Fire behaviour of plastic bottle ecobricks as an infill building material

by

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Declaration

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Abstract

A global increased awareness of plastic pollution, and the consequences of not addressing said problem, has led to increased interest and adoption of ecobricks as a building material. Ecobricks consist of any size plastic beverage bottle, densely filled with dry, non-recyclable plastic. As a result, places such as schools, shops and crèches around the world are collecting them and using them as an infill material in the construction of private and municipal projects. Construction projects incorporating ecobricks involve placing the plastic bricks inside a timber or reinforced concrete frame. The frame is sometimes covered with steel mesh ("chicken wire") and plastered with various plaster-mixes. Ecobrick structures have gained popularity, with over 200 schools in Guatemala having been built using ecobricks. With plastics being highly flammable, it is important that the construction and fire engineering industries understand how they may perform when exposed to fire. The problem this thesis aims to answer is: how do ecobrick walls behave when exposed to fire, and how can they be built to ensure that they are safe?

As construction using ecobricks is relatively new, minimal research has been done regarding fire safety. Two of the most common methods for constructing homes out of ecobricks were identified. One consists of laying ecobricks horizontally between cob (a clay-straw-sand-mortar mix). The alternative was to stack them vertically and encase them with a mesh and plaster. In this work, various plaster systems were tested, including, (a) traditional cement-sand mortar, (b) lime mortar, and (c) cob. This thesis investigates the placement of bottles, the application of plaster, and the use of mesh layers in relation to the thermal performance of ecobricks in a standard fire test.

Six wall samples were built to represent the two different construction methods and three different plasters. The samples were tested in a large-scale furnace where the temperatures were measured through the cross-section of each wall. The temperatures were then compared against 2D thermal modelled wall samples to understand the thermal behaviour of the plaster and ecobricks. The plaster of each wall sample proved to be critical in the fire behaviour of the samples. The most favourable ecobrick and plaster combination, a cob plaster of 40 mm on the horizontal ecobrick wall sample, was able to achieve a one-hour fire rating, where the ecobricks did not melt or ignite. Samples tested with a vertical ecobrick and cement mortar experienced severe flaming and failed after 56 minutes, with some samples failing significantly faster. The lime plaster delaminated early on resulting in rapid failure. Preliminary guidelines for ensuring suitable fire behaviour are presented.

Uittreksel

'n Wêreldwye toenemende bewustheid van plastiekbesoedeling en die gevolge rakende die feit dat die probleem nie aangespreek word nie, het gelei tot toenemende belangstelling en die gebruik van “ecobricks” vir boumateriaal. “Ecobricks” bestaan uit enige grootte plastiekbottels, dig gevul met droë, nie-herwinbare plastiek. As gevolg hiervan, versamel plekke soos skole, winkels en kleuterskole regoor die wêreld en gebruik dit as 'n aanvullingsmateriaal vir die bou van private en munisipale projekte. Bouprojekte wat “ecobricks” insluit, behels die plaas van die plastiekstene in 'n raam van hout of gewapende beton. Die raam is soms bedek met staalgaas ("hoenderdraad") en met verskillende pleister mengsels gepleister. “Ecobrick” strukture se gewildheid neem toe. Meer as 200 skole in Guatemala is reeds met aanvulling van “ecobricks” gebou. Omdat plastiek hoogs ontvlambaar is, is dit belangrik dat die konstruksie- en brandingenieursbedrywe verstaan hoe dit presteer as dit aan vuur blootgestel word. Die probleem wat hierdie proefskrif wil beantwoord, is: hoe “ecobrick” mure reageer as hulle aan vuur blootgestel word, en hoe dit veilig in bouprojekte gebruik kan word.

Aangesien konstruksie met behulp van “ecobricks” relatief nuut is, is daar nog minimale navorsing gedoen oor brandveiligheid. Twee van die mees algemene metodes om huise uit “ecobricks” te bou, is reeds geïdentifiseer. Die een bestaan daaruit om “ecobricks” horisontaal tussen die sand-klei mengsel te lê ('n mengsel van klei-strooi-sand-mortier). Die alternatief is om dit vertikaal te stapel en dit met 'n gaas en gips te omhul. In hierdie projek is verskillende gipsstelsels getoets, waaronder (a) tradisionele sement-sandpleister, (b) kalkpleister en (c) sand-klei pleister. Hierdie tesis ondersoek die plasing van ‘ecobricks’, die aanbring van gips en die gebruik van gaaslae in verhouding met die termiese reaksie van “ecobricks” in 'n standaard vuurtoets.

Ses toets mure is gebou om die twee verskillende konstruksiemetodes en drie verskillende pleistersoorte te ondersoek. Alle monsters is getoets in 'n groot toetsoond waarin die temperature in die deursnit van elke muur gemeet is. Die temperature is daarna vergelyk met 2D termiese gemodelleerde muurmonsters om die termiese reaksie van die gips en “ecobricks” te verstaan. Die gips van elke muurmonster was van kritieke belang om die reaksie van die monsters in ‘n brand te meet. Die beste kombinasie van “ecobricks” en ‘n pleisterlaag van 40 mm op die horisontale monster van die ecobrick-muur, kon 'n vuurklas (vuurweerstand) van een-uur behaal, waartydens die “ecobricks” nie gesmelt of ontvlam het nie. Monsters wat met 'n vertikale “ecobrick” en sementpleister getoets is, het erg ontvlam en het na 56 minute misluk. Die monsters het aansienlik vinniger misluk. Die kalkpleister het vroeg reeds begin delamineer, wat 'n vroeë mislukking tot gevolg gehad het. Voorlopige riglyne vir die versekering van geskikte brandgedrag word aangebied.

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List of Abbreviations

CEB	Compressed earth blocks
CLT	Cross laminated timber
FEA	Finite Element Analysis
HDPE	High-density polyethylene
HRR	Heat release rate
LDPE	Low-density polyethylene
NPO	Non-profit organisation
PET	Polyethylene terephthalate (PETE)
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride (V)

1 Introduction

Recently there have been drives to increase awareness regarding the usefulness of plastic waste. A movement known as 'ecobricks' has started to use waste in construction as an infill building material in walls to provide insulation and in turn provide a use for what would be landfill materials. An ecobrick is any size plastic bottle, densely filled with dry, clean, non-recyclable plastic. Usually, a two-litre cool drink bottle is used and is then filled with plastic wrap (cling-wrap), plastic printed labels, shopping bags and other plastics (Global Ecobrick Alliance, 2020). Figure 1-1 shows an example of walls being constructed using ecobricks. Ecobricks are a relatively new initiative and building material, which started to become popular between 2009 and 2014 in the Northern Philippines (Dieleman & Maier, 2018).

Figure 1-1: Images of (Above) vertical orientated ecobrick assembly with a cement plaster and (Below) horizontal orientated ecobrick assembly with cob infill

The movement has led to a large number of non-profit organisations (NPO) promoting ecobricks as a building material to make stools, outdoor benches, raised garden beds and an infill material in buildings (Maier *et al.*, 2015). Two of the most common methods for using ecobricks as an infill material is arranging them in a horizontal or vertical pattern. One construction specification consists of laying ecobricks horizontally between cob (a clay-straw-sand-mortar mix), where the process can be seen in the bottom images of Figure 1-1. The alternative is to stack them vertically and encase them with a mesh and plaster. The top images of Figure 1-1 show the process of encasing the ecobricks in a mesh and applying a cement plaster. Organisations are teaching residents of low-income communities that plastic waste, which litters the streets surrounding their homes, can be useful. As seen in the Figure 1-2 , litter or plastic waste can be used as infill building material.

Figure 1-2: (Left) Litter in a waterway in Khayelitsha, Cape Town (Green, 2018), (Right) Ecobricks used as an infill building material

1.1 Problem Statement

As more structures use ecobricks as a building material, unknown variables from an engineering perspective need to be addressed. One such unknown, and the largest from a safety perspective, is how will ecobrick structures perform in a fire, or how will they influence the fires that occur? Plastic is inherently flammable and stems from oil. Also, when plastic burns it produces noxious fumes and intense fires. Hence, are homes built from ecobricks safe? Should municipalities be encouraging or discouraging the use of such building systems? Are NPOs and charities producing homes that could endanger lives and make these organisations liable for what occurs?

Currently, negligible data exists on the behaviour of ecobricks in fire conditions, and this current work appears to be the first published data regarding standard fire testing of ecobrick walls. Without experimental data, it is impossible to assess the many failure mechanisms that could occur in buildings constructed from ecobricks.

1.2 Research Aims

The aim of this work is to understand the behaviour of ecobricks in fire through experimental testing and numerical modelling to understand if, and how, fire ratings can be obtained. Currently, a large number of questions remain unanswered, which form the objectives of this study:

1.2.1 Objectives

1. How do ecobrick walling systems, with a variety of construction and plaster types, behave when subjected to fire conditions?
2. What thickness of plaster is required to protect the ecobricks?
3. Should design fuel loads for these structures be increased to account for the fact that large amounts of combustibles are stored in the walls? How much energy will ecobricks contribute to a fire if they do burn?
4. How should the fact that ecobrick homes are often built in low-income areas with limited quality control be addressed?

1.2.2 Limitations

In addition to the questions raised above, there are a number of additional questions that are of importance, but must be addressed in future research, and are limitations of this work:

1. How should joints be designed such that they do not open up during a fire?
2. How should penetrations through walls be designed?
3. How should the insurance industry address ecobrick structures?
4. Can design codes be developed for ecobrick homes?

Overall, it is a cause for significant concern that these structures are being widely rolled-out without the necessary building regulations being in place. By answering the questions, it should enable ecobrickers (people who create ecobricks and build with them) to be able to produce safe homes, and to provide the technical data for fire safety practitioners to be able to assess such structures.

1.3 Methodology

A review of international standards and regulations, as well as completed academic research, sheds light on how the introduction of ecobricks has received negligible attention in the fire engineering field. Any shortcomings identified in the investigation allows for topics and focus points to be determined. This will ensure that safer building methods for this alternative building resource can be developed.

Standard fire furnace testing is conducted on a variety of samples and the results analysed to better understand the behaviour of ecobricks as an infill material. The failure criteria of structural resistance, integrity and insulation is assessed in both experimental and numerical tests. Also, simple numerical models are created to understand behaviour and make recommendations.

1.4 Thesis Outline

Chapter 2 – Literature Review: The chapter discusses fundamental theories associated with structural fire engineering and fire dynamics, to enable the reader to better understand fire resistance and fire safety.

Chapter 3 – Ecobricks: The history, purpose and construction of ecobricks, plastic bottles filled with non-recyclable plastic, is discussed to provide insight as to how they became a popular plastic capsule and teaching aid. Current research investigates the compression strength and thermal insulation provided by an ecobrick. Lastly, the potential fuel load is analysed when comparing ecobricks to common plastics.

Chapter 4 – Experimental Testing of Ecobrick Walls: Generic ecobrick wall samples were built to represent vertical and horizontal building techniques of the ecobricks. A sample of each plaster type in the two techniques were instrumented and tested in a furnace according to a standard fire test. Data from the tests is presented. Failure mechanisms and fire resistance times are provided based on the results. The experimental data and fire phenomena identified provide a significant novel academic contribution.

Chapter 5 – Thermal Finite Element Analysis: A simplified configuration of each wall sample was modelled to represent the physical testing setup. The finite element analysis (FEA) results are compared to the physical results to provide insight regarding behaviour and the plaster thickness required to provide protection.

Chapter 6 – Conclusion and Recommendations: The findings from Chapters 5 and 6 are analysed simultaneously to determine difference between the experimental and numerical data, while being compared to the melting and ignition temperatures of the ecobricks. Preliminary guidelines, as to which ecobrick orientation and plaster combination provides adequate fire protection, for ensuring suitable fire behaviour are presented. Lastly recommendations are provided for future work, based on the short comings and observations identified during the study.

2 Literature Review

In this chapter, fire resistance and building materials are discussed to provide a better understanding with which building materials are commonly used and how the fire resistance of these materials are tested. This chapter does not aim to reproduce the invaluable information already published by authors such as Buchanan & Abu (2017) and Drysdale (2011), but to rather reiterate the importance of fire safety through well-known concepts of fire dynamics and structural fire engineering. The layout of this chapter is shown in Figure 2-1.

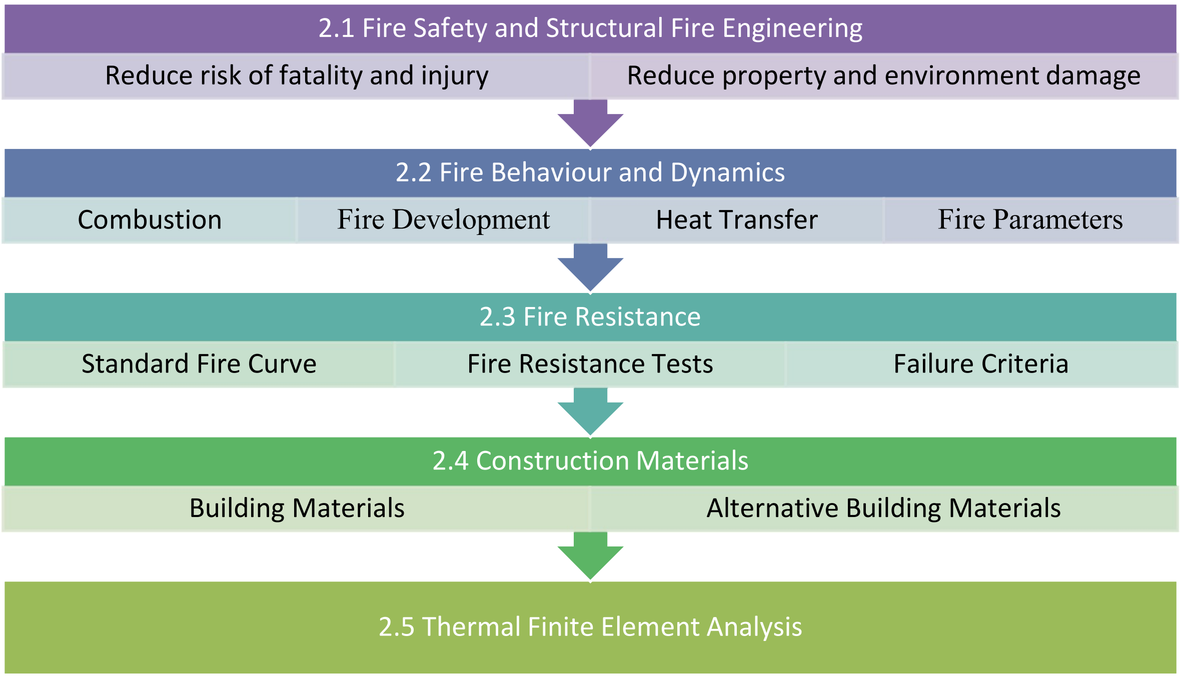


Figure 2-1: Flow diagram of Chapter 2

2.1 Fire Safety and Structural Fire Engineering

History has shown that property destruction and loss of lives lead to new or improved codes and legislations. This is evident throughout history, for example, the fires in Rome during the reign of Nero resulted in some of the earliest recorded building regulations (Klitzke, 1959). The 1189 fire in London resulted in some of the earlier legislations on usable building materials in the construction industry, namely the introduction of non-flammable walls between houses (Walford, 1877). Buchanan uses the example of the great fire of 1666 in London to showcase when the insurance industry encouraged the introduction of fire brigades and codes (Buchanan & Abu, 2017).

2.1.1 Fire Safety

The core objectives of fire safety are to reduce the risk of fatality and injury as well as reduce the damage to property and the environment, as represented in Figure 2-2 (Buchanan & Abu, 2016). Th objectives for fire safety are met by the use of active and passive systems. Active fire protection is initiated by a person or an automated mechanism to control the fire and its effects. However, a passive fire protection is not required to be initiated by a person or automated mechanism but is fabricated into the structure. Examples of active and passive fire protection are automated sprinklers and intumescent paint, respectively.

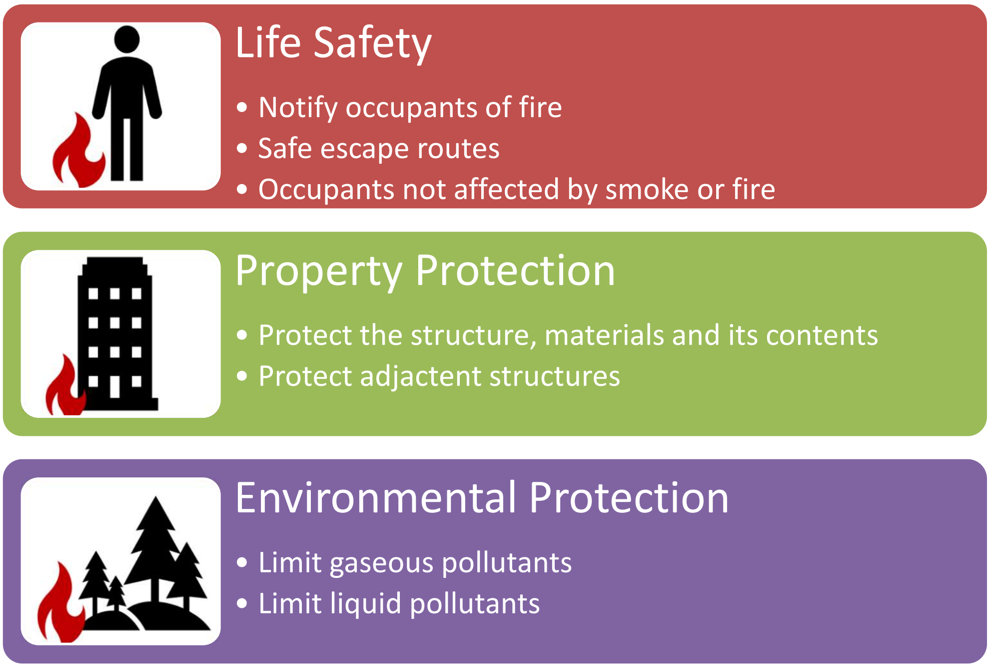


Figure 2-2: Fire safety objectives (adapted from Buchanan & Abu (2016))

2.1.2 Structural Fire Engineering

The objective of structural fire engineering is to support the objectives of fire safety. This is done by designing the structure to prevent, or at least delay, structural collapse and to contain the fire in the compartment of origin (Mowrer & Emberly, 2018).

2.2 Fire Behaviour and Dynamics

This section describes the general combustion, ignition, development and spread of a fire in an enclosed space. Furthermore, the heat transfer through different mechanisms as well as the parameters used in numerical modelling are discussed later in the chapter.

2.2.1 Combustion

For combustion to occur it requires three parts to be present, these are 1) a fuel source such as timber or a petroleum product, 2) oxygen to enable the oxidation reaction and 3) heat to increase the temperature of the fuel source to its ignition temperature. These three components of combustion, illustrated in Figure 2-3, are known collectively as the fire triangle. Combustion can occur with or without flames, known as flaming and smouldering combustion, respectively (Buchanan & Abu, 2017).

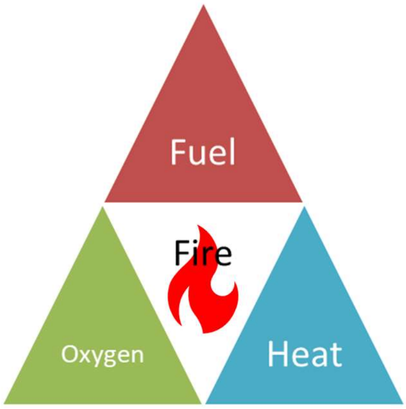


Figure 2-3: Illustration of the fire triangle to enable combustion (adapted from Quintiere (2017))

2.2.2 Fire Development

The development of an enclosed fire may be characterised by five distinct stages. These stages are ignition, growth, flashover, fully developed fire and a decay period. These stages of fire development are illustrated on a time-temperature curve of an enclosed fire in Figure 2-4.

