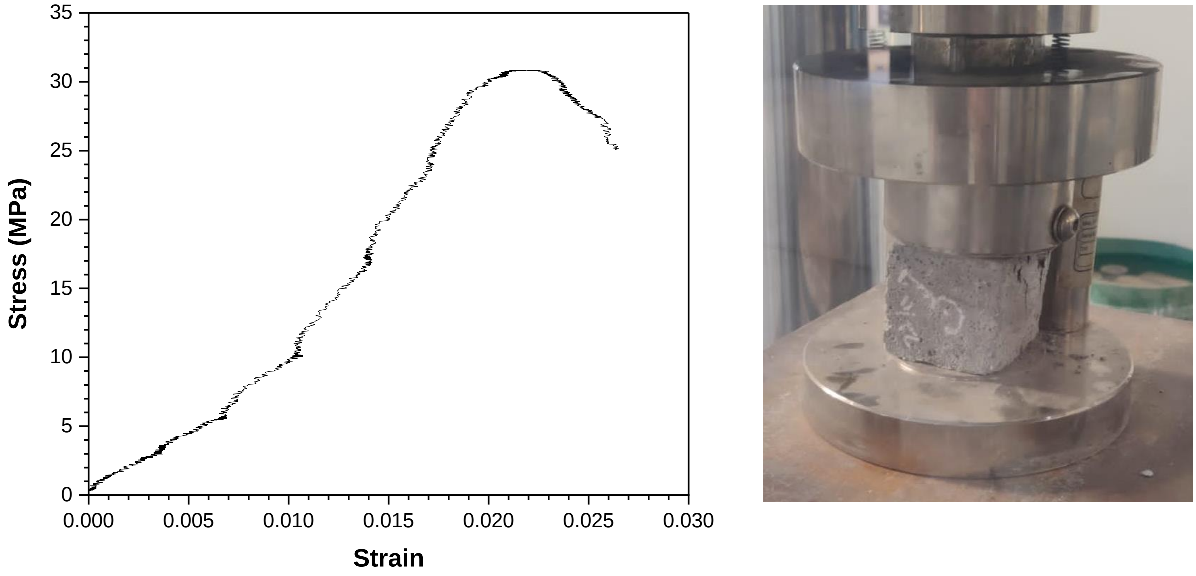


Figure 25: Stress strain plot of mortar cube

Flexural Strength

The flexural strength of the mortar was conducted after a prism of dimensions 160 x 40 x 40 mm was cast and cured for 28 days. The loading rate for the test was kept at 0.05 kN/sec and the flexural strength came out to be 5.72 MPa.

Figure 26: Flexural test on mortar prism

Friction coefficient of waste plastic brick

The friction coefficient of the waste plastic brick formulation 50:50 was determined using ASTM G99 [46] which is the standard test method for wear testing with a pin on disk apparatus. The details of the mold and equipment are shown in Figure 27 below.

Figure 27: (a) mould for sample preparation (b) test assembly for friction coefficient test