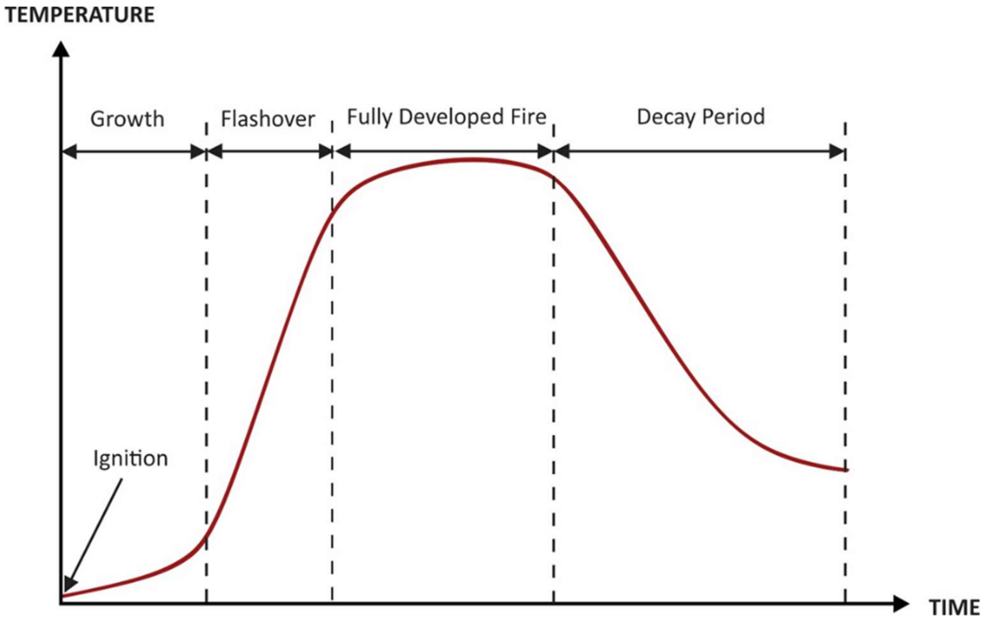


Figure 2-4: Time-Temperature curve of an enclosed fire development (Cicione & Walls, 2019)

Ignition is an exothermic reaction which occurs in two manners, namely piloted and spontaneous ignition. The point of ignition is defined by an increase in temperature, significantly above ambient, as the exothermic reaction occurs. Piloted ignition occurs when a pilot source such as a flame or spark initiates the exothermic reaction (Karlsson & Quintiere, 2000). Spontaneous ignition or autoignition is when an external heat source increases the temperature of the fuel to a point when it ignites without the need of a pilot source (Quintiere, 2017).

Growth is the stage which follows ignition. It depends on a few factors, such as the combustion type, fuel type and availability of oxygen, if the fire grows slowly or rapidly. If it is a smouldering fire, the heat release rate (HRR) would be low and the growth period would be prolonged, which may lead to the fire burning out before it reaches the next development stage. Whereas flaming combustion, with sufficient fuel, oxygen and heat, may lead to a rapid growth stage with a high HRR.

Flashover is the moment of transition between the growth phase and the fully developed fire. It may also be seen as the separation between pre- and post-flashover in an enclosed compartment fire.

Fully developed fire occurs post-flashover and is usually controlled by the amount of oxygen available for the combustion process, known as ventilation-controlled burning. During this stage, the HRR is usually at its highest.

Decay period is the stage when the fuel has been consumed, the HRR dwindles and therefore the gas temperature in the room decreases. At this point the fire usually transitions from ventilation-controlled to fuel-controlled (Karlsson & Quintiere, 2000).

2.2.3 Heat Transfer

Heat transfer occurs through three mechanisms which may take place simultaneously or separately; these mechanisms are conduction, convection and radiation (Buchanan & Abu, 2017). All three mechanisms transfer heat (energy) from one space, with a higher temperature or energy, to another, with a lower temperature or energy. These mechanisms are illustrated in *Figure 2-5* which has been adapted from Quintiere (2017). Heat transfer in Section 2.2.3 is taken from Buchanan & Abu (2016) unless otherwise stated.

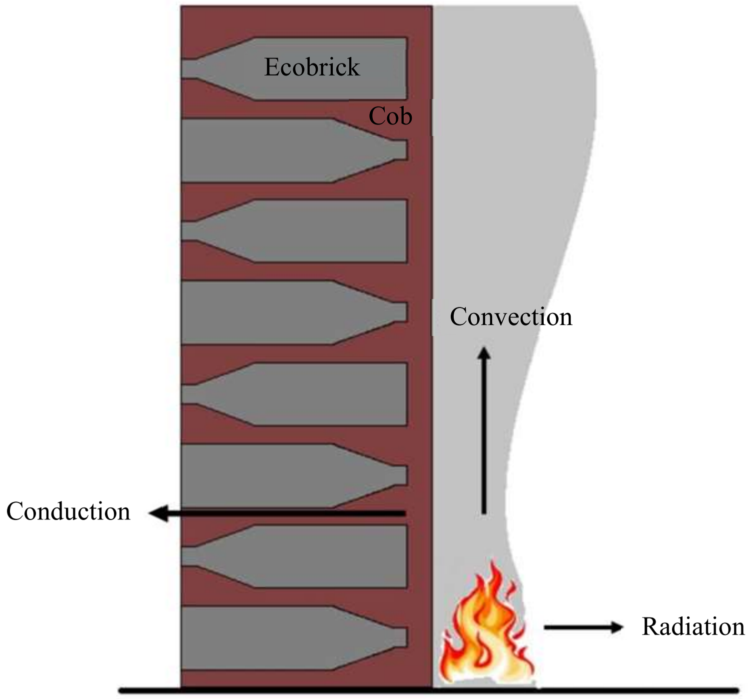


Figure 2-5: Heat transfer mechanisms illustrated with an ecobrick wall (adapted from Quintiere (2017))

2.2.3.1 Conduction

Transferring heat through solid materials is known as conduction. Materials which conduct electricity well will conduct heat well as heat is thermal energy. Similarly, poor electrical conductors will transfer heat poorly and thereby be good thermal insulators. Conduction is measured as the flow rate of heat through a specific thickness of a solid material and is calculated by Equation (2-1.

$$\dot{q}'' = kdT/dx \tag{2-1}$$

where

$\dot{q}''$ is the heat flow per unit area [W/m^2]

k is the thermal conductivity, which is the amount of heat transferred through a unit thickness of the material per unit temperature difference [W/mK]

T is the temperature [°C or K]

x is the distance in the direction of heat flow [m]

2.2.3.2 Convection

Transferring heat by the movement of fluids, such as gases or liquids, is known as convection. Flame spread is influenced greatly by convective heat transfer, which transports smoke and hot gases upwards towards the ceiling or out of a window. The formula for convection is given in Equation (2-2.

$$\dot{q}'' = h_c \Delta T \tag{2-2}$$

where

h_c is the heat transfer coefficient [W^2/m^2K]

ΔT is the temperature difference between the surface of the solid and the fluid [°C or K]

2.2.3.3 Radiation

Energy transferred by electromagnetic waves through a vacuum, or a transparent liquid or solid, is known as radiation. Radiation is the primary mechanism which transfers heat from flames to the surface of the fuel and is therefore exceptionally important in fires. It also transfers heat from smoke to objects, as well as from burning building to neighbouring structures. The radiant heat flux is given in Equation (2-3.

$$\dot{q}'' = \varphi \varepsilon_\epsilon \sigma T_e^4 \tag{2-3}$$

where

$\dot{q}''$ is the radiant heat flux at a point on a receiving surface [W/m^2]

φ is the configuration factor

ε_ϵ is the emissivity of the emitting surface, with a range from 0 to 1.0 where 1.0 is the emissivity of a 'black-body'

σ is the Stefan–Boltzmann constant [5.67×10^{-8} W/m^2K^4]

T_e is the absolute temperature of the emitting surface [K]

2.2.4 Fire Parameters

A number of material properties are used in calculating the heat transferred in solid materials. The material properties in this section have been taken from Buchanan & Abu (2016) unless otherwise stated. The material density ρ is the mass of the material per unit volume measured in kg/m^3, while the specific heat c_p is the amount of heat required to heat a unit mass of the material by one degree measured in J/kgK. Latent heat is the transfer of energy to or from a system causing a phase change at a constant pressure and temperature. Latent heat is the amount of heat required to heat a unit mass of a material from the solidus to liquidus temperatures (phase change) measured in J/kg (Çengel, 2004).

2.2.4.1 Calorific Value

The amount of heat released during complete combustion of a unit mass of fuel is known as the calorific value or the heat of combustion ΔH_c [MJ/kg]. For fuel which contains moisture under natural condition, such as wood, the effective calorific value $\Delta H_{c,n}$ [MJ/kg] can be calculated by Equation (2-4.

$$\Delta H_{c,n} = \Delta H_c(1 - 0.01m_c) - 0.025m_c \qquad (2\text{-}4)$$

where m_c is the moisture content as a percentage of weight.

The maximum possible energy, E [MJ], that can be released when fuel burns is the energy contained in the fuel, which can be calculated by Equation (2-5(2-5 for dry fuel and Equation (2-6 for fuels containing moisture.

$$E = M\Delta H_c \qquad (2\text{-}5)$$

$$E = M\Delta H_{c,n} \qquad (2\text{-}6)$$

where M is the mass of the fuel [kg].

2.2.4.2 Fire Load Energy Density

The fire load energy density (FLED) accounts for the combustible materials in a building and is expressed as the energy per square metre of floor area.The FLED, e_f [MJ/m^2], is calculated by Equation (2-7)

$$e_f = E/A_f \qquad (2\text{-}7)$$

where A_f is the floor area of a room in m^2.

2.2.4.3 Heat Release Rate

The heat release rate, Q [MW], is the amount of energy released over a period of time, which is calculated by Equation (2-8.

$$Q = E/t \qquad (2\text{-}8)$$

where

E is the total energy contained in the fuel [MJ]

t is the duration of the burning (s)

2.3 Fire Resistance

The capacity of a structure to prevent collapse and to avert the spread of a fire to other compartments within the building or to an adjacent structure is known as fire resistance. The fire resistance of a building, or part thereof, should be greater than the fire severity, which quantifies the damaging effect of a fire or the temperatures and forces, which may lead to collapse or failure due to the fire (Buchanan & Abu, 2017). The following section describes the failure criteria and tests which are used to evaluate the fire resistance of walls.

2.3.1 Standard Fire Curve

The standard fire curve, a time-temperature curve that is one of the most important relationships in the fire engineering industry, was established in 1916 for the development of products (Gales *et al.*, 2021). This curve represents the heating process of a furnace and forms the benchmark for all fire testing. The formula for the standard fire curve is given in Equation (2-9.

$$T_g = 20 + 345 \log{(8t + 1)} \tag{2-9}$$

where

T_g is the temperature in degrees Celsius [°C] and

t is the time in minutes [min].

According SANS 10177-2 (SABS, 2005), to ensure accuracy, the furnace temperature should not deviate outside of tolerances from the standard fire curve. The tolerances on the mean deviations are given in Table 2-1 and illustrated along with the standard fire curve in Figure 2-6.

Table 2-1: Tolerances for the mean deviation from the standard fire curve according to SANS 10177-2 (SABS, 2005)

Time	Mean Deviation
t < 10 min	± 15 %
10 min ≤ t < 30min	± 10 %
t ≥ 30 min	± 5 %

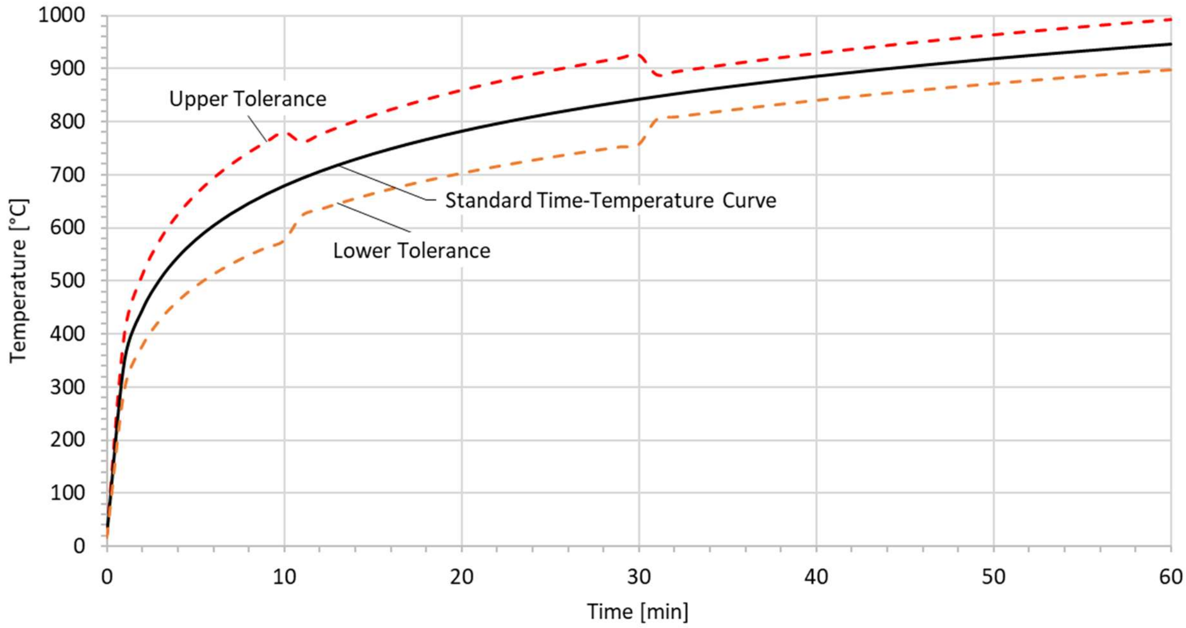


Figure 2-6: The time-temperature graph of the standard fire curve with the upper and lower tolerances

2.3.2 Fire Resistance Tests

Fire resistance tests establish the fire resistance or endurance of building elements, such as beam, column, wall or floor, and it is measured in hours or segments of hours. All countries have codes that specify the fire resistance ratings of different building elements (Buchanan & Abu, 2017).

The most common method of performing a physical test is by exposing a specimen/building element to a standard fire while constructed in a furnace or large steel box, lined with fire bricks and ceramic fire blanket. During the test, the element and the conditions surrounding the element are measured and controlled if necessary. The standards call for conditions of the building element and the surrounding environment to represent reality/actual construction as closely as possible (SABS, 2005).

SANS 10177-2 details that at least five thermocouples should be used and no fewer than one thermocouple per 1.5 m^2 of wall area. The thermocouples should not have a diameter less than 0.75 mm. The methods used during the experimental testing in this work are discussed in Section 4.

2.3.3 Failure Criteria

The three failure criteria of fire resistance of a structure, or part thereof, are defined by Buchanan and Abu (2016) as stability, integrity and insulation. To adhere to the stability criterion, a structural element must perform its load-bearing function and carry the applied loads for the duration of the test without structural collapse. Structural collapse could lead to fire fighters being in a greater danger as well as the loss of compartmentation, which aids in isolating the fire. The integrity criterion requires that the test sample does not crack nor develop any fissure, which allow hot gases or smoke through the sample. Large deflections lead to cracking, which allows smoke and flames through the wall barriers. Lastly, the insulation criterion requires that the temperature on the unexposed side of the test sample does not increase passed a specified limit. Large surface temperature increases on the unexposed side may cause materials to self-ignite thereby spreading the fire. These criteria are summarised in Table 2-2 and illustrated in Figure 2-7.

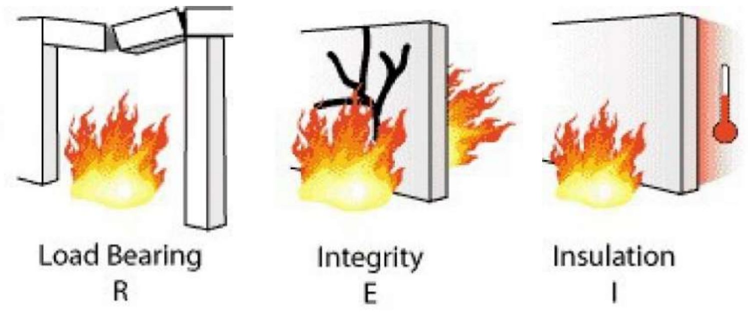


Figure 2-7: Criteria of fire resistance (Iris Coatings, 2021)

Table 2-2: Criteria of failure of fire resistance adapted from Buchanan & Abu (2016) and SABS (2005)

R – Structural Resistance	Element is required to perform its load bearing function Requirements: • Deflection limit x < L/20 • Rate of deflection < $L^2/9000d$ when the deflection is L/30 and d is the specimen thickness
E - Integrity	To separate building components and fails if: 1. Cracks or holes appear 2. Hot gases pass through which can ignite a piece of cotton 3. Flaming occurs on unexposed side
I - Insulation	To separate building components by limiting the temperature increase on the unexposed side above the initial temperature. Failure occurs if a sample: 1. Exceeds an average of 140 °C 2. Exceeds a single maximum temperature of 180 °C above ambient 3. Exceeds a single maximum temperature of 220 °C, irrespective of the initial temperature above ambient

The insulation and integrity failure criteria specific to this study are discussed in Section 4. The structural resistance is not assessed as it is assumed that the structural frame of the wall is load bearing.

2.4 Construction Materials

Structures exposed to fire, and the materials used to build these structures such as concrete, steel and timber, have been widely researched. The material properties are commonly known and readily available. The properties of alternative building materials, such as cob which is not commonly used in buildings and structures, is not readily available and quite often passed along via verbal instruction. This section briefly discusses concrete in fire and looks at available research on alternative materials.

2.4.1 Building Material: Concrete

Concrete is a commonly used building material which is widely used internationally, and the resistance to fire and its thermal behaviour is well understood. Concrete behaves well in fires as it is a non-combustible material and has a low thermal conductivity (Buchanan & Abu, 2017). For this study, the properties of concrete are used as the plaster which covers the ecobricks. The concrete temperature is calculated at different depths by using Wickström's method in Equations (2-10) to (2-13). These equations are used in the validation study in Section 5 and shown in Appendix B.

$$T_w = \eta_w T_f \tag{2-10}$$

where

$$\eta_w = 1 - 0.0616\, t_h^{-0.88} \tag{2-11}$$

T_f is the fire temperature [°C]

t_h is the time [hours]

At any depth x (m) into the slab, at time t_h, the concrete temperature T_c is a factor η_x of the surface temperature T_w with η_x given by:

$$\eta_x = 0.18 \ln(t_h / x^2) - 0.81 \tag{2-12}$$

$$T_c = \eta_x \eta_w T_f \tag{2-13}$$

As most masonry or concrete walls are not filled with flammable materials, the plaster thickness to thermally protect the infill is not studied alone. A relative comparison to make is that of the concrete cover of reinforcing steel. The concrete cover is used to protect the reinforcing from high temperatures which may cause the steel to lose tensile strength. Also once concrete reaches a temperature of 300 °C it is considered as damaged as the concrete strength is reduced significantly due to chemical changes (Buchanan & Abu, 2017). Various codes exist prescribing the plaster thickness of walls, such as SANS 10400 Part T , which prescribes that a minimum thickness of 12 mm of cement plaster shall be used on a 75 mm thick clay masonry or solid concrete wall to provide a 30 minute fire rating for non-loadbearing walls (SABS, 2011).

Concrete walls are usually studied as a whole and can be used to provide stability, integrity and insulation in fire, although it is generally assumed that the spalling of concrete (concrete layers or pieces breaking off) is negligible. Hayhoe & Youssef (2013) proposes that this assumption should be investigated further as this may not be true. The proposal by Hayhoe and Youssef may be compared to the delaminating plaster which occurs during the experimental testing of the ecobrick walls in Section 4.

The material properties of concrete used in the finite element analysis (FEA) that will be presented in Section 5.1 are shown below in Figure 2-8 to Figure 2-10, where the temperature dependent density, specific heat and conductivity of concrete are illustrated. A summary of the adapted values used in the FEA model as the cement plaster is provided in Table 5-4.

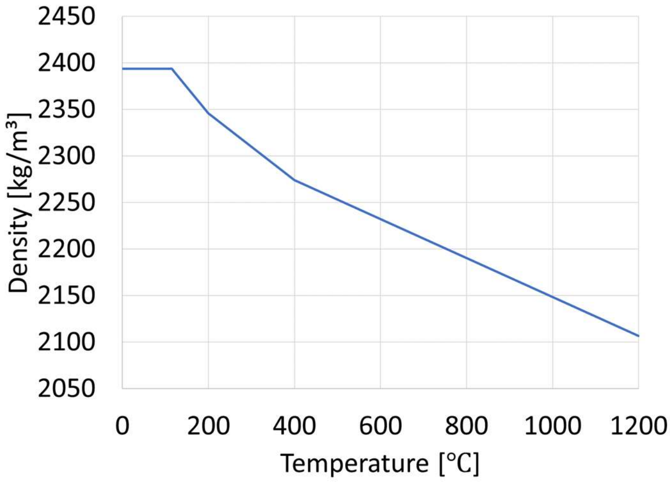


Figure 2-8: Temperature dependent density of concrete used in FEA model (adapted from Drysdale (2011))

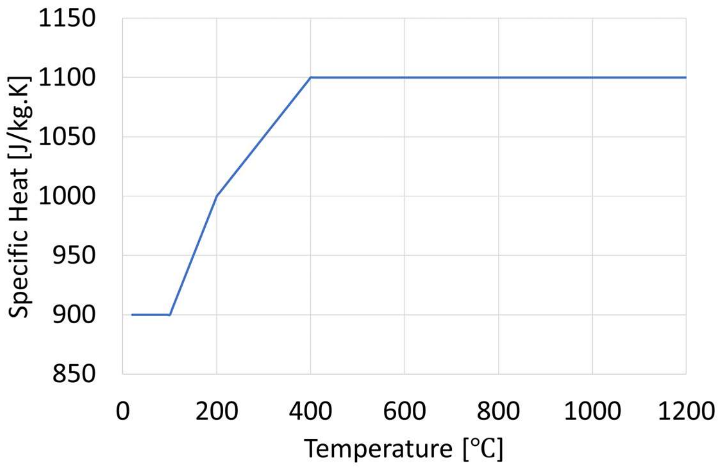


Figure 2-9: Temperature dependent specific heat of concrete used in FEA model (adapted from Drysdale (2011))

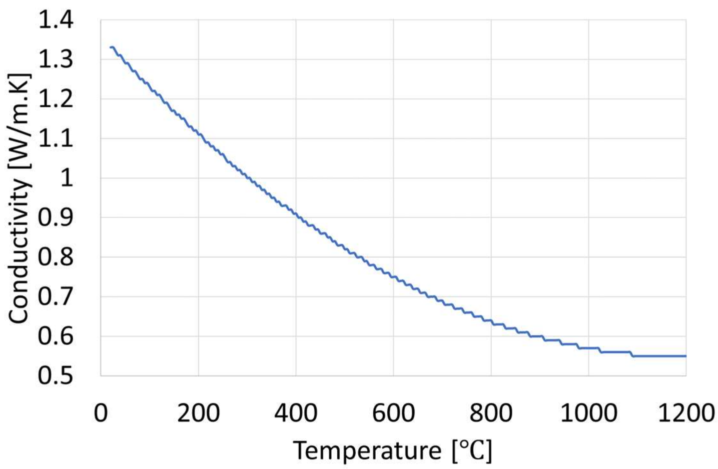


Figure 2-10: Temperature dependent conductivity of concrete used in FEA model (adapted from Drysdale (2011))

2.4.2 Building Material: Timber

Timber panels, in the form of cross laminated timber (CLT), have been used to provide a cost and construction efficient building material. CLT panels are widely used, although there is not enough data available to fully understand the thermal and structural behaviour in fire (Suzuki *et al.*, 2016). Although timber has a constant charring rate, the effect of the timber delaminating increases the charring rate as well as exposes new fuel (Johansson & Svenningsson, 2018). This is similar to the effect of the plaster delaminating and exposing the ecobricks to high gas temperatures which causes them to ignite and add to the fuel load.

2.4.3 Alternative Building Material: Cob

Cob or adobe is a mortar mix of clay, sand, straw, and water. Cob is a building material that has existed for thousands of years. Even though it is an ancient building material, there are many homes around the world that still use it today, such as in Devon, England, where over 20 000 homes are built from cob (Morris, 2014). South Africa, and many other countries, do not have building codes that apply to cob. The only two countries that have national building codes for cob are New Zealand and Germany, with France in the process of developing earth building specific codes (Lutge, 2009).

The cob used in this study followed the study conducted by Gavin Lutge (2009) on behalf of The Natural Building Collective for a dwelling constructed in Scarborough, Cape Town. The cob results provide a compressive strength of 1.6 MPa after 7 days, which is greater than the required 1.3 MPa of the New Zealand Standards (NZS 4298) Materials and Workmanship for Earth Buildings (Lutge, 2009). The mix consists of 2 parts clay soil, obtained from a farm outside of Stellenbosch, 2 parts sand, 1 to 2 parts water and 1-1.5% of wheat straw. The clay acts as a binder and the straw provides tensile strength to the mixture.

Figure 2-11: Manual mixing of cob where the (1) clay, sand and water are mixed, after the (2) straw is added. (3) Lastly the cob is rolled to ensure that is it thoroughly mixed.

Cob is a labour-intensive building material. It can be scaled with the use of large mixes, although the best results are obtained by a manual mixing such as the process seen in Figure 2-11. The cob is made by mixing the clay and soil on a large tarpaulin, forming a well, and slowly adding and mixing in the water (1). Once a good consistency is reached, the straw is added (2). To ensure the cob is thoroughly mixed, the tarp is used to roll and flip the cob, which is then rolled into a cylindrical form (3).

2.5 Thermal Finite Element Analysis

Numerical modelling is a valuable resource which allows the user to simulate a simplified or complex analysis as this may save valuable time and resources. Section 4 discusses the process and results of the ecobrick wall samples which were tested in a furnace, after which the samples were modelled and discussed in Section 5.

The accuracy of the numerical model is dependent on the accuracy of the material properties and interactions used in the model. The material properties include density, specific heat, conductivity, emissivity and the latent heat. FEA was used by Han *et al.* (2016) to determine the thermal stress in reinforced concrete columns during a fire, as well as the effects of cooling. Han *et al.* (2016) used FEA to better understand heat-induced concrete spalling. The reduced loading capacity, due to the thermal influence, is studied by Han *et al.* (2015) in reinforced concrete beams. The thermal finite element analysis (FEA) of the ecobrick walls and the properties which were used are discussed further in Section 5.

2.6 Summary

In Section 2 , fire resistance and building materials were discussed to provide a better understanding with which building materials are commonly used and how the fire resistance of these materials are tested. The importance of fire safety, through well-known concepts of fire dynamics and structural fire engineering, was discussed to provide critical topics used during this study. The above mentioned elements of fire engineering are used to analyse the behaviour of ecobricks as an infill building material in walls when exposed to a fire.

The literature review continues in Section 3, with a focus on ecobricks, before an analysis of ecobrick fuel loads is carried out. There is limited data available on ecobricks as a construction material, and no peer-reviewed reports currently available on ecobricks in fire. Chapter 3 also analyses data obtained for this study through research conducted by the author.

3 Ecobricks

The following chapter presents information which introduces ecobricks and provides information in relation to their potential behaviour in fire. The chapter describes, based on both the literature and interviews with local ecobrickers (people building ecobrick homes), how and why individuals and organisations started to make them for the purpose of building and how they are used to construct homes. An investigation into the mass and contents of ecobricks is carried out by analysing samples of ecobricks collected from a public collection site. Fuel loads are calculated, along with the distribution of mass of the bottles, and this provides novel insight regarding the potential increase in fuel load that ecobrick homes may contribute.

3.1 A Brief History of the Ecobrick

Ecobricks were not created by a single individual, but was rather concurrently pioneered by various activists. One of these pioneers is Susana Heisse, an eco-activist and founder of Pura Vida, who became inspired, to utilise non-recyclable plastics as a building material to solve the local waste situation, by a woman who built her house with plastic bottles filled with plastic waste (Lenkiewicz, 2016). Many of the ecobrick pioneers aimed to utilise the local solid waste materials, which usually end up in ravines or rivers as they have no, or poor, municipal waste management (Rodic-Wiersma & Bethancourt, 2012). Since then, ecobricks have become a popular tool for collecting unrecyclable plastics as well as a teaching aid to make the users aware of the single use plastics they purchase on a daily basis (Mostert, 2019).

Ecobricks, which reuse solid, non-recyclable, often petroleum-based waste, previously disposed of in landfills, repurpose waste to create furniture or be used as infill material in the construction of garden beds and benches, or even buildings (LeFevre, 2021). An example of a bench is shown in Figure 3-1 where it was built in Noordhoek, Cape Town by Earth & Co and Project Noordhoek using 800 ecobricks. A popular use for ecobricks, which creates awareness of single use plastics as well as is a free building material, is building schools and homes with them as an infill material in the construction industry. This is true for projects in Guatemala, Philippines, and South Africa which are either run partially, or in-full, by non-profit organisations such as Hug It Forward, Pura Vida and EcoBrick Exchange (Hopkins, 2014). The use of ecobricks as a construction material is discussed in more detail in Section 3.3.

Figure 3-1: Example of ecobricks being used to construct a bench, built by Earth & Co and Project Noordhoek using 800 ecobricks at Noordhoek Beach, South Africa (Vivier, 2020)

3.2 Making an Ecobrick

An ecobrick is any size plastic bottle, densely filled with dry, clean, non-recyclable plastic. Acceptable filling includes, but is not limited to: plastic bags and packaging, plastic straws, cling wrap and polystyrene. Filling that is not allowed are items such as glass, metal, paper, biodegradables and recyclable materials (Cullen, 2017). The most common bottles used are 500 millilitre and 2 litre bottles, made out of polyethylene terephthalate (PET). An ecobrick is made by filling the bottle with small pieces of non-recyclable plastic in layers and compacting these layers with a wooden stick or metal rod until the layer is compacted to a desired degree as illustrated in Figure 3-2. The global ecobrick alliance recommends that an ecobrick should have a minimum density of 0.33g/ml, such that, for example, a 2 l bottle should weigh at least 660 g (Global Ecobrick Alliance, 2019). Ecobricks may be made by anyone, from school children to individuals at home or at work, as there is no special equipment or specific skills necessary (Global Ecobrick Alliance, 2020).

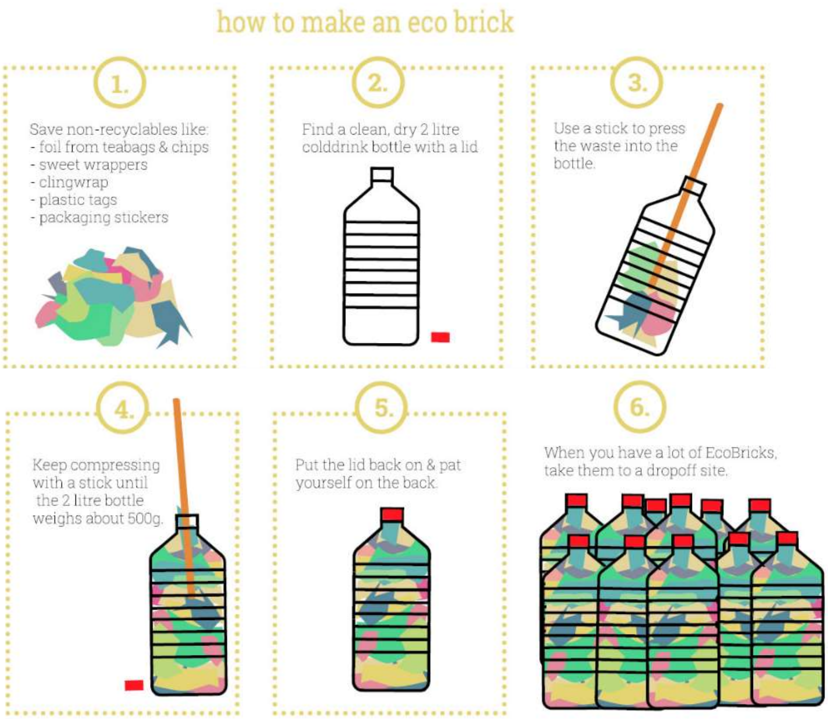


Figure 3-2: How to make an ecobrick (LaMinx, 2018)

3.3 Ecobrick: A Construction Material

There are various methods of building with ecobricks, but the most common methods are reinforced concrete (RC) framed and timber framed buildings. These structures consist of beams and columns, horizontal and vertical members respectively, joined by fixed joints (Yakut, 2011). The walls of these structures do not carry any other loads besides the weight of the wall itself, which is transferred to the beams. These loads are then carried by the beam which are transferred down the columns to the foundation.

Hug It Forward is a non-profit organisation which focuses on building bottle schools in Guatemala (Hug It Forward, 2021a). They have built over 100 schools (Hug It Forward, 2021b), using ecobricks as an infill building material for the walls of RC framed buildings. Each school consists of one to three classrooms, using approximately 6 500 ecobricks on average per school (Hug It Forward, 2013). Figure 3-3 illustrates a broad overview of the construction process of a bottle school, where the (1) RC frame and (2) ecobrick infilled wall is shown before (3) the plaster is added and painted.

Figure 3-3: Construction process of a bottle school built by Hug It Forward in Guatemala (1) RC framed structure (2) Ecobrick infill being added to walls (3) Completed school, plastered and painted (Hug It Forward, 2019)

3.4 Research to Date

At the time of writing, there are few journal papers and technical reports available on the topic of the structural or fire performance of ecobricks. It has been found that no study has been done which investigates ecobricks at high temperatures, although an empirical test was done on a single ecobrick and cob wall in Morgan Bay, South Africa. A fire was built alongside the wall and continually fed for 3 hours, after which the fire was extinguished by the fire brigade. The cob wall appeared to have protected the ecobricks in this open air and non-instrumented test (Moller, 2019). The following section discusses literature relevant to the construction of ecobrick homes.

The ecobricks analysed in this work are filled with non-recyclable plastic, although some studies filled ecobricks with other materials. Antico *et al.* (2017) who studied four different ecobricks contents, namely PET, paper, tetrapack and metal, to develop characteristics from experimental data. Characteristics studied include physical and mechanical properties such as the density, thermal shrinkage and modulus of elasticity.

A limited number of studies have tested the compressive strength of ecobricks with a variety of fillers such as Mokhtar *et al.* (2016) who analysed ecobricks filled with sand to be used as bricks to build the walls of green houses. They found that the compressive strength of a 250 ml and 1.5 l ecobrick was 4 and 3 times greater respectively than a clay brick with a maximum compressive strength of 8.58 MPa.

Conversely, the compression tests done by Taaffe *et al.* (2014) on 500 ml ecobricks filled with non-recyclable plastic, such as plastic bags, only produced a maximum strength of 2.96 MPa as shown in Table 3-1.

Table 3-1: Compressive strength of ecobricks filled with sand and plastic compared to the compressive strength of a clay brick. Adapted from Mokhtar et al. (2016) and Taaffe et al. (2014)

Brick Type	Size	Filling	Area [m^2]	Maximum Compressive Strength
Brick	0.09 m x 0.22 m	Clay	0.021 m^2	8.58 MPa
Ecobrick	250 ml	Sand	0.002 m^2	38.34 MPa*
Ecobrick	1.5 l	Sand	0.006 m^2	27.39 MPa*
Ecobrick	500 ml	Plastic waste	0.014 m^2	2.96 MPa

**The above results are as per the paper (Mokhtar et al., 2016), though seem unrealistically high and should be validated.*

The compression tests address the structural performance criteria of a rational design (Byron, 2013), Taaffe *et al.* (2014) performed sound insulation tests as well which address the acoustic performance of an ecobrick. The results from the sound insulation tests showed that the ecobricks have a lower sound reduction index (i.e. perform worse) than a concrete hollow brick, although not significantly enough to state that they have poor acoustic insulative properties. This may be due to the irregular shape of the ecobricks with no mortar between. Taaffe *et al.* (2014) believes that this could improve with the use of mortar between the ecobricks.

Thermal insulation is a well-known criterion of a rational design, this is addressed for both ecobricks filled with sand as well as ecobricks filled with non-recyclable plastic by the study done by Mokhtar *et al.* (2016) and the tests done at Los Alamos National Laboratory for Upcycle Santa Fe (Rahn, 2017) respectively. Mokhtar found that the ecobricks filled with sand yielded a similar thermal insulative result as standard bricks and could therefore be used to replace bricks with respect to the themal insulation. The insulation tests performed by the Los Alamos National Laboratory's were relatively empirical (test with limited data and measurements) and the ecobricks performed similarly compared to industry standard materials.

As discussed in the section above, there have been no formal studies analysing ecobricks at high temperatures and addressing the fire resistance.

3.5 Material Composition and Properties of an Ecobrick

The ecobricks this study addresses are filled with waste, non-recyclable, plastics. Thus, the fuel load of each individual ecobrick differs due to the contents consisting of a variety of plastics as well as cooldrink bottle labels, cling wrap, plastic bags and other miscellaneous materials. In Table 3-2 are the well-known plastics along with their melting points, piloted ignition temperatures and calorific values. The values are used to calculate an estimated fuel load for ecobricks in Section 3.6.

Table 3-2: Melting points, ignition temperatures and calorific values of common plastics. Adapted from Cafe (2007), Tewarson et al. (1999), Drysdale (2011) and Devasahayam et al. (2019).

Code	**Abbreviation**	**Plastic**	**Melting Point Range [°C]**	**Piloted Ignition Temperature [°C]**	**Calorific Value [MJ/kg]**
1	PET/PETE	Polyethylene terephthalate	260	374	23.2
2	HDPE/PEHD	High-density polyethylene	122 - 137	349	46.5
3	PVC/V	Polyvinyl chloride	75 - 110	435 - 557	19.9
4	LDPE/PELD	Low-density polyethylene	107 - 124	349	46.5
5	PP	Polypropylene	158 - 168	570	46.0
6	PS	Polystyrene	100 - 120	488 - 496	41.6
7	OTHER	Nylon	160 - 275	424 - 532	31.9

Most plastics are quite flammable, in that they have low piloted ignition temperatures and/or critical heat fluxes. However, the amount of energy that an ecobrick will contribute to fire behaviour is also of importance, where high calorific values are a concern. Materials such as PVC have a low melting point and relative to other plastics in Table 3-2 have a lower calorific value of 19.9 MJ/kg. Whereas LDPE and HDPE have slightly higher melting points due to the density difference, but have a much higher calorific value of 46.5 MJ/kg. Overall, it is important to note that the melting point for materials ranges from 75-275°C, whilst the piloted ignition temperature ranges between 349-570°C. At the melting point gases will be produced, which can be potentially noxious. The calorific value for materials considered ranges between 19.9-46.5 MJ/kg. The upper limit is comparable to that of petrol or diesel which have calorific values of around 45 MJ/kg (Buchanan & Abu, 2017).

The composition of an ecobrick may vary considerably, although the lid and bottle of most ecobricks are made from HDPE and PET respectively. Therefore, in this study HDPE and PET temperature limits will be used and compared to experimental temperatures. This is to ensure that the plastics do not melt, nor ignite and add to the fuel load of the room.

3.6 Fuel Load Calculation

The most popular and known use of ecobricks are as an infill building material in schools in countries such as Guatemala and Cambodia (Lenkiewicz, 2018), as discussed above. The ecobricks are used in walls both with and without plaster, as shown in Figure 3-4 where the ecobricks have been used decoratively for an early childhood development centre in Delft, Cape Town (Cobute, 2016). In terms of fire engineering considerations, the contribution of a material to the total fuel load is very important. Hence, in this section the fuel load contribution of ecobrick wall configurations will be determined based on an assumed house size, with a typical informal settlement house being used as benchmark. Due to the high wall-to-floor-area ratio of such houses the calculated values will also be relatively conservative.

Figure 3-4: Decorative ecobrick wall filled with cob at the Delft Early Childhood Development Centre (Cobute, 2016)

A typical dwelling for informal housing in South Africa can be seen in the left image of Figure 3-5, where the dwelling has an exterior cladding of corrugated metal sheeting. The right image Figure 3-5 is of a dwelling built by using horizontal ecobricks.

Figure 3-5: Typical informal settlement dwelling in Cape Town (Gontsana, 2020) (Left) Ecobrick dwelling proposed to be used in informal settlements (Pace, 2020) (Right)

According to Eurocode 1-2, the fire load density for a typical dwelling is 780 MJ/m² of floor area with an 80% fractile fuel load of 948 MJ/m² (CEN, 2002). This fuel load represents the contents and furnishings of the home. However, it does not account for a contribution of the building skeleton to the fuel load. For informal homes the fuel load may vary from published formal home data, and a study by Maree (2015) found it to be approximately 414 MJ/m². As the contents and building materials of these dwellings vary, and no regulatory body controls which materials are used, there could be individual dwellings that may have a fire load density up to 1000 – 2000 MJ/m² (Walls *et al.*, 2017). For comparison purposes Eurocode guidelines for representative fuel loads will be used as a comparison to the contribution of ecobricks if they were all to become exposed and fully burn.

As discussed in Section 3.2 above, Global Ecobrick Alliance (2019) recommend that ecobricks from 2 l bottles should weigh at least 660g. However, in South Africa it appears this guideline is often not applied. A typical locally produced two litre ecobrick used as an infill building material weights between 400 g and 600 g, which has approximately between 8 MJ and 28 MJ of energy depending on the contents. Based on having 35 bottles per square meter for a horizontally orientated ecobrick wall, and 28 bottles per square meter of vertically orientated ecobrick wall the range in fuel load contribution per 1m² of wall is as follows:

- Horizontally orientated ecobricks – 35 ecobricks per m² -
    - Fuel load contribution of wall: 817 to 2 865 MJ/m² of wall area
- Vertically orientated ecobricks – 28 ecobricks per m² -
    - Fuel load contribution of wall: 654 to 2 292 MJ/m² of wall area

An informal settlement dwelling, of approximately 2.4 m wide, 3.6 m long and 2.3 m high (Cicione *et al.*, 2020), built from ecobricks would have a lower limit contribution to the fire load density of 654 MJ/m² and an upper range of 2865 MJ/m² relative to floor area (i.e. converted from a wall fuel load to an equivalent floor area fuel load as typical in fire engineering design). These fire load densities are based on varying ecobrick orientations and using a 400 g ecobrick filled with polyvinylchloride (PVC) and a 600 g ecobrick filled with polyethylene (PE) respectively. Figure 3-6 illustrates the different fuel loads per m² based upon their orientation, weight, and filling material.