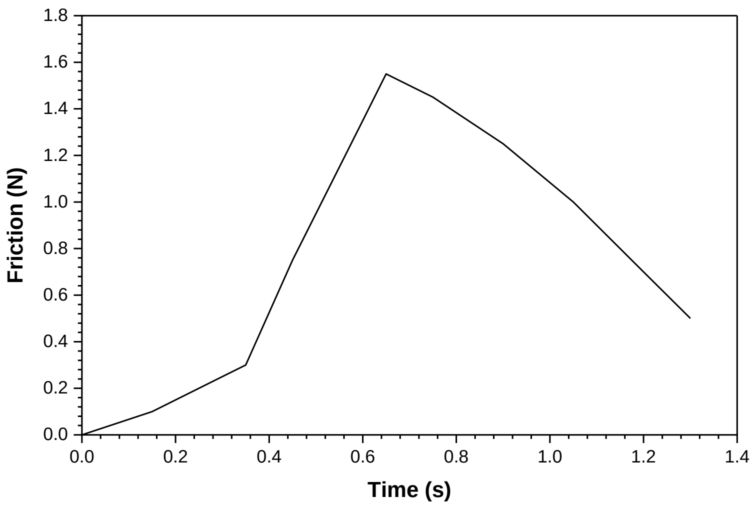


Figure 28: Friction versus time plot for friction coefficient test

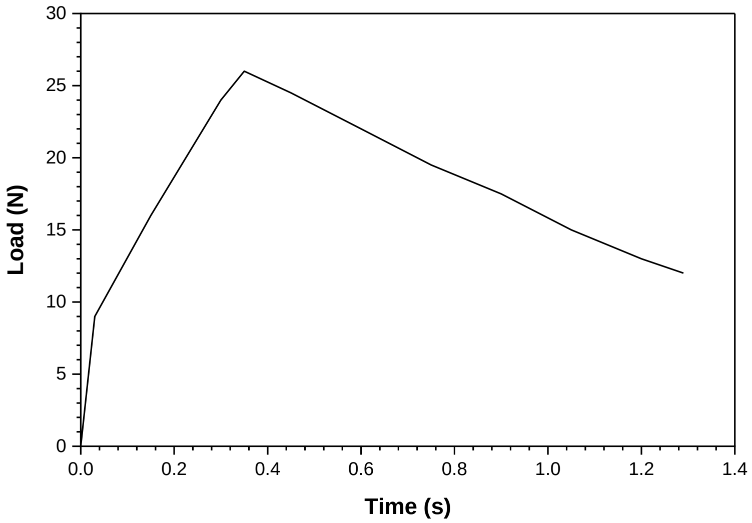


Figure 29: Load versus time plot for friction coefficient test

From Figure 28 it can be inferred that friction increases linearly with time to a point that it reaches the maximum value of 1.6 N and then decreases linearly with time. A similar trend was also observed in the case of load vs time graph as illustrated in Figure 29 where load increased linearly to maximum value of 25 N and then decreased subsequently.

For this test the preload set was 100 N and the spindle speed was kept was 200 revolutions per minute. The friction coefficient obtained from the apparatus was 0.783.

Tensile Test

The tensile strength test was conducted as per JSCE guidelines. The samples were cast in the mold as shown in Figure 30 below and were then mounted on tensile testing machine as shown in Figure 31 with the hooks.

Figure 30: Mould prepared for casting of tensile specimens

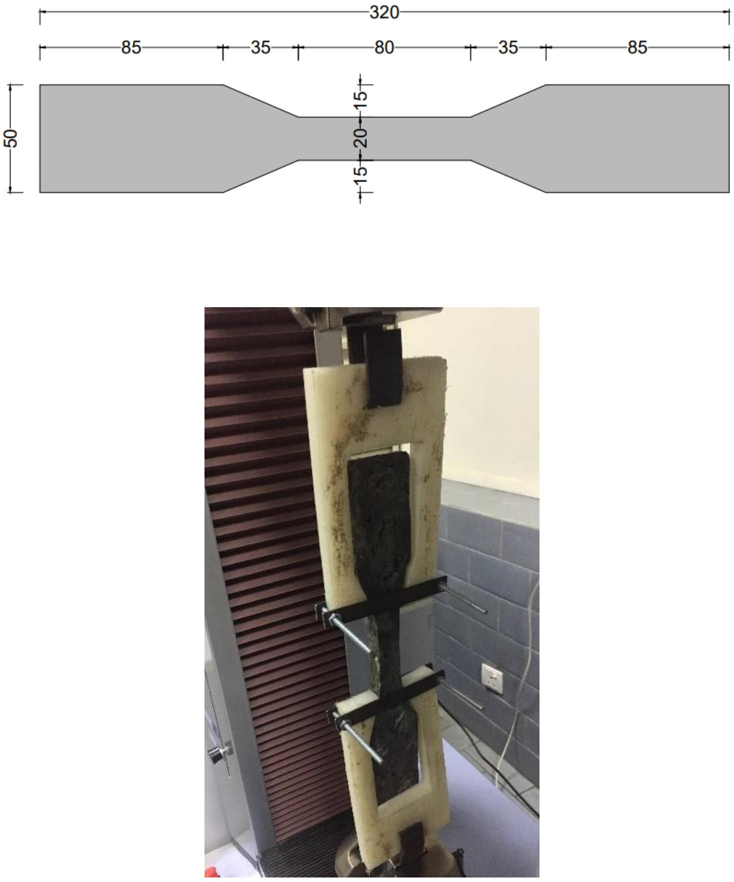


Figure 31: (a) Dimension of prepared sample (b) sample mounted on tensile testing machine

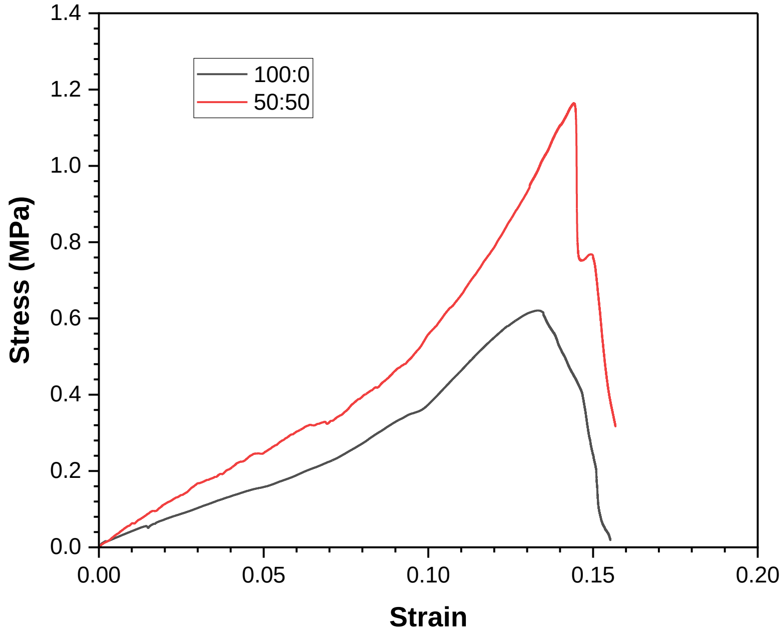


Figure 32: Stress strain plot for tensile strength of the specimens

The loading rate for the test was kept as 0.8 mm/min and the test results are illustrated in Figure 32 above.

From the test results it can be seen that both samples 100:0 and 50:50 underwent similar failure trend. The sample achieved an ultimate tensile strength before the specimen ruptured as seen in Figure 33. The ultimate tensile strength of waste plastic brick formulation 50:50 was almost twice as compared to 100:0 formulation.

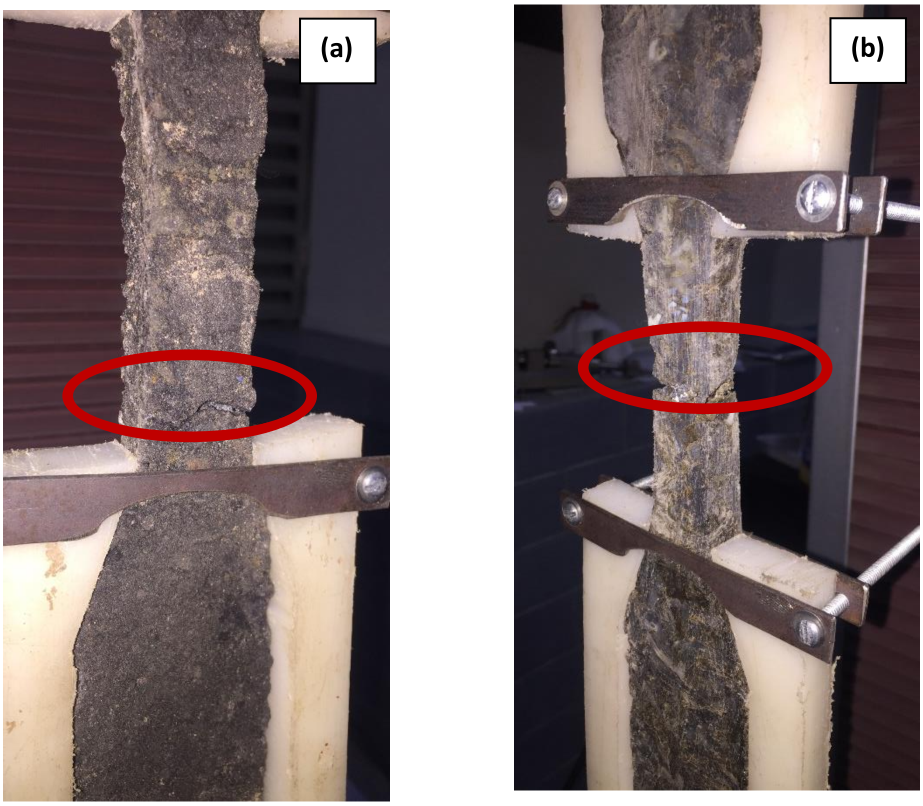


Figure 33: Failure of specimens under tension (a) 50:50 (b) 100:0

Compressive Test of Brick Prism

The compressive strength of the brick prism consisting of three masonry units bonded with cement sand mortar, as illustrated in Figure 34 below, was determined as per ASTM C1314.