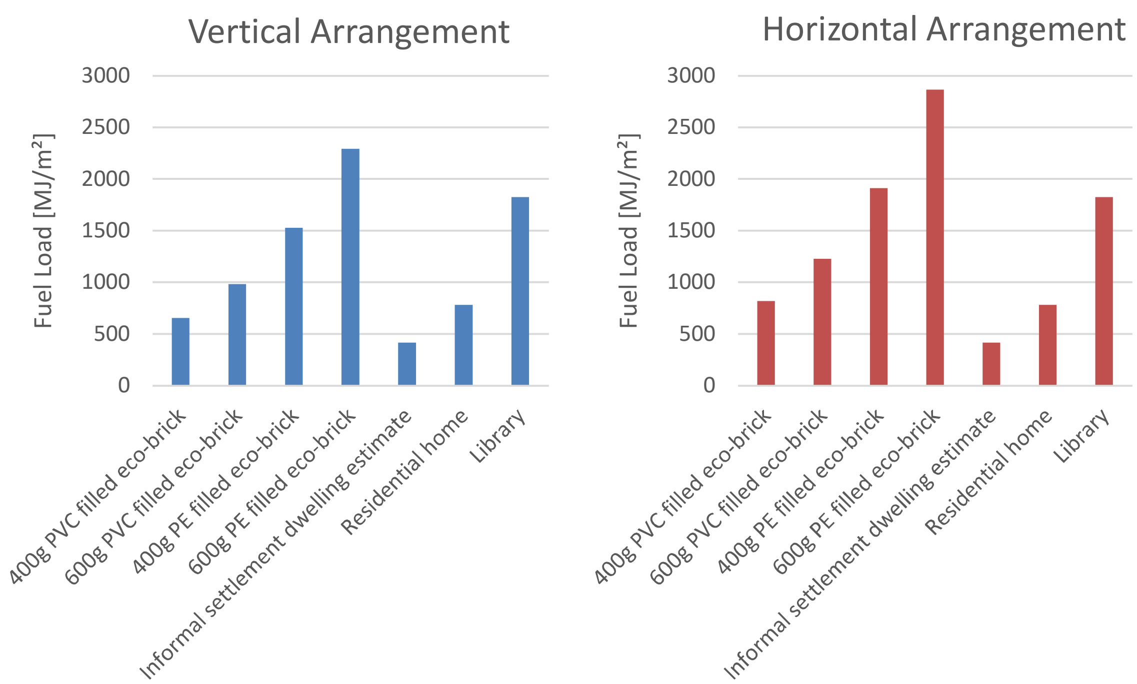


Figure 3-6: Equivalent floor area fuel load based on a 2.4m x 3.6m x 2.3m high dwelling showing the contribution of ecobrick walls to the fuel load, along with Eurocode guidelines for fuel loads for different occupancies

With reference to the right image in Figure 3-5 and a horizontal ecobrick placement, a total fire load density of between 1900 MJ/m² and 2865 MJ/m² for PVC and PE respectively is achieved, which is higher than the 80% fractile fire load of a library of 1824 MJ/m² (CEN, 2002). Hence, a library built with ecobricks would need to be designed for a fuel load of over 4000 MJ/m² if it was considered that all ecobricks could burn. This is concerning when considering that most ecobrick homes are built in low-income communities, and a typical informal settlement fire spreads rapidly. The ecobrick dwellings could increase the fuel load of an informal settlement by a factor of 4.5 as well as the rate of spread may increase due to the flammable exterior.

Based on the above analysis it is imperative that ecobricks be prevented from contributing to fire behaviour and must be protected within wall cavities.

3.7 Summary

The chapter presented ecobricks and their potential behaviour in fire. Individuals and organisations started to make them for the purpose of reducing waste and building homes. The investigation into the mass and contents of ecobricks provided novel insight regarding the potential increase in fuel load to a structure.

Section 4 discusses the preparation of ecobrick wall samples, and the testing thereof in a standard fire testing furnace. The section details the density of the ecobricks used in the samples, along with the assembly process of the frames used to house the walls and materials used as infill and plaster material.

4 Experimental Testing of Ecobrick Walls

Based on an understanding of ecobrick homes, as presented in the previous chapter, this chapter now discusses the experimental standard fire testing of plastic bottle ecobricks as an infill material. The chapter includes discussions regarding the assembly process of the walls, such as the construction techniques, as well as the instrumentation placement for furnace testing. The samples were placed in a standard fire furnace, at Ignis Testing in Cape Town, South Africa, with 5 out of the 6 samples being tested. The chapter will conclude by analysing the experimental testing results in the form of comparing the temperatures at the back of the plaster layer to the properties of the plastic and insulation criteria. One sample, the vertical orientated ecobrick wall with lime plaster, was not tested as the plaster and infill crumbled while assembling the wall and could not be moved into the furnace.

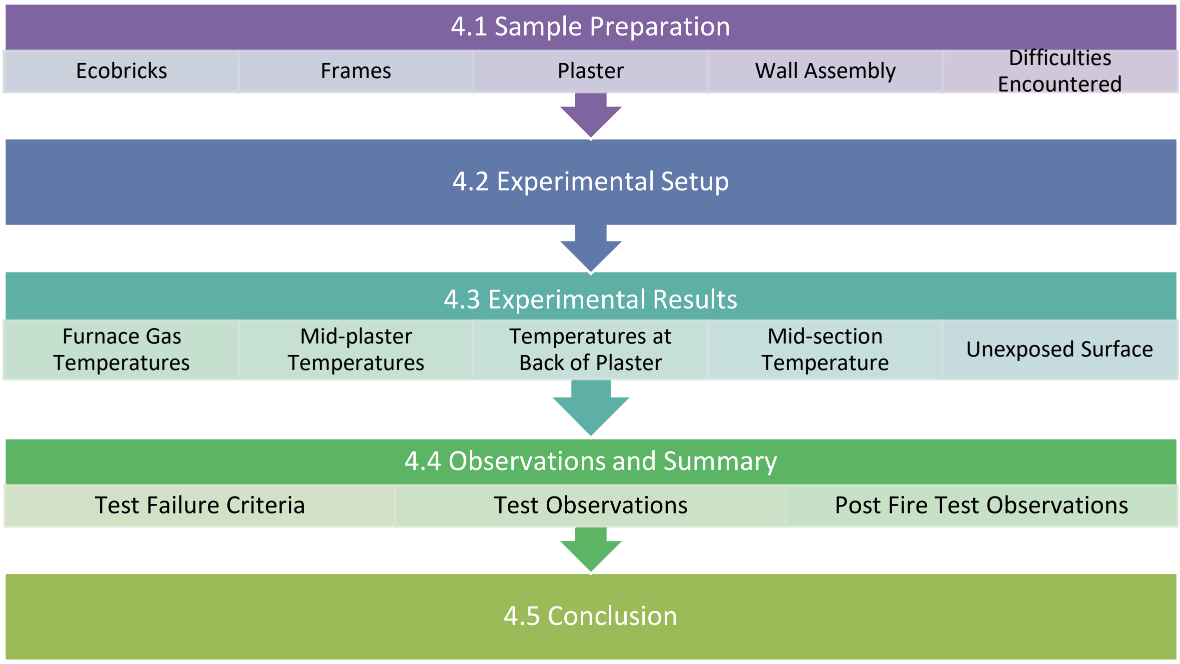


Figure 4-1: Flow diagram of chapter presentation

4.1 Sample Preparation

To represent a wall built from ecobricks, as would be done in a school or similar building, a team of volunteers, engineering vacation students and professionals contributed to build six wall samples, of which five were tested, of approximately 1 m^2 in area each. Having a variety of builders with different skill levels and building experience allows for the sample assembly to represent an actual build. The samples consisted of horizontal and vertical bottle orientation using a cob, cement, and lime plaster. Once the samples were built and instrumented, they were allowed to cure for at least 30 days. After the samples had cured, they were placed in a furnace and subjected to a burn test using a standard time-temperature fire curve.

The following sections discuss the elements which make up the wall samples such as the ecobricks, the frames which housed the wall samples and the plaster used to provide an insulative cover for the ecobricks. This is followed by the assembly process of the wall samples.

4.1.1 Ecobricks

The ecobricks used were provided by Waste-ED and Oceano Reddentes, non-profit organisations teaching people to be aware of their single use plastics usage through eco-bricking (the process of constructing with ecobricks). As mentioned in Section 3.2, the global ecobrick alliance recommends that a 2 litre ecobrick should weight 660 g. A total of 183 samples were obtained and weighed. The samples received had a range between 150 g and 700 g, and only 6% of the samples conformed to the global ecobrick alliance recommendations. It was decided due to the distribution, as seen in Figure 4-2, that the minimum allowable weight of a useable ecobrick would be 400 g. This increased the usable ecobricks to 65% and represented a more accurate representation of a real-world scenario.

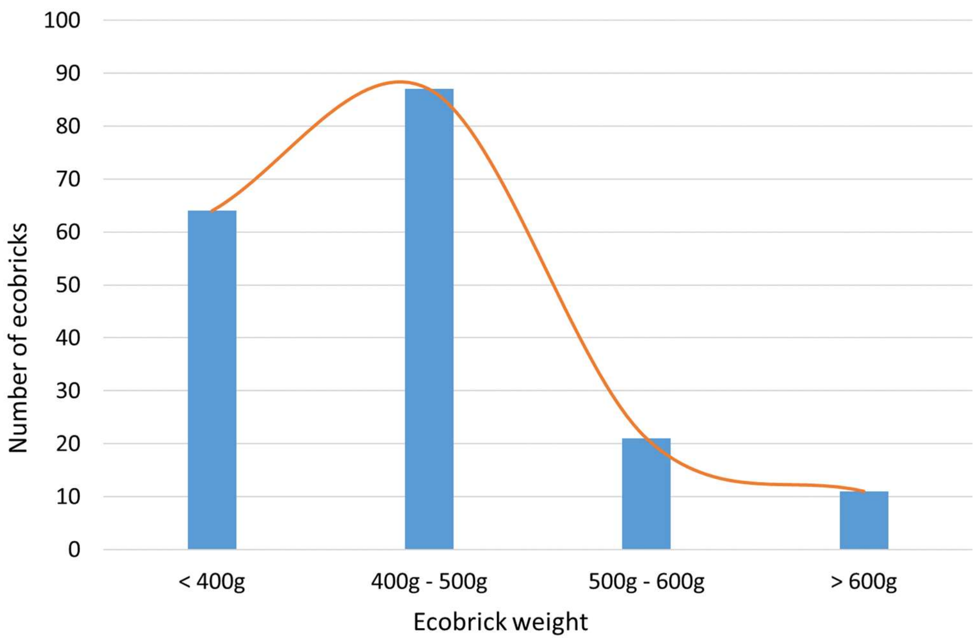


Figure 4-2: Sample weight distribution of ecobricks received from non-profit organisations used for constructing experimental setups. Samples below 400g were not used. (n = 183)

4.1.2 Frames

The experimental setup used is designed to represent a non-load bearing, ecobrick wall as mentioned in Section 3.3. Therefore, the frames used to house the samples are not designed to have any structural significance. The frames are only used to contain the sample structure during assembly and placement into the furnace. The exterior frames were built using 22 mm plywood. The horizontal and vertical orientation frames have an internal dimension of 1110 mm by 840 mm and 1330 mm by 830 mm respectively. The frames vary in size to be in increments of the bottle sizes according to their orientation. The frames have a depth of 375 mm and 185 mm. The 375 mm depth allows the horizontal orientation to have a 40 mm plaster layer beyond the 335 mm bottle height, on one side. Whereas the 185 mm depth on the vertical frame allows the wall sample to have a 40 mm plaster layer on both sides of the 105 mm diameter ecobrick. This aids in supporting the infill and keeping it centred in the wall sample. Additional timber diagonals were added as bracing to ensure that the frame remained square until it was placed and built into the furnace. The timber frames, as can be seen in Figure 4-3 and Figure 4-4, contain 51 horizontal and 32 vertical ecobricks respectively. The timber frame, of the vertical orientated ecobrick wall sample provides, a mounting surface for the wire mesh to be fixed to support the ecobricks during construction and provide attachment for the plaster.

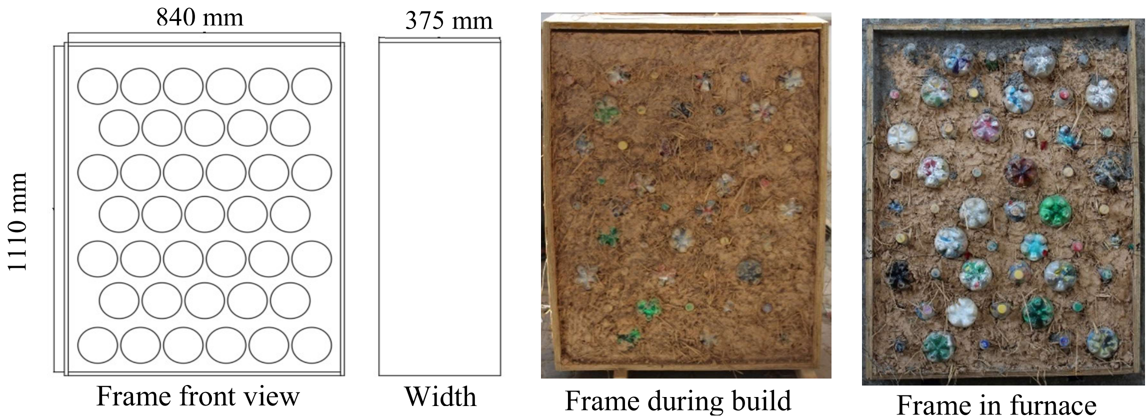
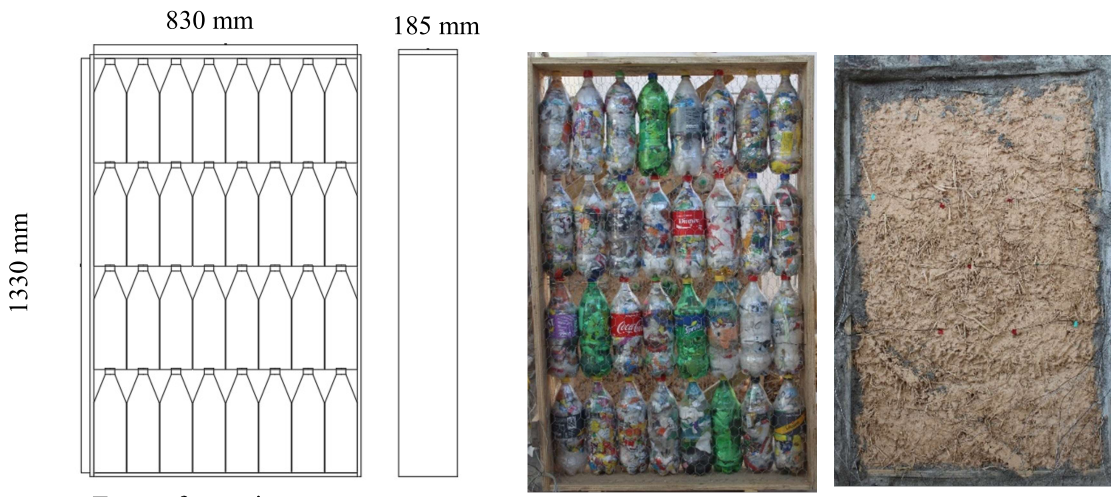


Figure 4-3: Horizontal orientation ecobrick frame



Frame front view Width Frame during build Frame in furnace

Figure 4-4: Vertical orientation ecobrick frame

4.1.3 Plaster

A large variety of different building materials exist that can be used as plaster to cover walls, such as the commonly used cement plaster and gypsum dry walling boards. Ecobrickers tend to build with more natural, and free, materials, such as cob. Figure 4-5 provides the details of the ratios used to mix the plasters of the wall samples.

Cob Ratio	Cement Plaster Ratio	Lime Plaster Ratio
• 2 parts Philippi sand • 2 parts clay soil • 1.5 parts water • 0.25 parts straw	• 1 part 42.5N cement • 7 parts Philippi sand • 2.8 parts water	• 1 part lime • 4 parts Philippi sand • 1 part water

Figure 4-5: Plaster mix ratios, by volume, used to plaster the wall samples

As discussed in Section 2.4.2, building with cob is a labour-intensive process as it is usually mixed by using one's feet on top of a tarpaulin. The ratio used to plaster the cob wall samples was 2:2:1.5 of sand, clay soil and water respectively. A few handfuls of straw, approximately 2 litres per 30 litres of sand were added to the infill cob, as well as the scratch coat (rough plaster coat, added before the final smooth plaster finish). The final plaster layer did not contain any straw. The consistency of cob varies significantly depending on how well it is mixed and the material proportions used, as neither are typically accurately controlled.

The cement plasters had a ratio of 1:7, cement to sand ratio. The cement used was a locally available 42.5 N grade. Lastly, the lime plaster had a ratio of 1:4, slaked lime to sand ratio. The cement and lime plasters were mixed in a wheelbarrow with a spade as this is the most common method used when building with ecobricks.

4.1.4 Wall Assembly

The wall samples were built as consistent as possible to ensure the best results. The main difference between the horizontal and vertical orientation samples is that the horizontal oriented wall samples had a cob wall infill and the vertical oriented samples were held together with wire mesh, but the infill stayed the same as the plaster. Below the building techniques of each are discussed.

4.1.4.1 Horizontal Orientation Ecobrick with Cob Plaster

Figure 4-6 illustrates the 7-step process which took place to build the cob horizontal wall sample. (1) The ecobricks were placed on top of a 30 mm layer of cob and were placed 30 mm apart whilst swapping the orientation of alternate ecobricks. (2) Another 30 mm layer of cob was placed in between the first layer and second layer of ecobricks. (3) The wall sample was built as described until the frame was filled, ensuring throughout that the layers had 30 mm of cob in between. This is essential as it gives a path for the loads to travel down. During the sample build, the cob was compacted to ensure that there were no voids. (4) and (5) shows a view of the completed cob horizontal wall sample. The infill of the sample was allowed to cure for 30 days before the 40mm plaster was added. (6) The scratch coat of cob is clearly visible with the straw showing. This coat provides the first 20mm of plaster over the ecobricks and the straw provides tensile strength, as well as providing an anchor for the final (7) plaster layer to adhere to. After assembly the plaster was allowed to cure for 14 days. Therefore, in total the sample cured for 44 days of which consisted of 30 days for the infill to cure and another 14 days for the plaster. The samples were allowed to cure in a well-ventilated warehouse structure during the summer months, in Cape Town. This meant that although they were in an enclosed and shaded area, the temperature during the day reached 34°C.

Figure 4-6: Assembling horizontal orientation ecobrick wall sample with cob plaster

4.1.4.2 Horizontal Orientation Ecobrick with Cement Plaster

The same process was followed as the horizontal orientation ecobrick with cob plaster, where the infill was constructed from cob and horizontal laying ecobricks, as was shown in steps (1) through (5) in Figure 4-6. The difference came when the wall sample was plastered. The plaster was applied in 2 layers of 20 mm each. Image (1) of Figure 4-7 shows the rough coat of 20mm, and (2) shows the final 40 mm layer. The 40 mm thickness of the plaster is ensured by floating the plaster to the edge of the frame. The first plaster layer was allowed to cure for 1 day before the final plaster was added. After which the completed sample was allowed to cure for 14 days.

Figure 4-7: Assembling horizontal orientation ecobrick wall sample with cement plaster

4.1.4.3 Horizontal Orientation Ecobrick with Lime Plaster

Similarly, as discussed above in Section 4.1.4.2, the lime plaster horizontal orientation ecobrick also uses the cob infill. The lime plaster was placed in the same manner as the cement plaster, with the first 20 mm layer curing for a day then adding a second 20 mm layer of plaster. After this time the samples were left to cure for a further 14 days.

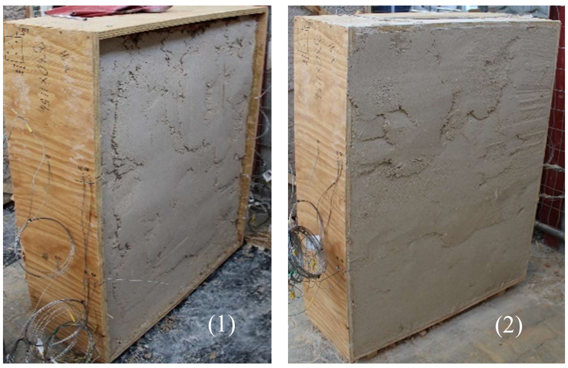


Figure 4-8: Assembling horizontal orientation ecobrick wall sample with lime plaster

4.1.4.4 Vertical Orientation Ecobrick with Cob Infill and Plaster

A similar process to the horizontal orientated samples was used to construct the walls with vertically orientated ecobricks, as shown in Figure 4-9. (1) To use vertically orientated ecobricks a chicken wire mesh was used to support the ecobricks. The mesh was secured to the frame by using either U-nails or staples. The wire mesh was placed as taut as possible. In (2) and (3) it is shown that once the frame was filled with ecobricks, the cob was added in between. To ensure that there is little to no voids in the cob infill, the cob was rolled into small, compacted balls and placed between the mesh. During this process the cob was compacted as much as possible. (4) The straw was visible to allow the plaster to adhere to. Once the frame was filled, it was allowed to cure for 30 days. (5) After the infill had cured, the 40 mm plaster layer was added. Throughout the assembly process, it was ensured that the ecobricks were centred in the wall sample. This ensured that on completion, the wall had a 40 mm plaster layer. The outer plaster cob does not contain any straw, but is only made up from clay, sand, and water, as advised by industry practitioners. The plaster was smoothed to the edge of the frame, thereby ensuring a minimum thickness of 40 mm.

Figure 4-9: Assembling vertical orientation ecobrick wall sample with cob plaster and infill

4.1.4.5 Vertical Orientation Ecobrick with Cement Infill and Plaster

The cement plaster was applied to the vertical orientated ecobrick wall sample. This method is commonly used in Guatemala by the Bottle School Project (Hug It Forward, 2013). Once the frame in Figure 4-10 (1) was assembled and the ecobricks were held in place by the wire mesh, (2) a cement plaster was applied by using a metal trowel from the bottom of the frame upwards. (3) While adding the plaster, it was made sure that there were little to no voids. (4) After covering the ecobricks with plaster the cement was allowed to cure for 30 days. (5) The final two plaster layers, of 20 mm each, were added on both sides of the sample, until the plaster reached the edge of the sample frame. The sample was allowed to cure for another 14 days before testing.

Figure 4-10: Assembling vertical orientation ecobrick wall sample with cement plaster and infill

4.1.4.6 Vertical Orientation Ecobrick with Lime Infill and Plaster

The lime plaster and infill wall sample were built in the same manner as the vertical orientated ecobrick cement sample, as well as the plaster was added to the wall with a trowel. As can be seen in Figure 4-11, the sample remained incomplete. This is discussed in more detail in Section 4.1.5.

Figure 4-11: Assembling vertical orientation ecobrick wall sample with lime plaster and infill

4.1.5 Difficulties Encountered

This section discusses the problems encountered during the assembling process with the cob and lime wall samples as well as how those problems were faced. Since these walls are commonly constructed in low-income communities with limited quality control mechanisms in place it is important to identify aspects that may hinder construction quality, or influence the characteristics of the final system attained.

4.1.5.1 Cob Plaster Shrinkage

During the assembling of the interior walls of the vertical and horizontal orientation ecobrick wall samples, there was minimal cracking while it cured for 30 days. Once the plaster was added, which had less or no straw in the mix, the plaster experienced significant cracking (1, 2, 4) and delamination (3) due to shrinkage as seen in Figure 4-12. This is due to the high temperatures encountered during the month of January and February in Cape Town, when the samples were built, as well as applying a moist plaster to a dried wall sample. This caused the plaster's moisture to be absorbed faster by the dry wall sample, which in turn caused the plaster to shrink causing the cracking.

To fix the damaged wall samples, the delaminated plaster was removed, and a new plaster layer was added. The new plaster was then wrapped in plastic to ensure that the drying was slowed. The samples which only had limited cracking, were repaired with a slurry form of plaster, and covered in plastic as well. The covered samples can be seen in Figure 4-13. When constructing homes, it may not be possible to wrap walls to prevent shrinkage so care will be required regarding when items are constructed (i.e. ambient conditions) and possibly mix design / materials may influence the amount of shrinkage that occurs.

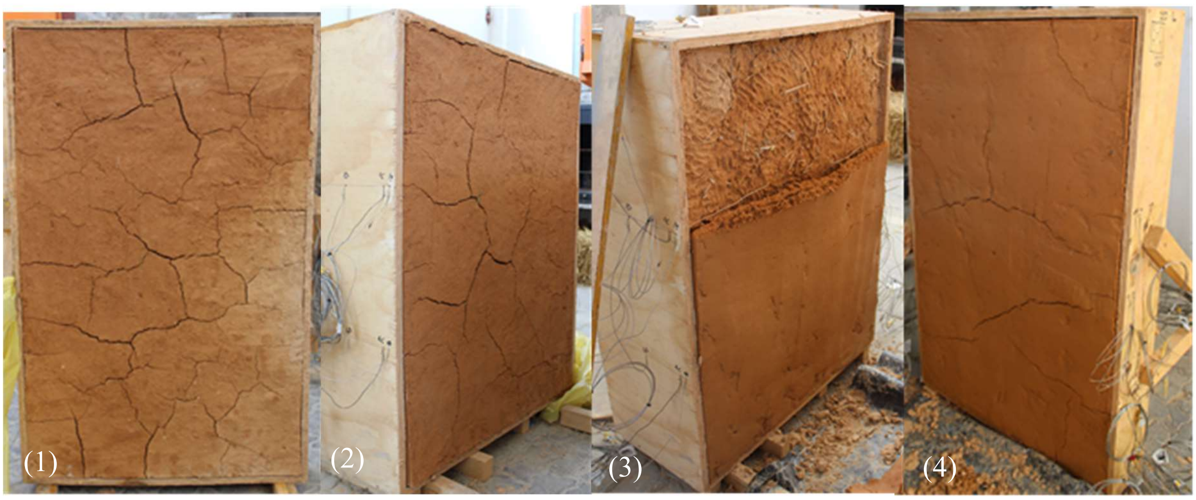


Figure 4-12: Problems encountered during the wall sample assembling process showing the result of cob plaster shrinking which caused cracking and delamination

Figure 4-13: Solution to the cob shrinking too fast, by covering the plaster with plastic to slow the drying process

4.1.5.2 Non-bonding Lime

It is common practice for building materials to be donated to non-profit organisations to be used to build ecobrick structures. These materials are usually not stored under proper conditions and might be aged, causing them to lose most of their structural properties. This was the case with the lime used for the experiment. The lime plaster failed to adhere and remain within the frame. The vertical sample was not completed due to the lime plaster crumbling and, thus, the sample could not be used to test. Any movement of the vertical sample caused delamination of the lime plaster. The horizontal sample held its shape due to the cob interior providing structural stability for the plaster.

The plaster on the horizontal orientated ecobrick wall had to be replaced 3 times before it adhered to the cob interior. Adhesion was achieved by first adding a slurry made from the lime plaster and then adding the lime plaster mix over it. The slurry acted as an adhesive between the cob and lime plaster.

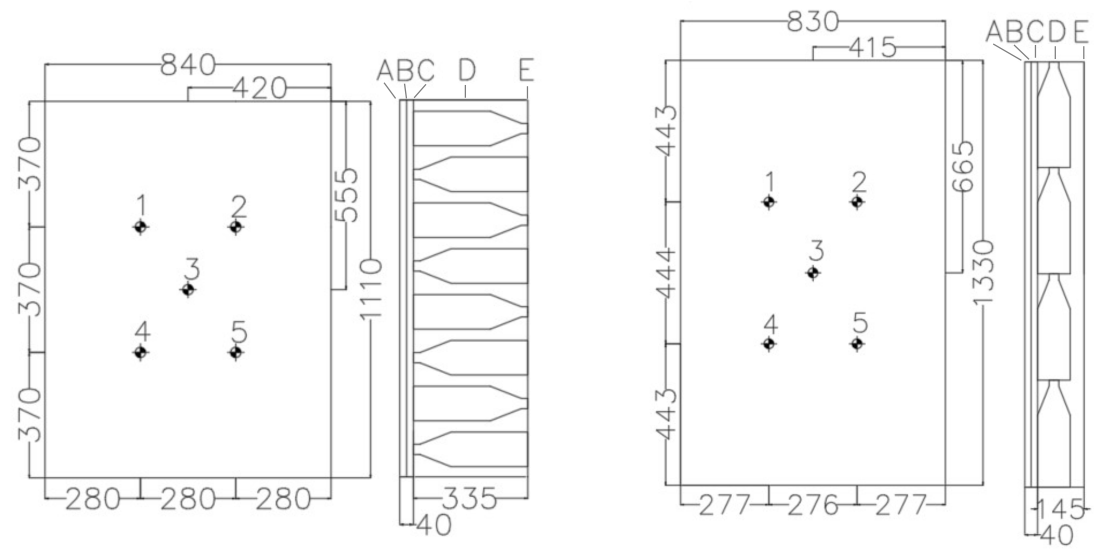
After the vertical ecobrick orientated wall sample with the lime infill and plaster had collapsed multiple times, it was decided to use the horizontal orientated ecobrick sample only as it provided insight as to what may happen when poorly constructed ecobrick walls are used. The vertical orientated ecobrick wall with lime infill and plaster was not reconstructed as it was felt that the number of samples tested was sufficient.

4.2 Experimental Setup

The samples were all tested in a standard test furnace complying with SANS 10177-2 with the ISO 834 standard time-temperature curve being used. The temperatures inside the wall samples were measured with 1.5 mm Type K thermocouples which was logged by a Keysight datalogger. The thermocouples were placed in 5 positions at 5 different depths. The depths were at the surface (position A at 0 mm) mid-way through the plaster (position B at 20 mm) at the back of the plaster (position C at 40 mm) mid-way through the section (position D at 113 mm and 208 mm for the vertical and horizontal respectively) as well at the back of the sample (position E). Figure 4-14 illustrates the positions and depths of the thermocouple placement as well as shown in Table 4-1.

Table 4-1: Thermocouple depths in the ecobrick wall samples

Label	A	B	C	D	E
Depth from surface: Vertical Orientated Ecobrick	0 mm	20 mm	40mm	112.5 mm	185 mm
Depth from surface: Horizontal Orientated Ecobrick	0 mm	20 mm	40 mm	207.5 mm	375 mm



Horizontal Orientated Ecobrick

Vertical Orientated Ecobrick

Figure 4-14: Thermocouple placement on the horizontal and vertical orientation ecobrick samples

Figure 4-15 shows how the thermocouples were placed during the assembly process. To ensure that the thermocouples were placed at the correct depths, holes were drilled into the frames to the depths from the front face of the frame. The thermocouples were then placed through the holes and the correct distance from the edge was measured to ensure that the thermocouple was at the correct depth and position. The next layer of plaster was then placed over the thermocouple. Care was taken to ensure that thermocouples were not moved. However, when the plaster was repaired due to delamination it was difficult to ensure 100% accuracy.

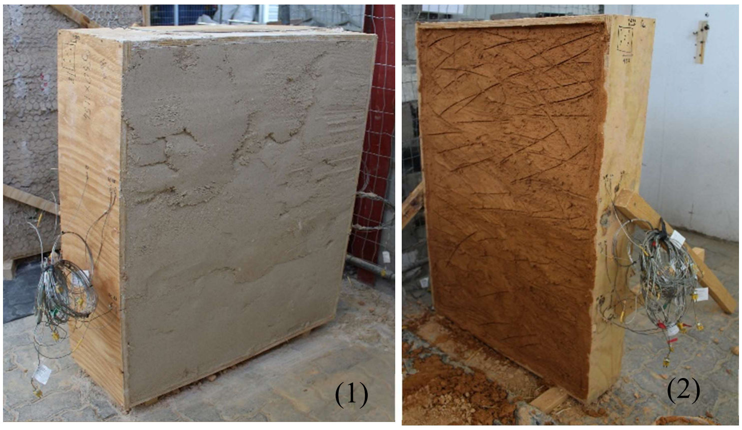


Figure 4-15: Thermocouple placement in ecobrick wall samples during assembly. Thermocouple cables are seen on the left of (1) and right of (2).

In each furnace test two samples were installed, the horizontal orientated and vertical orientated ecobrick samples. They were built into a furnace of 1.1 m x 2.6 m x 2.6 m. The furnace had 2 burners which followed the standard time-temperature curve shown in Figure 4-17. The furnace works on a feedback system to assist with maintaining the time-temperature curve. The plate thermocouples used in the furnace feedback system are shown in
Figure 4-16 (2). This means that even if the ecobricks contributed significantly to the fuel load, it would not have influenced the time-temperature curve as the burners reduce their output to compensate accordingly. Therefore, the heat release rate contribution of the bricks cannot be directly studied in this work and requires future research.

Figure 4-16: (Left) Exterior furnace setup with monitoring system shown and (Right) plate thermocouples inside the furnace

4.3 Experimental Results

4.3.1 Overview

After the samples were allowed to cure, they were all tested, with the exception of the vertical lime orientated ecobrick sample which was not stable enough to be placed in the furnace without cracking. The following section discusses the results and compares them to critical temperature limits.

4.3.2 Definition of Failure

The plastic temperature limits are the criteria by which the back of the plaster of the wall samples are evaluated to ensure that the bottles and lids of the ecobricks do not melt. The limits have been established in this work as a means of trying to quantify failure. Failure criteria are typically based upon a specific temperature on the *unexposed surface* being reached. However, since flammable materials are housed within the walls more conservative criteria have been identified to try ensure that ecobricks do not melt or are ignited. As will be discussed later in this work, once ecobricks ignite they become a significant safety hazard, and this must be avoided. It should be noted that the properties of ecobricks will vary significantly, and almost any type of plastic could potentially be used, meaning that lower bound values are more suitable.

The melting temperature of a HDPE lid and a PET bottle are 130 °C and 260 °C respectively as shown in Table 4-2. The table includes the standard insulation criteria of an average surface temperature of 160 °C and a maximum temperature at any point of 200 °C. HDPE is a common plastic used for bottle lids, and PET, plastic used for most bottles, as well as an average ignition temperature. Due to both its widespread usage, and its low melting temperature, the failure criteria of ecobricks will be assumed to be when the front of the ecobricks (fire exposed side) experiences a temperature of 130 °C. Hence, the back of plaster (i.e. 40 mm into the sample) temperature will be most critical, although the mid-plaster depth (i.e. 20 mm into the sample) temperature will also be considered. If a different failure criterion is used a number of the calculated failure times provided below will change accordingly.

Table 4-2: Failure criteria temperatures used to assess the ecobrick wall samples. The HDPE melting temperature is highlighted as it is the threshold of the failure criteria.

Criteria	Temperature
Average Plastic Ignition Temperature	360 °C
PET Melting Temperature	260 °C
Standard Fire Insulation Criteria Maximum	200 °C
Standard Fire Insulation Criteria Average	160 °C
HDPE Melting Temperature	**130 °C**

4.3.3 Furnace Gas Temperatures

Thermocouples were placed against the surface of each wall sample to measure the gas temperature during the tests. The gas temperatures near the surface of each wall sample and the standard time-temperature curve with its allowable tolerances are shown in Figure 4-17.

The furnace control algorithm adjusted the burners to follow the time-temperature curve as best as possible. It can be seen in Figure 4-17 that the cob samples gas temperature (blue lines) dipped slightly below the lower tolerance at 4 minutes, although this is likely to have had negligible influence on the results. Whereas the lime sample's gas temperature (grey line) struggled to be maintained within the upper tolerance and fluctuated substantially. The fluctuation was caused by a fuel error with the one burner, and therefore the single burner was not able to maintain a steady temperature. The furnace with the cement sample test was able to follow the time-temperature curve well.

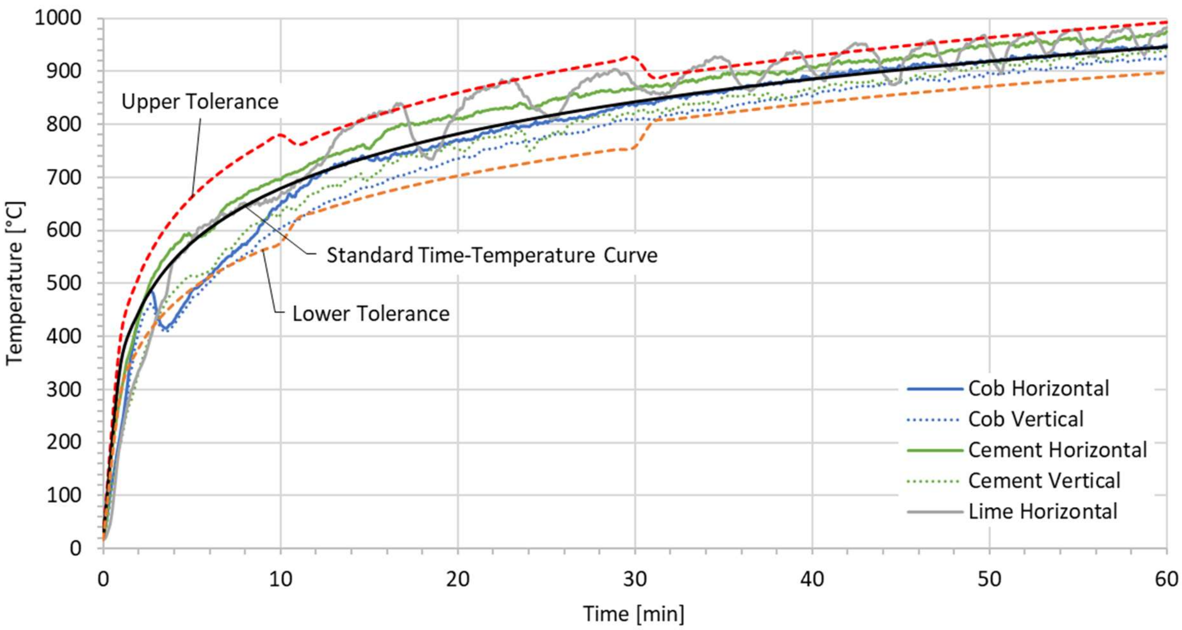


Figure 4-17: Time-temperature graph showing experimental temperature of the furnace gases against the sample surface during testing

4.3.4 Mid-plaster Temperatures

As shown in Figure 4-18, all of the test sample temperatures in the middle of the fire exposed plaster layers exceed the HDPE melting temperature of 130 °C within 20 minutes. All the tests besides the cement horizontal orientated ecobrick wall sample surpass the average plastic ignition temperature of 360 °C before 30 minutes. The only mid-plaster temperature which is below the average plastic ignition temperature is the cement horizontal orientated ecobrick wall sample. This highlights that significantly more than 20 mm of plaster is required to protect ecobrick walls for fire exposure times of 30 minutes or more.

During the testing, delamination was seen on the vertical orientated ecobrick wall sample with cement plaster, as discussed in Section 4.4. The temperature increased as the plaster delaminated from the sample. This is clearly seen in the graph in Figure 4-18 at 24 min and at 48 min.

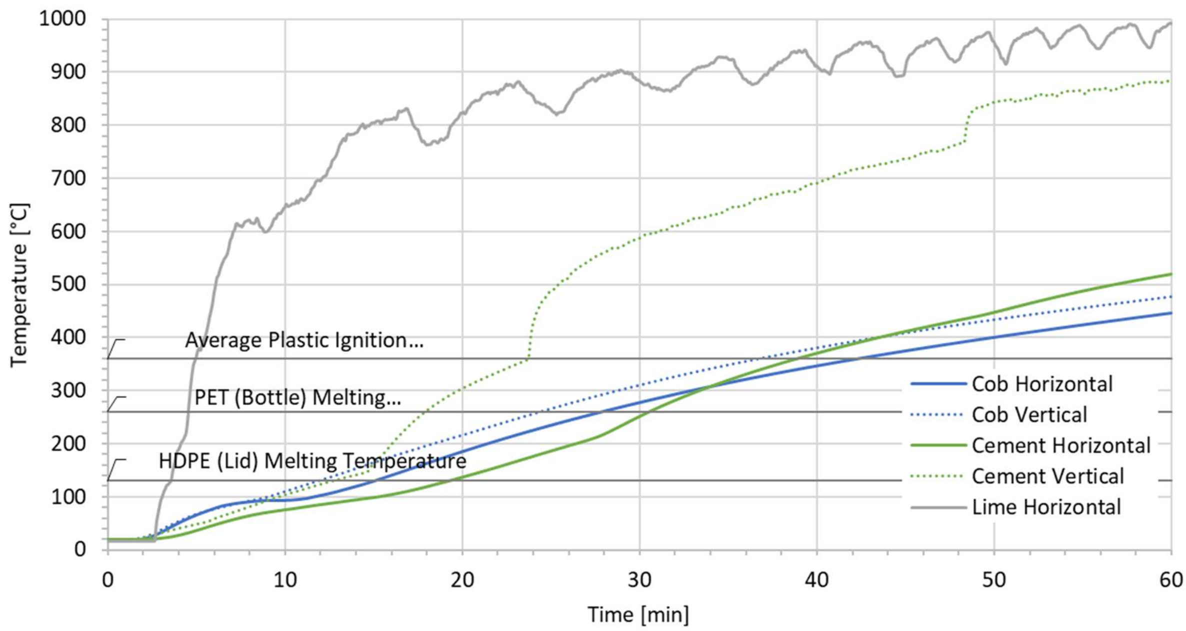


Figure 4-18: Time-temperature graph showing experimental temperature in the middle of the plaster at 20 mm during testing

As explained in Sections 4.1.4.3 and 4.1.4.6 the lime plaster was problematic. Besides the fluctuations, caused by the furnace burners during the experiment, the graph in Figure 4-18 showed the significant temperature increase at 3 min which is explained by the plaster delaminating. Figure 4-19 shows a photo of the lime plaster before the testing had started (left) and the lime plaster which started delaminating after a few minutes into the test (right). This phenomenon is also highlighted by the sudden increase in temperature at the back of the 40 mm plaster layer in Figure 4-20 as well as the second plaster layer delaminating at approximately 12 minutes. After the temperature increase, in the lime sample graphs, the thermocouples record a similar temperature to the gas temperature, confirming that the plaster had delaminated.