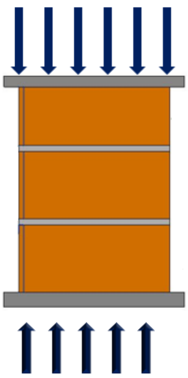


Figure 34: Schematic diagram illustrating the compressive test for brick prism

The loading rate for the test was kept as 1mm/min and the test results are summarized in Figure 35 below.

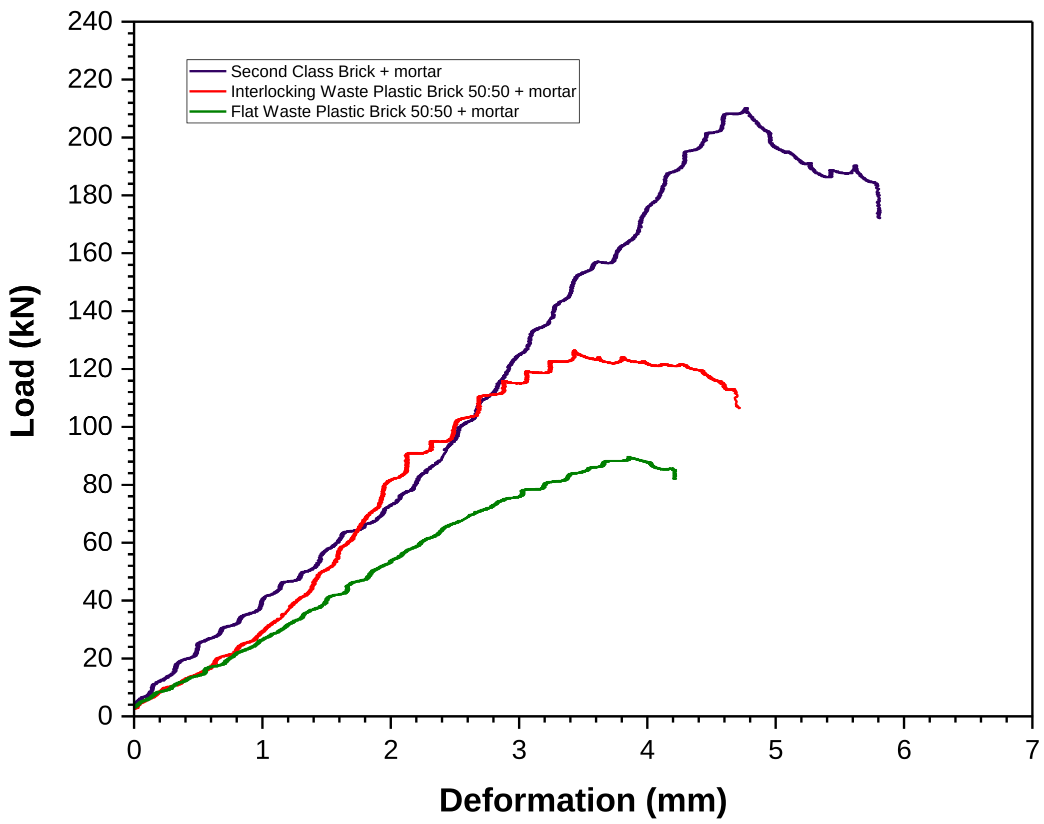


Figure 35: Load deflection curve for various brick formulations

From the test results it can be inferred that second class clay fired brick has almost double the compressive strength of masonry prism as compared to interlocking waste plastic brick and the interlocking waste plastic brick compressive load carrying capacity almost 1.5 times as compared to flat waste plastic interlocking brick.

Casting of waste plastic interlocking brick

The casting of waste plastic interlocking brick involves using specially designed molds which are shown in Figure 36 below. The brick dimensions are shown in Figure 37 below along with its render in Sketchup as seen in Figure 38.