Figure 4-19: (Left) Lime plaster before testing and (Right) delaminating within 3 minutes

4.3.5 Temperatures at the Back of Plaster

As discussed above, temperatures at the back of the fire exposed plaster layer, 40 mm into samples, are critical as they influence whether ecobricks will melt or ignite. Figure 4-20 presents the temperatures that were recorded during experiments. The horizontally orientated ecobrick wall samples, which were built into cob, performed better than the vertically orientated ecobrick wall samples. The solid blue and green lines in Figure 4-20 show that the horizontal orientation, with cob and cement plaster respectively, kept the back of plaster temperature below the melting point of the HDPE at 30 minutes. While the vertically orientated ecobrick cob plaster wall provided a temperature below the PET melting point at 30 minutes and did not reach the ignition temperature at 30 minutes. Unfortunately, the vertically orientated ecobrick cement plaster wall did not fair nearly as well as the cob did. It exceeded the HDPE melting temperature at 16 minutes and reached ignition temperature by 27 minutes. The temperature increase, as shown in Figure 4-18, at 24 min is also visible in the graph of Figure 4-20.

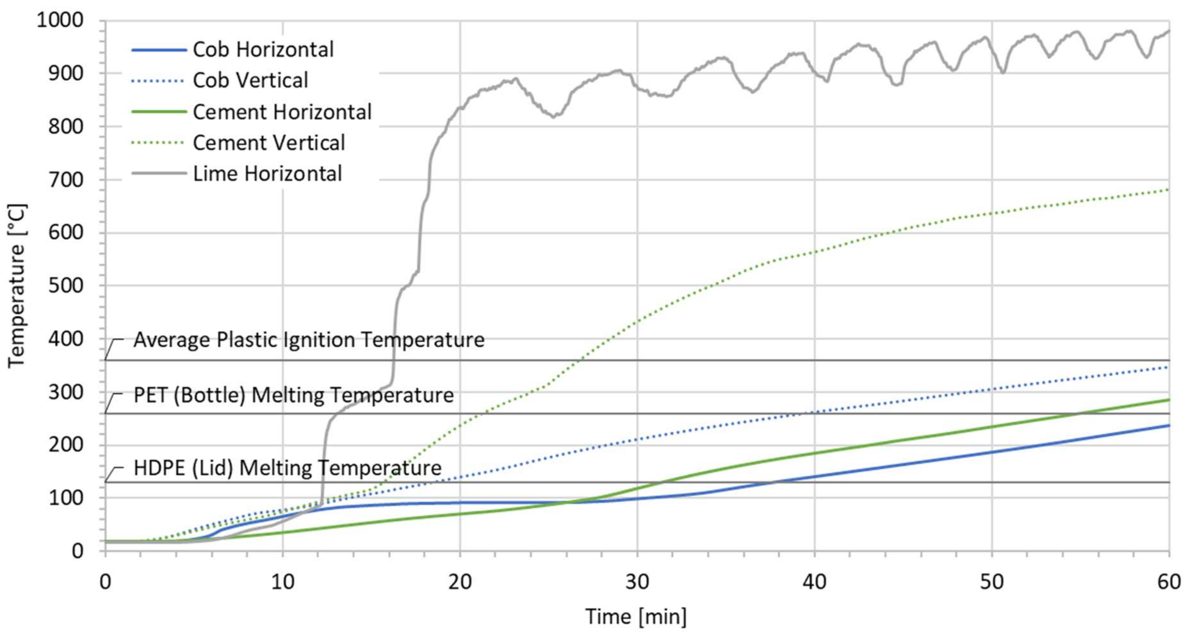


Figure 4-20: Time-temperature graph showing experimental temperature at the back of 40 mm plaster during testing

4.3.6 Mid-section Temperatures

The mid-way point of the wall was determined without considering the plaster thickness, these widths are 167.5 mm and 72.5 mm for the horizontal and vertical orientated ecobrick walls respectively. As shown in Table 4-1, the depth to the mid-way point including the plaster thickness is 207.5 mm and 112.5 mm respectively.

The temperatures in the mid-section are shown in Figure 4-21 alongside standard fire insulation criteria of a 160 °C as an average and 200 °C as a maximum temperature difference assuming the ambient temperature is 20 °C (SABS, 2005). Figure 4-21 illustrates that the average temperature of each wall sample remained below 160 °C, with the exception of the cement vertical.

The larger surface area between the plaster and ecobricks, in the horizontal orientated ecobrick wall, act as a heatsink conducting energy into the samples. Rather than having a wall of low conductivity, as in the vertical orientated ecobrick sample that provides an insulating layer and led to increased temperatures in the wall.

The cement vertical mid-section temperature went above the insulation criteria average at 56 minutes. The sudden spike indicates there could have been a crack which opened and was resealed by a melting ecobrick.

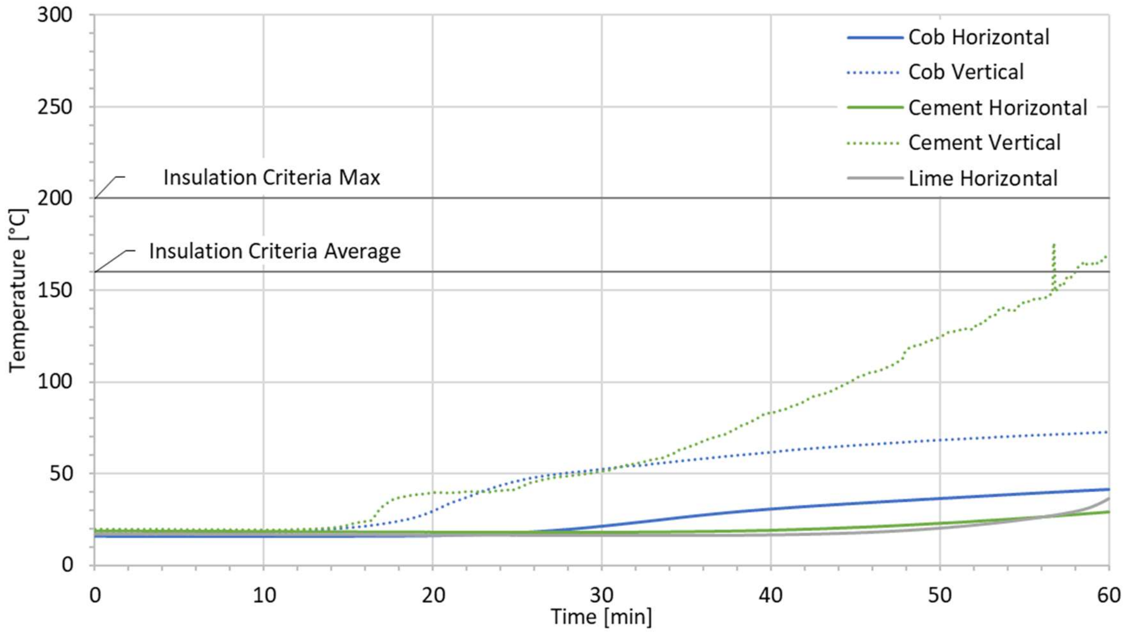


Figure 4-21: Time-temperature graph showing experimental temperature mid-section of the wall samples during testing (Note: The scale on the graph has been adjusted to a max of 300 °C)

4.3.7 Unexposed Surface

For walling systems, the temperatures on the unexposed face typically governs the insulation resistance. The gas temperatures of the unexposed surface are measured with thermocouples and the surface temperatures was measured with a thermal imaging camera. The following section discusses the results.

4.3.7.1 Gas Temperatures

The gas temperatures measured at the unexposed surface of the wall samples can be seen below in Figure 4-22. It is clear that the type of plaster does not significantly affect the unexposed temperature of the horizontal samples. The gas temperature remains fairly constant during the tests. The only significant change in gas temperature is after 50 minutes during the lime plaster horizontal test where the gas temperature starts to rise due to the lime plaster crumbling and falling off.

The gas temperatures of the vertical samples started to increase from 22 minutes onwards and exceeded 50 °C by 60 minutes. This was to be expected due to the fact that the vertical samples width is approximately one third of the thickness of the horizontal samples. Furthermore, ecobricks in the vertical samples burnt during the tests, as will be shown below, and this is likely to have contributed to the temperature rise in samples.

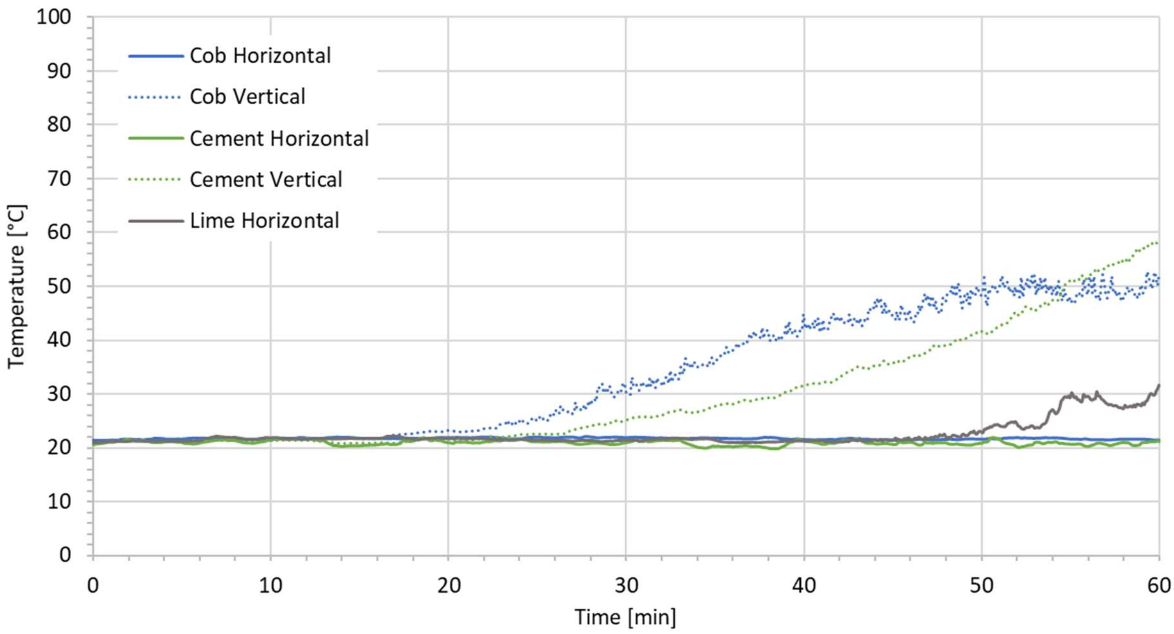


Figure 4-22: Time-temperature graph showing experimental temperature of the unexposed surface gases during testing (Note: The scale on the graph has been adjusted to a max of 100 °C)

Comparing the data from the thermocouples to the thermal imaging camera data, as presented below in Figure 4-23, it is clear that there is a noteworthy discrepancy between the two data sets. This is due to the fact that there were only 5 thermocouples used to measure the gas temperature thus, the resolution of the surface temperature over the unexposed surface is very low. Also, the thermocouples are not able to detect rapid spikes in temperature whereas the thermal imaging camera was able to do this. The next section will use thermal images to illustrate the unexposed surface temperatures more accurately and show how samples failed.

4.3.7.2 Surface Temperatures based on Thermal Images

A thermal imaging camera was used as a secondary temperature logging device. As the emissivity of the cob is not accurately known, and can change with temperature, recorded temperatures are not highly accurate, although general trends and approximate values measured are very important. The initial temperature measured before the tests started showed good correlation with ambient conditions.

In the case of the cob plaster test, as shown in Figure 4-23, the furnace had a false start which led to the sample being pre-heated, which also resulted in the ecobricks in Figure 4-23 (2) being warmer than the ambient temperature. The test started at 11:20 (Figure 4-23 (2)). At the 30-minute mark (Figure 4-23 (4)), the temperature increased significantly in parts of the vertical wall sample. As shown in Figure 4-23 (4) the surface temperature reached 84.8 °C. This is still below the average insulation criteria of 160 °C.

As shown in Figure 4-23 (3) soot started to form above the vertical frame near the concentration of heat on the unexposed surface. During the last 30 minutes of the test the maximum surface temperature of the vertical wall sample did not increase, but the average temperature increased as the heat spread across the surface. The horizontal sample had significant heat increases near the edges of the wall sample initially. This was to be expected as the wood frame was not insulated from the furnace. The heat spread gradually from the frame to two of the ecobricks in the left top corner.

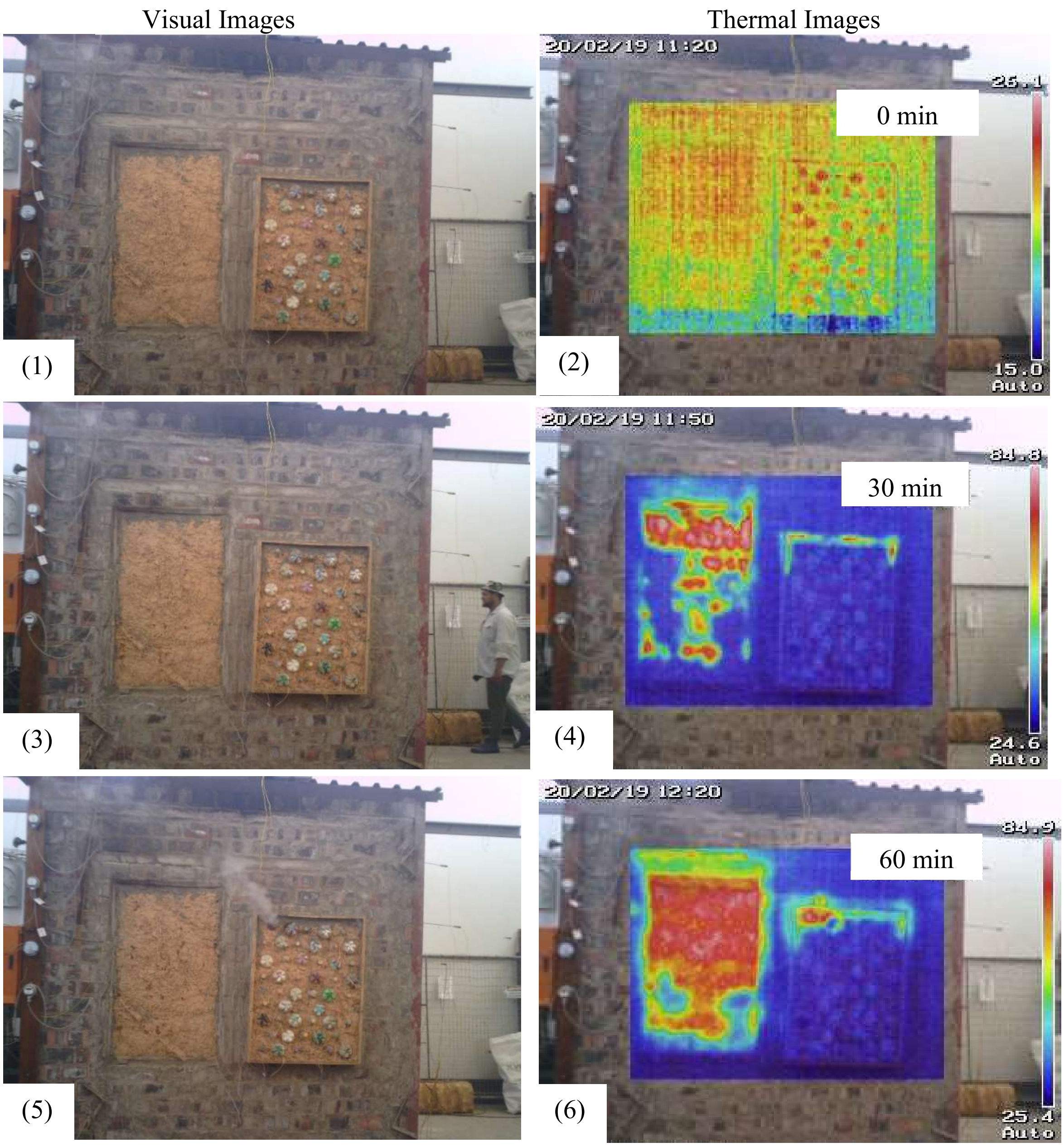


Figure 4-23: Horizontal and vertical orientation ecobrick wall samples with cob plaster. The left images are the visible image of the right overlaid thermal image. (Note: The temperature scale varies in each to show the maximum temperature in that specific image)

As with the cob test, the cement plaster test results are similar when comparing the vertical and horizontal samples. The cement test is shown in Figure 4-24. After 30 minutes, as shown in Figure 4-24 (4), the vertical sample shows a single point of failure that subsequently reached 167 °C. Smoke was released as the ecobricks started to burn. At 30 minutes the horizontal sample's frame started to fail but the sample stayed intact as shown in Figure 4-24 (4).

After 60 minutes it is clear that the vertical sample was severely compromised, as the surface temperature has reached 600 °C. Flames were visible as can be seen in Figure 4-24 (6) indicating that the ecobricks had been set alight. The horizontal sample did not show any signs of ignition. The ecobricks created voids in the samples due to the plastic starting to shrink and melt as the temperature increased. This in turn contributed to the release of a noticeable amount of smoke.

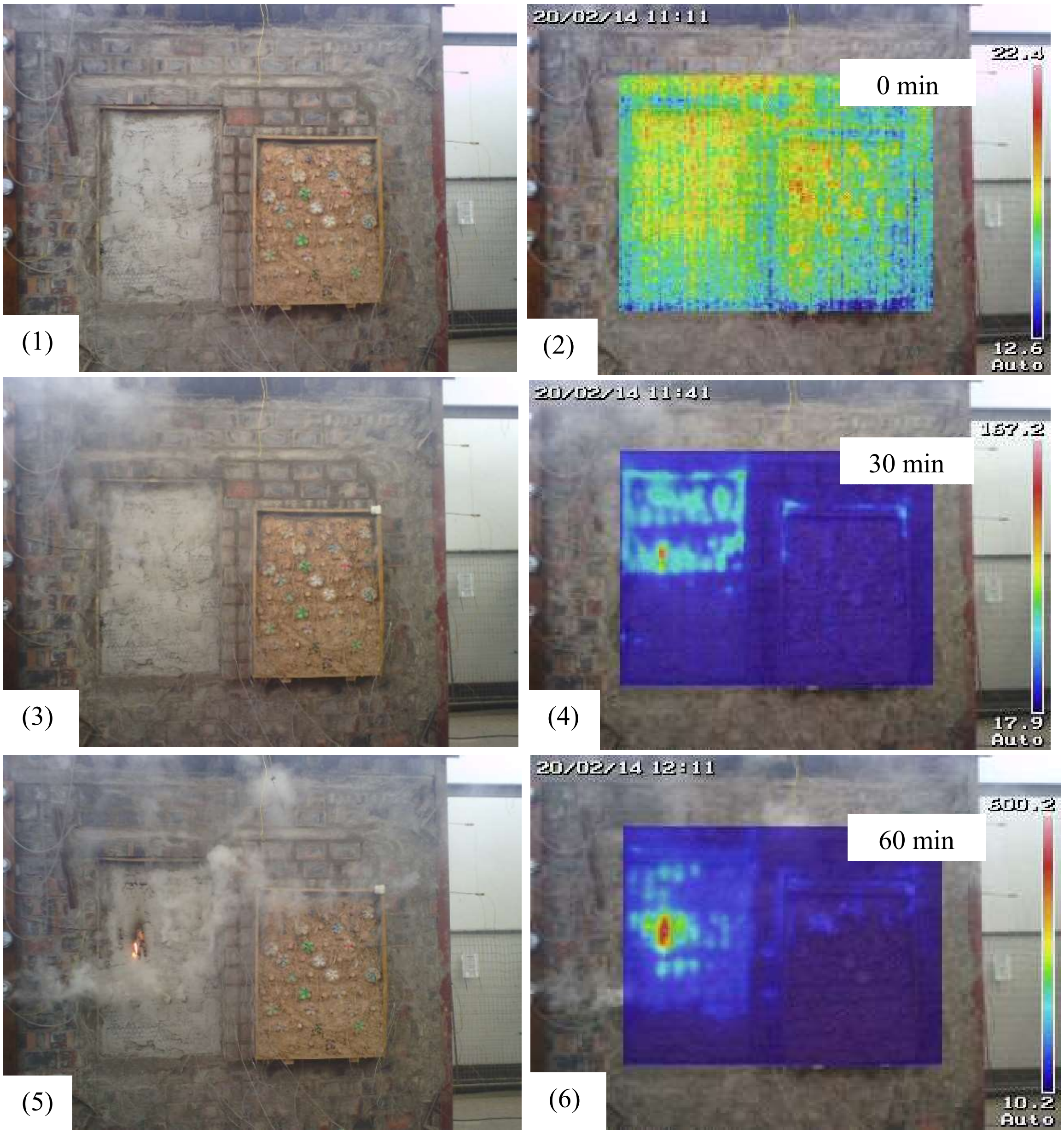


Figure 4-24: Horizontal and vertical orientation ecobrick wall samples with cement plaster. The left images are the visible image of the right overlaid thermal image. (Note: The temperature scale varies in each to show the maximum temperature in that specific image)

The poorest performing sample was the lime plaster horizontal sample. The thermal images for the test can be seen below in Figure 4-25. This figure shows the possibility of what could happen during a fire in a poorly constructed ecobrick structure. The initial temperature was approximately 26 ℃. In Figure 4-25 (3) and (4), it shows that an ecobrick was releasing a large amount of smoke and had increased in temperature after 30 minutes. Towards the end of the test, due to the plaster delaminating, a few of the ecobricks has caught alight as can be seen in Figure 4-25 (5) and (6). The burning ecobrick caused the timber bracing to ignite, which in turn ignited the melting plastic dripping down the unexposed side of the wall sample. At 60 minutes the temperature reached 905 ℃ which is close to the furnace gas temperature at that time. The sample exceeds all temperatures including failing the insulation and integrity criteria.