Figure 36: Moulds used for casting waste plastic interlocking brick

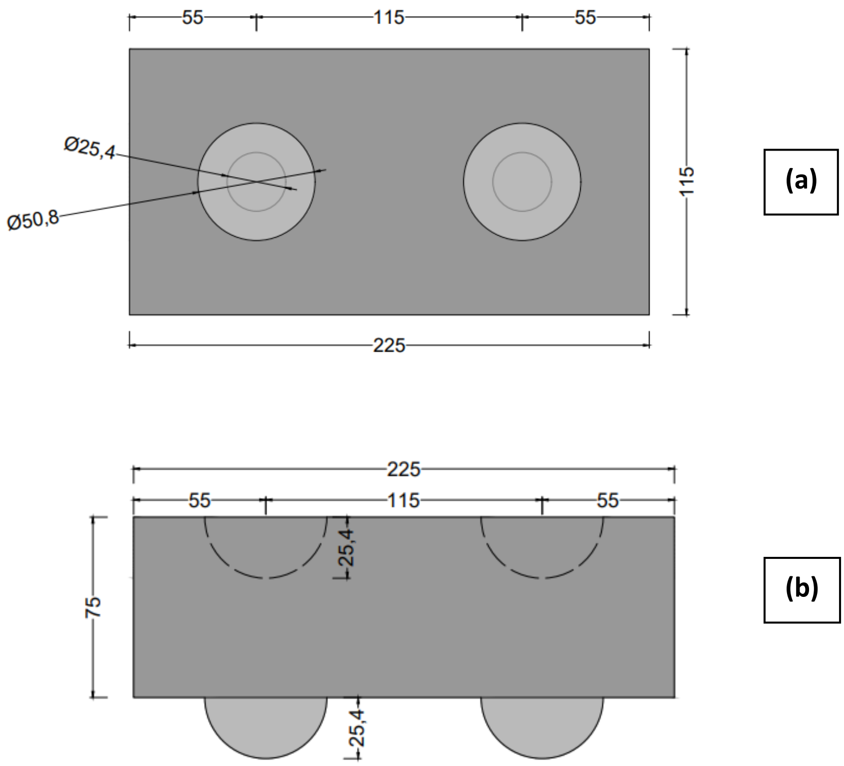


Figure 37: Dimensions of waste plastic interlocking brick (a) plan view (b) side view

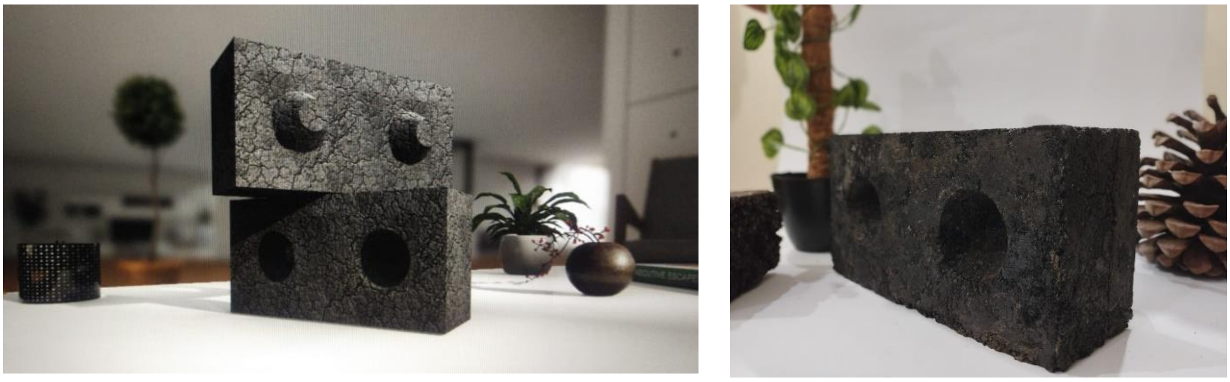


Figure 38: (a) Rendered image of waste plastic interlocking brick on Sketchup (b) real image of waste plastic interlocking brick

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this research, the mechanical properties of waste plastic brick were investigated thoroughly which were fabricated from plastic waste in general and PET/HDPE/LDPE in particular, in combination with WFS. The following conclusions were drawn based on experimental results and discussion.

1. Optimum formulation for waste plastic brick is 50:50 which produces optimal mechanical properties to be utilized in masonry structures.
2. Waste plastic brick is more durable compared to conventional clay fired bricks with reduced water absorption and no visible sign of efflorescence
3. Waste plastic brick has adequate adhesion with mortar and can be used in construction of walls
4. Waste plastic brick is a better thermal and electrical insulator in comparison with conventional clay fired bricks
5. Waste plastic brick has twice the modulus of rupture and splitting tensile strength of 1.35 times the conventional clay fired brick thus can be used for nonstructural applications such as in laying industrial floors

RECOMMENDATIONS

Following recommendations have been proposed in regard to future work relating to structural performance assessment of waste plastic brick.

1. Static and dynamic analysis of both flat and interlocking waste plastic brick of multi storey building
2. Experimental testing regarding the impact test and out of plane loading and shake table testing of both flat and interlocking waste plastic walls
3. Development of mortar that encourages sustainability and also addresses the deficiency of bond between waste plastic brick and mortar
4. lifecycle assessment of waste plastic interlocking brick and business model to manufacture bricks at commercial level
5. Fire and acoustic assessment of waste plastic brick as per ASTM standards

REFERENCES

[1] A. Al-Fakih, B. S. Mohammed, M. S. Liew, and E. Nikbakht, “Incorporation of waste materials in the manufacture of masonry bricks: An update review,” *Journal of Building Engineering*, vol. 21, pp. 37–54, Jan. 2019, doi: 10.1016/J.JOBE.2018.09.023.

[2] K. M. Safar, M. R. Bux, U. Faria, and S. Pervez, “Integrated model of municipal solid waste management for energy recovery in Pakistan,” *Energy*, vol. 219, p. 119632, Mar. 2021, doi: 10.1016/J.ENERGY.2020.119632.

[3] P. O. Awoyera and A. Adesina, “Plastic wastes to construction products: Status, limitations and future perspective,” *Case Studies in Construction Materials*, vol. 12, p. e00330, Jun. 2020, doi: 10.1016/J.CSCM.2020.E00330.

[4] K. Tempa *et al.*, “An experimental study and sustainability assessment of plastic waste as a binding material for producing economical cement-less paver blocks,” *Engineering Science and Technology, an International Journal*, vol. 26, p. 101008, Feb. 2022, doi: 10.1016/J.JESTCH.2021.05.012.

[5] N. H. Zulkernain, P. Gani, N. Chuck Chuan, and T. Uvarajan, “Utilisation of plastic waste as aggregate in construction materials: A review,” *Constr Build Mater*, vol. 296, p. 123669, Aug. 2021, doi: 10.1016/J.CONBUILDMAT.2021.123669.

[6] R. Dhawan, B. M. S. Bisht, R. Kumar, S. Kumari, and S. K. Dhawan, “Recycling of plastic waste into tiles with reduced flammability and improved tensile strength,” *Process Safety and Environmental Protection*, vol. 124, pp. 299–307, Apr. 2019, doi: 10.1016/J.PSEP.2019.02.018.

[7] R. Alyousef, W. Ahmad, A. Ahmad, F. Aslam, P. Joyklad, and H. Alabduljabbar, “Potential use of recycled plastic and rubber aggregate in cementitious materials for sustainable construction: A review,” *J Clean Prod*, vol. 329, p. 129736, Dec. 2021, doi: 10.1016/J.JCLEPRO.2021.129736.

[8] J. Zhao and S. Li, “Life cycle cost assessment and multi-criteria decision analysis of environment-friendly building insulation materials - A review,” *Energy Build*, vol. 254, p. 111582, Jan. 2022, doi: 10.1016/J.ENBUILD.2021.111582.

[9] T. Santos, J. Almeida, J. D. Silvestre, and P. Faria, “Life cycle assessment of mortars: A review on technical potential and drawbacks,” *Constr Build Mater*, vol. 288, p. 123069, Jun. 2021, doi: 10.1016/J.CONBUILDMAT.2021.123069.

[10] P. G. Asteris *et al.*, “Soft computing-based models for the prediction of masonry compressive strength,” *Eng Struct*, vol. 248, p. 113276, Dec. 2021, doi: 10.1016/J.ENGSTRUCT.2021.113276.

[11] F. I. Aneke and C. Shabangu, “Green-efficient masonry bricks produced from scrap plastic waste and foundry sand,” *Case Studies in Construction Materials*, vol. 14, p. e00515, Jun. 2021, doi: 10.1016/J.CSCM.2021.E00515.

[12] Q. Afzal, S. Abbas, W. Abbass, A. Ahmed, R. Azam, and M. Rizwan Riaz, “Characterization of sustainable interlocking burnt clay brick wall panels: An alternative to conventional bricks,” *Constr Build Mater*, vol. 231, p. 117190, Jan. 2020, doi: 10.1016/J.CONBUILDMAT.2019.117190.

[13] S. Iftikhar, K. Rashid, E. Ul Haq, I. Zafar, F. K. Alqahtani, and M. Iqbal Khan, "Synthesis and characterization of sustainable geopolymer green clay bricks: An alternative to burnt clay brick," *Constr Build Mater*, vol. 259, p. 119659, Oct. 2020, doi: 10.1016/J.CONBUILDMAT.2020.119659.