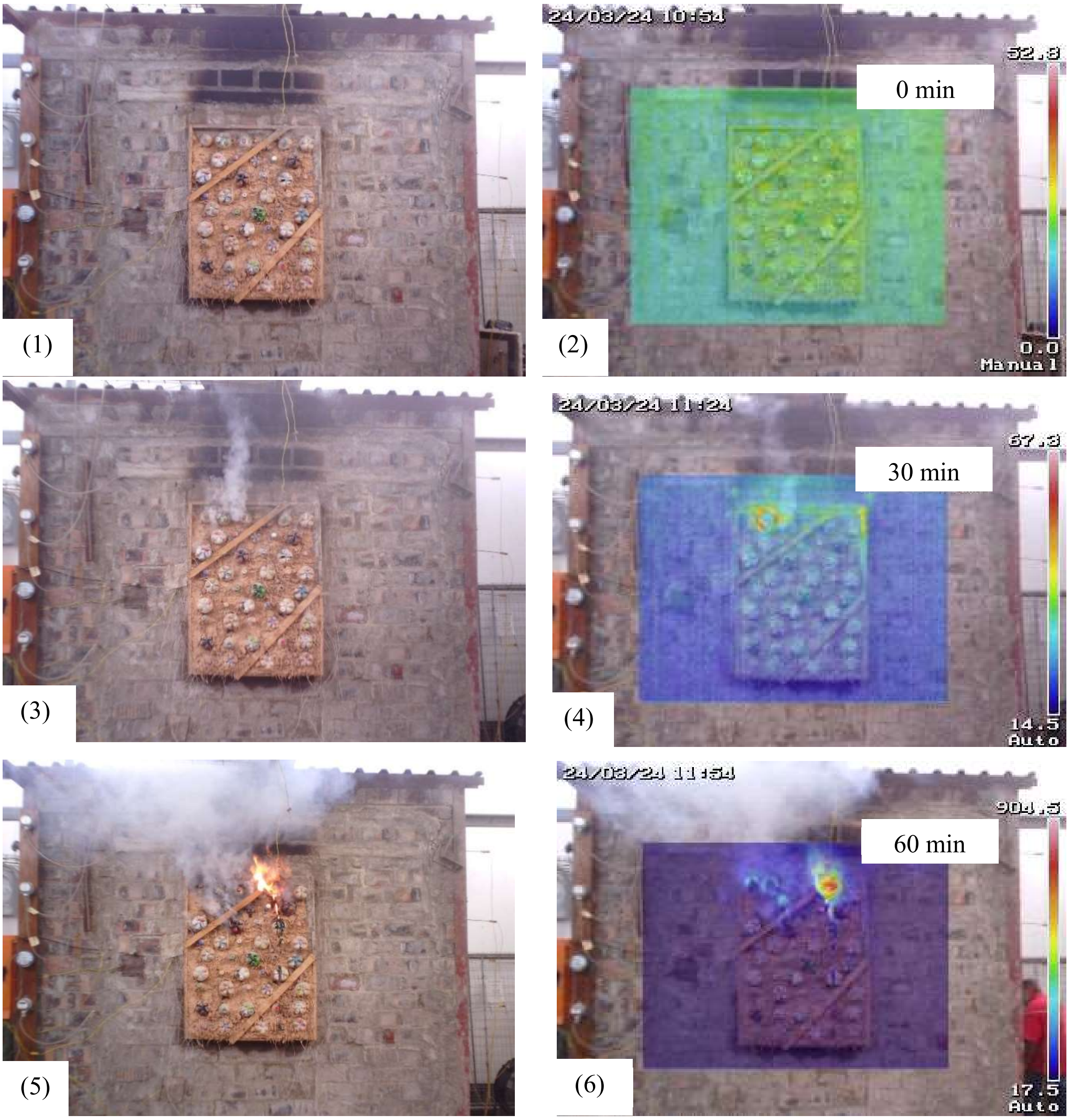


Figure 4-25: Horizontal orientation ecobrick wall sample with lime plaster. The left images are the visible image of the right overlaid thermal image. (Note: The temperature scale varies in each to show the maximum temperature in that specific image)

4.4 Observations and Summary

The results from the experimental tests in Section 4.3 varied greatly amongst the wall samples. Some walls, such as the horizontal orientated ecobrick sample with cob or cement performed well while another sample was not even tested due to poor building. The following section serves as a summary of the experimental results as well as includes the observations made during the testing.

4.4.1 Test Failure Criteria

The plastic melting failure criteria used to analyse the experimental results was considered to ensure that the ecobricks do not contribute to the fuel load of the building, as shown in Table 4-3. It is also specified to meet the insulation and integrity criteria of SANS 10177-2, as shown in Table 4-4. In the section that follows a number of failure criteria are considered to try quantify the fire resistance of the samples using different metrics, such that ultimately a single fire resistance rating could be assigned to them.

Table 4-3 has two levels of criteria. The first criteria looks at the temperature at which the lid, usually made from HDPE, and the bottle, usually made from PET, melt at. These temperatures are 130 °C and 260 °C respectively, as discussed above. The second criteria is an average plastic ignition temperature of 360 °C. The temperatures were measured with 1.5 mm thermocouples, at five positions, at the back of the 40 mm plaster layers against the ecobricks. To simplify Table 4-3, the time taken to reach the different criteria temperatures are colour coded to indicate if the temperature was reached in less than 30 min, between 30 min and 60 min or above 60 min. These are shown in red, yellow and green respectively.

Table 4-3: Experimental time taken to reach critical plastic temperatures at the back of the plaster at 40 mm against the ecobricks. Green, yellow and red cells indicate fire resistance ratings of above 60 minutes, below 60 minutes and below 30 minutes respectively.

	Cob Plaster		Cement Plaster		Lime Plaster
	Horizontal	Vertical	Horizontal	Vertical	Horizontal
HDPE Lid Melting Temperature Reached 130 °C	37.7 min	18.5 min	31.4 min	15.7 min	12.3 min
PET Bottle Melting Temperature Reached 260 °C	64.6 min	39.6 min	55.1 min	21.3 min	13.2 min
Plastic Ignition Temperature Reached 360 °C	90.9 min	63.8 min	> 72 min	26.7 min	16.3 min

The failure criteria of smoke emissions from bottles, based on the melting of the lids, will be affected by the nature of the wall construction. In the current work the horizontal ecobricks do not have an outer plaster layer, which allowed for smoke emissions to be identified. As ecobricks contract at elevated temperatures a pathway to the unexposed face is readily available for smoke movement. However, if a back plaster layer was to be added it may contain the smoke within the wall cavity and prevent emissions on the unexposed face of the wall. This requires further research. If this was to be done, and smoke emissions prevented, the higher fire resistance ratings excluding smoke emissions, as discussed in Section 4.4.2 below, could be adopted.

For the ecobrick lids to reach melting temperatures causes two different phenomena to occur, which is either the plastic melts or the plastic initially shrinks. Either phenomenon may influence convection, conduction and radiation of the wall samples. Not all the effects are yet understood or known, but a few observations were made during and after the testing.

4.4.2 Test Observations

When the plastics shrinks, it causes a void in the wall sample, as shown in Figure 4-26 (Right) where (Left) is the same image before the testing started. This void allows for the ecobrick to be exposed directly to the gas temperatures, if cracks have developed in the front plaster, thereby not being insulated by the wall infill material, such as cob or cement.

Figure 4-26: Shrinkage of the bottle visible on the unexposed side of the wall sample, (Left) before testing started, (Right) during testing.

Ignited and melting plastic is a problem which may occur, as can be seen in Figure 4-27. The horizontally orientated ecobrick lime plaster wall sample was an example of an ecobrick wall with a poor plaster. As the plaster was poorly made, it led to the exposed plaster delaminating. This in turn exposed the ecobrick directly to the gas temperatures of the furnace which caused the ecobrick to ignite and melt. The melting plastic was dripping down the wall and eventually onto the floor, and this could ignite other flammable materials.

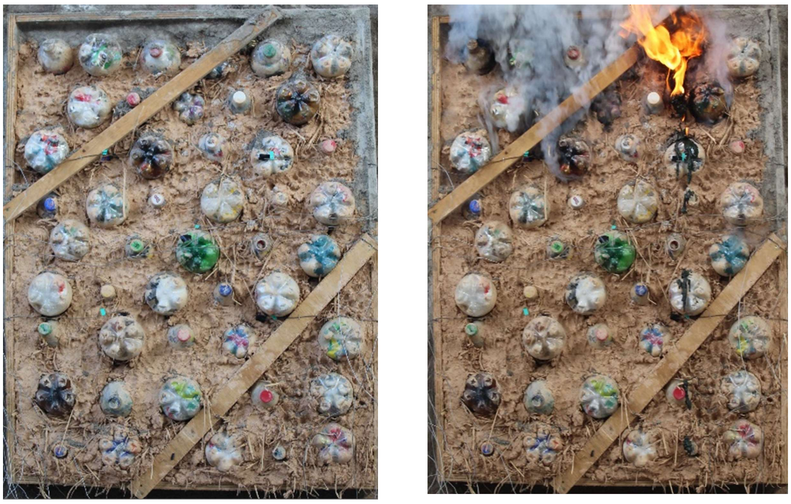


Figure 4-27: Horizontal cob test showing (Left) sample before testing started and (Right) behaviour during testing highlighting plastic which is dripping and ignited, visible on the unexposed side of the wall sample

Figure 4-27 (2) illustrates the possibility of the wall failing the integrity requirement of preventing the spread of flames from one compartment to another. Table 4-4 summarises the time at which the samples failed to meet these criteria. The Table 4-4 includes when insulation criteria of the average and maximum surface temperature remaining below 160 °C and 200 °C respectively are exceeded, as well as other visible events. These events include visible smoke, flaming and melted plastic dripping. The analysis is based on thermal and visual images from the thermal imaging camera. From the criteria mentioned above, in Table 4-4, an estimated fire resistance time is given to each sample based on the minimum time it took to fail a criterion.

Table 4-4: Time for critical temperatures to be reached based on thermal images, and visible events on the unexposed side of the test sample. Green, yellow and red cells indicate fire resistance ratings of above 60 minutes, below 60 minutes and below 30 minutes respectively

	Cob Plaster		Cement Plaster		Lime Plaster
	Horizontal	Vertical	Horizontal	Vertical	Horizontal
HDPE Lid Melting Temperature Reached 130 °C	37.7 min	18.5 min	31.4 min	15.7 min	12.3 min
PET Bottle Melting Temperature Reached 260 °C	64.6 min	39.6 min	55.1 min	21.3 min	13.2 min
Plastic Ignition Temperature Reached 360 °C	90.9 min	63.8 min	> 72 min	26.7 min	16.3 min
Insulation Criteria Average 160 °C	90 min	90 min	-	30 min	35 min
Insulation Criteria Maximum 200 °C	95 min	95 min	-	33 min	36 min
Smoke Visible	35 min	-	44 min	27 min	9 min
Large Quantities of Smoke	98 min	-	-	33 min	31 min
Flaming Occurred	-	-	-	56 min	51 min
Plastic Dripping	-	-	-	-	51 min
Furnace Run Time	122 min	122 min	66 min	66 min	60 min
Estimated Fire Resistance excl. smoke production	**60 min**	**60 min**	**30 min**	**None**	**None**
Estimated Fire Resistance incl. smoke production	**30 min**	**None**	**30 min**	**None**	**None**

In the different experiments, the furnace was run until a clear failure could be seen on the unexposed exterior wall. The durations of the experiments are 122 min, 66 min and 60 min for the cob, cement and lime plaster respectively as shown in Table 4-4.

The wall plaster materials performed significantly differently. The cob plaster performed well as it did not allow any flames through the wall sample and the furnace ran for 122 minutes. There was ecobrick shrinkage and smoke from the horizontal wall sample as can be seen in Figure 4-28. The cement plaster experiment only ran for 66 minutes as the vertical wall had failed. It had allowed a considerable amount of flames to penetrate the wall at 56 minutes, although the flames did self-extinguish on the unexposed surface before the furnace burners were switched off as shown in Figure 4-29 only the internal flames can be seen glowing in the left vertical sample. As mentioned before, the horizontal lime sample was problematic and the furnace was turned off at 60 minutes as flaming had occurred on the unexposed surface from 51 minutes. Figure 4-30 shows the sample at 60 minutes with the bracing and an ecobrick still alight.

Figure 4-28: Photograph of the vertical (Left) and horizontal (Right) cob wall samples at the end of the experiment at 122 minutes

Figure 4-29: Photograph of the vertical (Left) and horizontal (Right) cement wall samples at the end of the experiment at 66 minutes

Figure 4-30: Photograph of the vertical lime wall sample at the end of the experiment at 60 minutes

4.4.3 Post Fire Test Observations

After the furnace burners were turned off a number of observations were made on the inside of the furnace on the exposed side of the wall samples which should be noted. At the end of the cob experiment the horizontal sample, on the left of Figure 4-31, only shows minor cracking on the wall and a joining failure where the heat penetrated. Whereas the vertical sample, on the right of Figure 4-31, has significant cracking where hot gases have ignited the ecobricks within. The flames are visible and on-going after the furnace has been turned off.

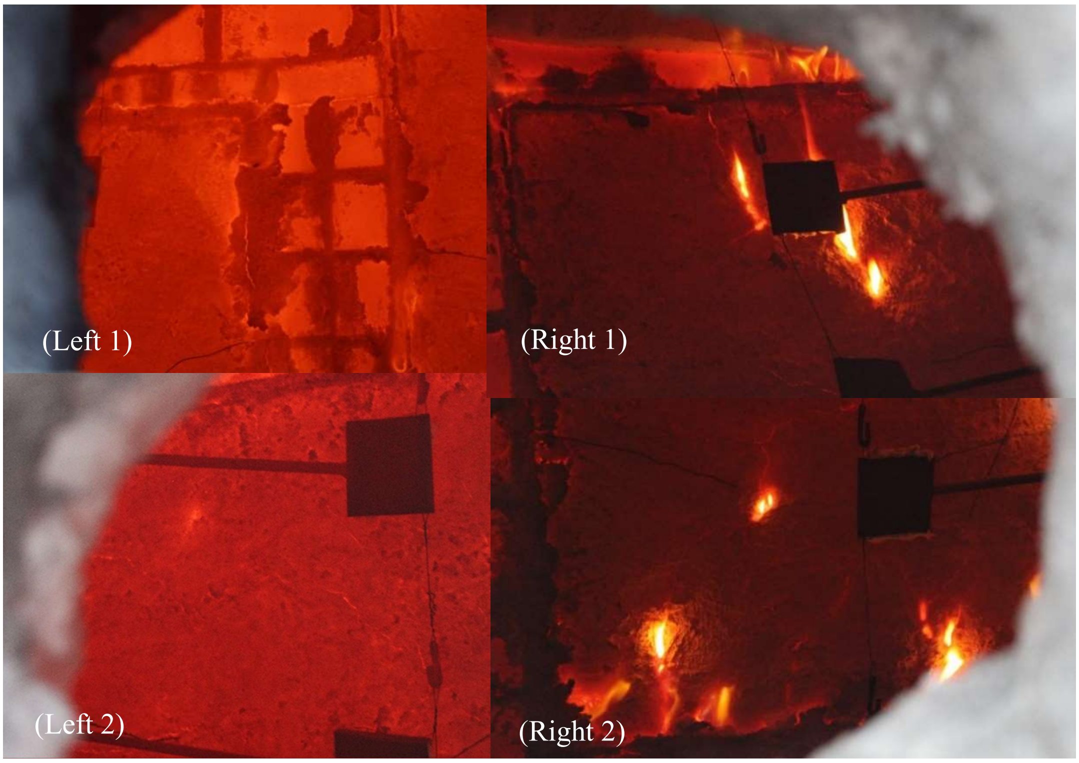


Figure 4-31: Photograph taken on the exposed surface of the horizontal (Left) and vertical (Right) cob wall samples after the furnace was turned off at 122 minutes, flames from ignited ecobricks are visible. [The white/grey material around the perimeter of the images is the insulation material of the viewing hole.]

The cement wall samples not only had cracking occurring, but the plaster delaminated as well as shown in Figure 4-32. The delamination is clearly seen on the horizontal wall sample on the left of Figure 4-32, whereas the vertical wall sample on the right shows the flames from the ignited ecobricks through the cracks.

Figure 4-32: Photograph taken on the exposed surface of the horizontal (Left) and vertical (Right) cement wall samples after the furnace was turned off at 66 minutes, flames from ignited ecobricks with in the vertical are visible

Figure 4-33 illustrates the possible outcome of an ecobrick wall if the entirety of the plaster delaminates, thereby exposing the end of the ecobricks directly to the hot gases of the furnace. The left of Figure 4-33 shows the ecobricks ignited and contributing significantly to the fuel load during the experiment. The right shows the ecobricks remaining ignited after the furnace was switched off at 60 minutes. Hence, the samples do not self-extinguish and could potentially burn for extended periods of time once ignited.

Figure 4-33: Photograph taken on the exposed surface of the horizontal lime sample taken during the experiment (Left) and after the burners were switched off (Right), flaming ecobricks are visible in both

4.5 Conclusion

The five ecobrick wall samples were tested in accordance to SANS 10177-2 at Ignis Testing in Cape Town, South Africa. The testing provided much needed insight as to how to build with ecobricks so that the building technique can be used to meet the insulation and integrity criteria of SANS 10177-2 and to ensure that the ecobricks do not contribute towards the fuel load of the structure. It was clear that the plaster layer had to be cured correctly and applied in such a manner to prevent delamination and cracking, which was the main reason for the failure of the wall samples.

The testing also showed that the horizontal orientated ecobrick wall samples, due to the thickness and nature of cob, provided a better protection as well as providing a heat sink effect around bottles.

In Section 5 the numerical modelling method and results of the ecobrick wall samples, tested in Section 4, are discussed. A preliminary thermal finite element model represents the ecobrick wall samples, where the physical properties of the ecobricks and their various plasters are used to investigate the theoretical results compared to the measured experimental results. There are other phenomena, such as the plaster cracking or delaminating, which are not represented in the finite element model. As some of the material properties are not well researched or readily available, the numerical results differ slightly from the experimental results although there is a respectable correlation.

5 Thermal Finite Element Analysis

This chapter uses thermal finite element analyses (FEA) carried out in ABAQUS CAE (2018) to model the physical experiments to determine if the numerical properties yield a similar result to the experiments or if there are more unknowns which could be playing a role in the thermodynamic behaviour of the wall samples. The experimental tests carried out in Section 4 sought to find a basis for determining what type of plaster, thickness and ecobrick wall assembly combination is suitable with regards to thermal insulation to prevent the ecobricks wall from adding to the fire load of the dwelling and to attain a specific fire rating. The results from the experimental test at 30 minutes indicates that the temperature at the back of the 40 mm plaster layer of the horizontal orientation ecobricks, which are surrounded by cob, with either a cob or cement plaster, remains below the HDPE (Lid) melting temperature, but soon thereafter significant quantities of smoke were observed, potentially indicating failure.