[14] A. F. Ikechukwu and C. Shabangu, "Strength and durability performance of masonry bricks produced with crushed glass and melted PET plastics," *Case Studies in Construction Materials*, vol. 14, p. e00542, Jun. 2021, doi: 10.1016/J.CSCM.2021.E00542.

[15] R. K. Sandhu and R. Siddique, "Strength properties and microstructural analysis of self-compacting concrete incorporating waste foundry sand," *Constr Build Mater*, vol. 225, pp. 371–383, Nov. 2019, doi: 10.1016/J.CONBUILDMAT.2019.07.216.

[16] Y. W. Choi, D. J. Moon, Y. J. Kim, and M. Lachemi, "Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles," *Constr Build Mater*, vol. 23, no. 8, pp. 2829–2835, Aug. 2009, doi: 10.1016/J.CONBUILDMAT.2009.02.036.

[17] S. Wang, L. Gainey, D. Baxter, X. Wang, I. D. R. Mackinnon, and Y. Xi, "Thermal behaviours of clay mixtures during brick firing: A combined study of in-situ XRD, TGA and thermal dilatometry," *Constr Build Mater*, vol. 299, p. 124319, Sep. 2021, doi: 10.1016/J.CONBUILDMAT.2021.124319.

[18] T. Shi, X. Zhang, H. Hao, and C. Chen, "Experimental and numerical investigation on the compressive properties of interlocking blocks," *Eng Struct*, vol. 228, p. 111561, Feb. 2021, doi: 10.1016/J.ENGSTRUCT.2020.111561.

[19] ASTM International, "ASTM C62-17, Standard Specification for Building Brick (Solid Masonry Units Made From Clay or Shale)," 2017 doi: 10.1520/C0062-17.

[20] J. O. Akinyele, U. T. Igba, T. O. Ayorinde, and P. O. Jimoh, "Structural efficiency of burnt clay bricks containing waste crushed glass and polypropylene granules," *Case Studies in Construction Materials*, vol. 13, p. e00404, Dec. 2020, doi: 10.1016/J.CSCM.2020.E00404.

[21] J. Chwast, J. Todorović, H. Janssen, and J. Elsen, "Gypsum efflorescence on clay brick masonry: Field survey and literature study," *Constr Build Mater*, vol. 85, pp. 57–64, Jun. 2015, doi: 10.1016/J.CONBUILDMAT.2015.02.094.

[22] M. Mercuri, M. Pathirage, A. Gregori, and G. Cusatis, "Computational modeling of the out-of-plane behavior of unreinforced irregular masonry," *Eng Struct*, vol. 223, p. 111181, Nov. 2020, doi: 10.1016/J.ENGSTRUCT.2020.111181.

[23] L. Zhang, "Production of bricks from waste materials – A review," *Constr Build Mater*, vol. 47, pp. 643–655, Oct. 2013, doi: 10.1016/J.CONBUILDMAT.2013.05.043.

[24] Y. Li, K. Wen, L. Li, W. Huang, C. Bu, and F. Amini, "Experimental investigation on compression resistance of bio-bricks," *Constr Build Mater*, vol. 265, p. 120751, Dec. 2020, doi: 10.1016/J.CONBUILDMAT.2020.120751.

[25] H. T. Mohan, K. Jayanarayanan, and K. M. Mini, "Recent trends in utilization of plastics waste composites as construction materials," *Constr Build Mater*, vol. 271, p. 121520, Feb. 2021, doi: 10.1016/J.CONBUILDMAT.2020.121520.

[26] J. Z. Liang, “Melt strength and drawability of HDPE, LDPE and HDPE/LDPE blends,” *Polym Test*, vol. 73, pp. 433–438, Feb. 2019, doi: 10.1016/J.POLYMERTESTING.2018.12.007.

[27] M. M. Khan, S. M. Mahajani, G. N. Jadhav, R. Vishwakarma, V. Malgaonkar, and S. Mandre, “Mechanical and thermal methods for reclamation of waste foundry sand,” *J Environ Manage*, vol. 279, p. 111628, Feb. 2021, doi: 10.1016/J.JENVMAN.2020.111628.

[28] A. Al-Fakih, M. M. A. Wahab, B. S. Mohammed, M. S. Liew, N. A. Wan Abdullah Zawawi, and S. As’ad, “Experimental study on axial compressive behavior of rubberized interlocking masonry walls,” *Journal of Building Engineering*, vol. 29, p. 101107, May 2020, doi: 10.1016/J.JOBE.2019.101107.

[29] X. Zhang and W. K. Biswas, “Development of eco-efficient bricks – A life cycle assessment approach,” *Journal of Building Engineering*, vol. 42, p. 102429, Oct. 2021, doi: 10.1016/J.JOBE.2021.102429.

[30] A. Al-Fakih, B. S. Mohammed, M. A. Al-Osta, and R. Assaggaf, “Evaluation of the mechanical performance and sustainability of rubberized concrete interlocking masonry prism,” *Journal of Materials Research and Technology*, vol. 18, pp. 4385–4402, May 2022, doi: 10.1016/J.JMRT.2022.04.115.

[31] A. Rezaee Javan, H. Seifi, S. Xu, D. Ruan, and Y. M. Xie, “The impact behaviour of plate-like assemblies made of new interlocking bricks: An experimental study,” *Mater Des*, vol. 134, pp. 361–373, Nov. 2017, doi: 10.1016/J.MATDES.2017.08.056.

[32] M. S. Jaafar, W. A. Thanoon, A. M. S. Najm, M. R. Abdulkadir, and A. A. A. Ali, “Strength correlation between individual block, prism and basic wall panel for load bearing interlocking mortarless hollow block masonry,” *Constr Build Mater*, vol. 20, no. 7, pp. 492–498, Sep. 2006, doi: 10.1016/J.CONBUILDMAT.2005.01.046.

[33] R. R. Nayaka, U. J. Alengaram, M. Z. Jumaat, F. S. Fonseca, and A. Banerjee, “Structural performance of masonry prisms, wallettes and walls containing high volume of industrial by-products – Sustainable housing perspective,” *Constr Build Mater*, vol. 303, p. 124439, Oct. 2021, doi: 10.1016/J.CONBUILDMAT.2021.124439.

[34] S. M. S. Kazmi, M. J. Munir, I. Patnaikuni, Y. F. Wu, and U. Fawad, “Thermal performance enhancement of eco-friendly bricks incorporating agro-wastes,” *Energy Build*, vol. 158, pp. 1117–1129, Jan. 2018, doi: 10.1016/J.ENBUILD.2017.10.056.

[35] ASTM C136, “ASTM C136/C136M Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” *ASTM Standard Book*, 2019.

[36] ASTM C128, “ASTM C128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate,” *Annual Book of ASTM Standards*, 2022.

[37] ASTM C67/C67M-21, “Standard test methods for sampling and testing brick and structural clay tile,” *ASTM International, West Conshohocken, PA*, 2021.

[38] A. Cabané, L. Pelà, and P. Roca, “Anisotropy and compressive strength evaluation of solid fired clay bricks by testing small specimens,” *Constr Build Mater*, vol. 344, p. 128195, Aug. 2022, doi: 10.1016/J.CONBUILDMAT.2022.128195.

[39] J. N. Chang, W. C. Wang, H. Y. Wang, and C. Y. Hu, “A study of the mechanical properties and appearance of efflorescence in paving bricks under different curing environments,” *Constr Build Mater*, vol. 265, p. 120148, Dec. 2020, doi: 10.1016/J.CONBUILDMAT.2020.120148.

[40] ASTM C410, “ASTM C410-11 Standard Specification for Industrial Floor Brick 1,” *ASTM International*, 2018.

[41] ASTM C1006-13, “Standard Test Method for Splitting Tensile Strength of Masonry Units,” *ASTM*, vol. 07, no. Reapproved 2013, 2013.

[42] ASTM C1072, “Standard Test Method for Measurement of Masonry Flexural Bond Strength 1,” *ASTM International*, 2022, Accessed: Apr. 12, 2023. [Online]. Available: https://www.astm.org/c1072-19.html

[43] ASTM-C109, “ASTM C109 / C109M - 20b. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens),” *Annual Book of ASTM Standards*, vol. 04, no. 2, 2020.

[44] M. Kubiś *et al.*, “On the anisotropy of thermal conductivity in ceramic bricks,” *Journal of Building Engineering*, vol. 31, p. 101418, Sep. 2020, doi: 10.1016/J.JOBE.2020.101418.

[45] A. M. Seddik Hassan, R. M. H. Aly, A. M. Y. Alzahrani, M. M. Abd El-razik, and H. Shoukry, “Improving fire resistance and energy performance of fast buildings made of hollow polypropylene blocks,” *Journal of Building Engineering*, vol. 46, p. 103830, Apr. 2022, doi: 10.1016/J.JOBE.2021.103830.

[46] ASTM International, “Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus 1,” 2010. doi: 10.1520/G0099-05R10.