A two-dimensional model is created to represent a cross section of the horizontal and vertical wall samples. The properties of the model are derived from previous literature, although are simplified as the properties of ecobricks are relatively unknown in fire. Further work is required to develop detailed thermal FEA models that can capture the complex 3D behaviour the is present. However, the models in this chapter provide insight regarding general behaviour and can be used to guide further developments through results that can be readily interrogated and studied parametrically. The layout of this chapter is represented by a flow diagram in Figure 5-1.

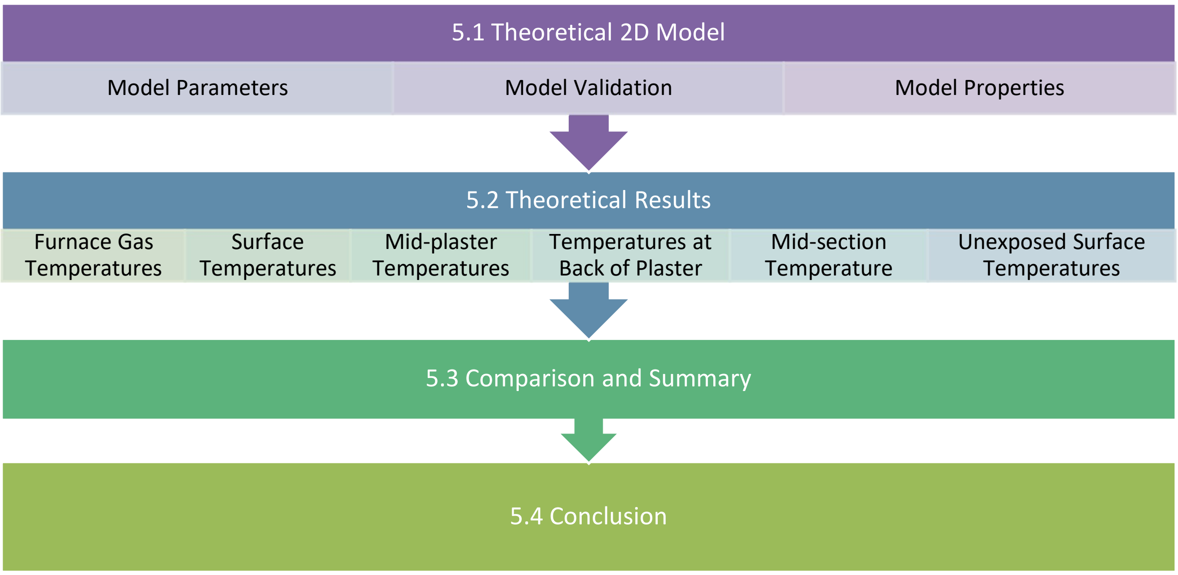


Figure 5-1: Flow diagram of chapter presentation

5.1 Numerical 2D Model

In order to model the ecobricks in their respective wall samples, the thermal FEA is simplified to a two-dimensional representation of the wall section. The following three sections discuss the parameters, model validation and properties used to represent the ecobrick wall samples.

5.1.1 Model Parameters

The thermal finite element model is made up of three different parts, which is a plaster layer, the ecobricks and an infill between bottles. In the case of the horizontally orientated ecobrick wall samples, the infill consists of a cob, whereas the vertically orientated ecobrick wall sample infill consists of the same material as the plaster. Figure 5-2 illustrates the assembled model, with the three parts being indicated. The ecobricks are a simplified profile modelled off the dimensions of commonly found 2-litre bottles, which are often used to make ecobricks and were used in all the experiments conducted. The cob infill surrounds the ecobricks to imitate the experimental horizontal wall sample. The plaster consists of two layers, which are made up of either cob, cement or lime plaster properties. These layers are then merged to create a single part for the analysis while maintaining its separate material properties for the respective mesh layers.

An initial ambient temperature of 20 °C is applied to the whole model. The furnace gas temperatures are applied, as a surface film condition to represent convection, to the exposed plaster surface on the right of each model as well as the surface radiation. The unexposed surface film condition is kept at the ambient temperature of 20 °C to best represent the exterior temperature.

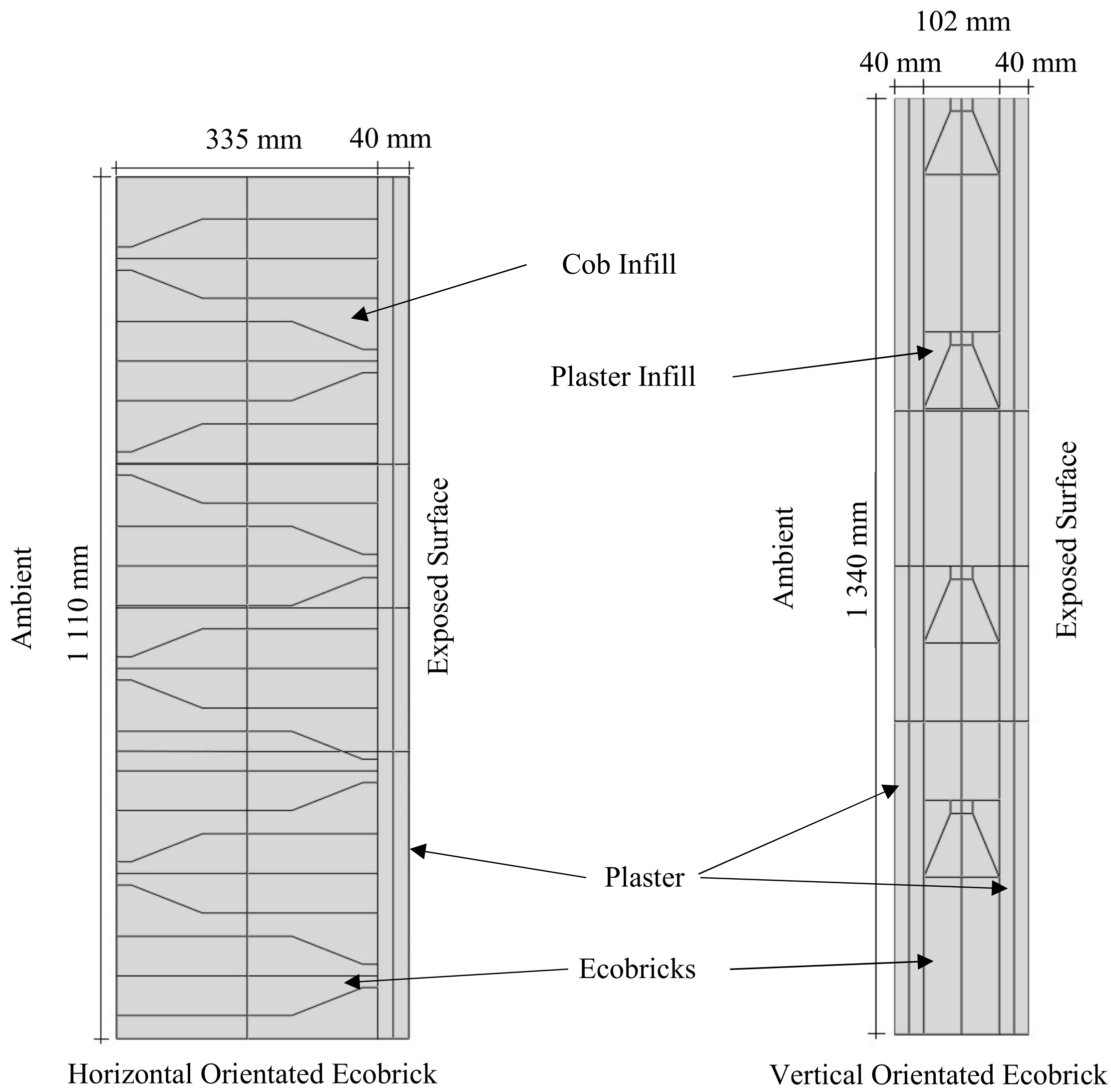


Figure 5-2: Two-dimensional thermal finite element model representation of the wall samples

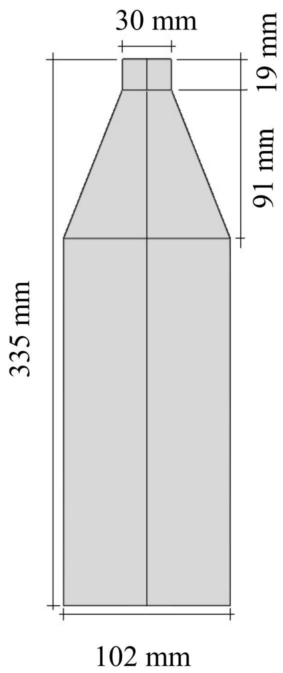


Figure 5-3: Two-dimensional thermal finite element model representation of an ecobrick with approximated dimensions based on experimental samples used

5.1.2 Model Validation

A validation study is used to ensure that the model is set up correctly, by initially treating the setup as a solid concrete wall as results for concrete slabs are readily available for validation. Known material properties are applied to the model and compared to the calculated temperatures, while using the gas temperatures of the standard fire curve. The material properties of concrete are applied to the 3 parts of the assembly. As an initial set up, the analysis is simulated as a steady-state model. Once the steady-state validation is satisfied, a transient-state validation takes place. This validation is useful for indicating that the mesh and linking of elements have a limited effect on results, prior to introducing updated material models for thermal properties.

5.1.2.1 Steady-state Validation

The steady-state validation uses the constant thermal material properties of concrete and the gas temperatures of the standard fire curve to calculate the concrete temperatures. The temperatures calculated, using Wickström's equation as provided in Section 2.4.1, are compared to the concrete temperatures modelled by the FEA. The concrete parameters are provided in Appendix B, with a summary shown in Table 5-1 as well as a summary of the results is shown in Table 5-2.

Table 5-1: Concrete steady-state parameters and their origins

	Conductivity	Specific Heat.	Density
Concrete	1.33 [W/m°C]	900 [J/kg°C]	2394 [kg/m³]
Origin	Buchanan & Abu, 2017	Buchanan & Abu, 2017 Adapted	Buchanan & Abu, 2017 Adapted

5.1.2.2 Transient-state Validation

The transient-state validation uses temperature dependent properties of concrete to model the FEA. These properties include the density, conductivity and specific heat of concrete. The results are compared to the results given by Wickström's empirical equation in Table 5-2, as provided in Section 2.4.1. The transient conditions provide a better correlation to the calculated concrete temperatures as expected, since the results are highly time and temperature-dependent. The steady-state temperatures do not correlate well with Wickström's equation as it does not consider the material properties changing with the increase in temperature.

Table 5-2: Temperatures calculated and measured as a FEA model validation study

Calculation Method	**Analysis**	**Layer Depth:**			
		0 mm	**20 mm**	**40 mm**	**206.5 mm**
Wickström's Equation	Empirical / Transient	945.3°C	530.8°C	309.4°C	20°C
Finite Element Analysis	Steady-state	938.7°C	903.5°C	868.3°C	565.1°C
Finite Element Analysis	Transient	902.4°C	525.5°C	309.7°C	20.5°C

5.1.3 Model Properties

As the preliminary model has been prepared and geometric influences validated in Section 5.1.1 and 5.1.2, the material-specific properties were applied to the various models with the gas temperatures measured at the respective experiments.

5.1.3.1 Ecobricks

Ecobricks consist of a number of plastics and it is not in the scope of this study to determine the material properties of a test sample of ecobricks. It has, therefore, been decided for the purpose of this study and to simplify the model, that polypropylene will be used as the material for the simulated ecobricks. Polypropylene (PP) is one of the most commonly used plastics (Heckman *et al.*, 1967) and the thermal material properties are readily available from various sources. Although PP has a density of 905 kg/m³ (Beyler, 2014), an ecobrick is not compacted densely enough to achieve this density. It has, therefore, been calculated to a density of 300 kg/m³ by the average mass and volume used. A summary of the adapted properties is given in Table 5-3.

Table 5-3: Material properties of polypropylene used in the FEA (adapted from Heckman et al. *(1967) and Beyler (2004))*

Specific Heat	Conductivity	Density
100 J/kg.K	0.05 W/m.K	300 kg/m³

5.1.3.2 Plaster and Infill Material Properties

The cob material properties are not readily available and are not analysed for this study, but rather derived from the clay properties at elevated temperatures as described by the equations provided by Han et al (2017). As the cob experimental data proved to be considerably different from the expected temperatures modelled from the existing material properties, Han's data has been used as a guideline and adapted to predict similar results as the recorded experimental temperatures.

The latent heat was derived from the moisture content, which was measured with a moisture meter before the start of each test, of the cob and cement plaster and the specific heat has been altered to allow for the changes. Latent heat is the energy required for the material to change phase. These can be seen in Figure 5-4 for the cob, cement and lime plasters. The specific heat equations in Figure 5-4 exclude the latent heat, which are provided in Table 5-4.

The lime plaster material properties such as the specific heat, density and conductivity are taken directly from Johanna et al. (2021), a paper on clay and lime plasters . The specific heat for cob, cement and lime plaster are shown in Figure 5-4, along with the accompanying equations. The equations in Figure 5-4 exclude the latent heat of vaporisation of water. Figure 5-5 illustrates the temperature dependent conductivity of the cob, cement and lime plaster. Similarly, Figure 5-6 illustrates the temperature dependent density of the plasters. The cement plaster was assigned the material properties of concrete, which have already been used in the validation study and are provided in Appendix B. The cement material properties are applied to the plaster layers as well as the infill for the vertical orientated ecobrick wall sample.

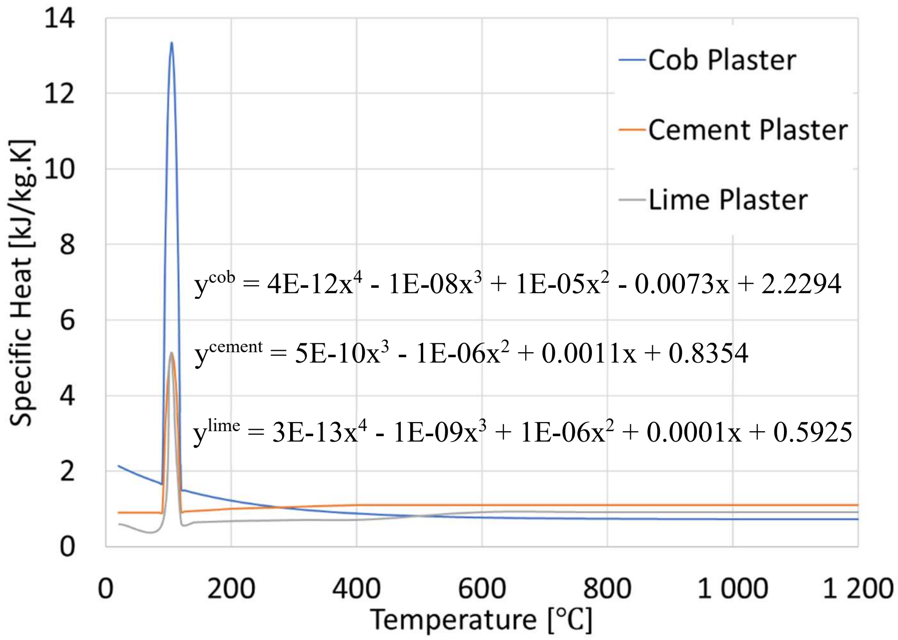


Figure 5-4: Specific heat graphs of the numerical models including the latent heat of the plaster and infill. Specific heat equations provided do not account for the latent heat of vaporisation of the water which is accounted for in a separate term in the model

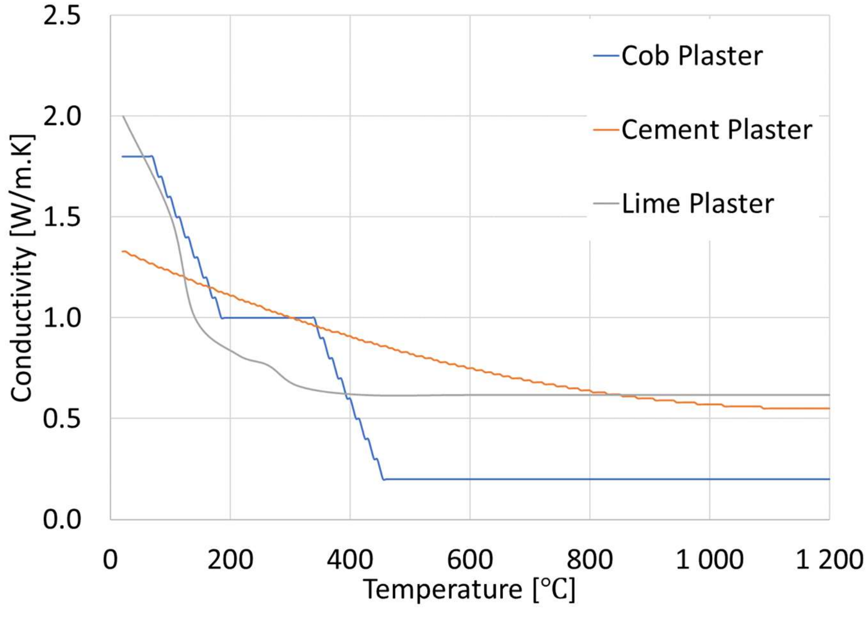


Figure 5-5: Conductivity graphs of the plaster and infill of the numerical models

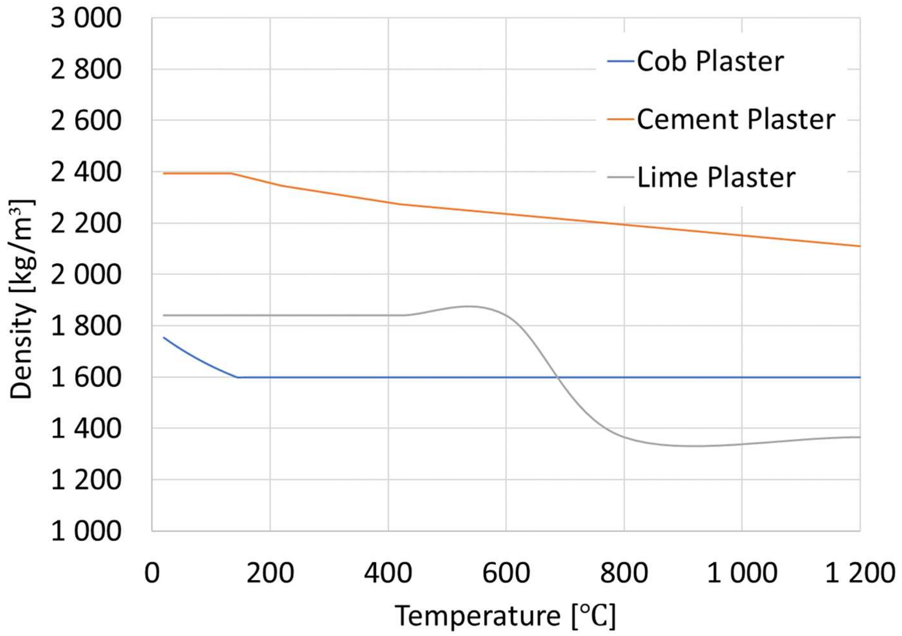


Figure 5-6: Density graphs of the plaster and infill of the numerical models

A summary of the upper and lower bound coefficients at 1200 °C and 20 °C of the specific heat, conductivity and density of the cob, cement and lime plasters are shown in Table 5-4 for the graphs above. The sources of the properties, in Table 5-4, are provided in

Table 5-4: Upper and lower bound summary of plaster and infill material properties used in the numerical models (modified and adapted from Han et al. (2017) and Johanna et al. (2021))

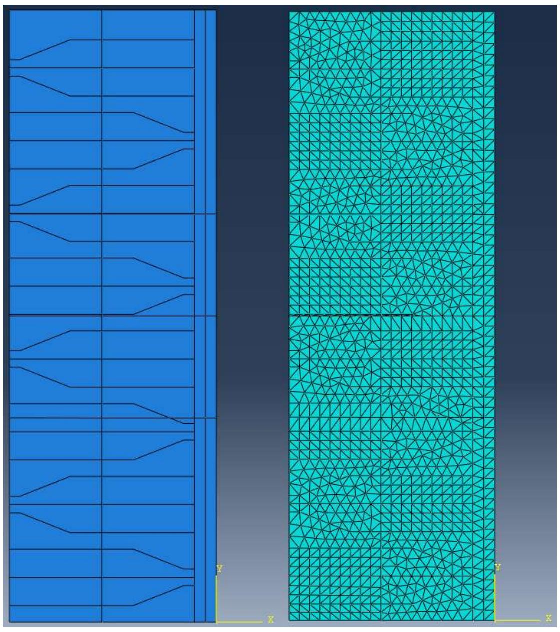
Material Properties		**Cob**	**Cement**	**Lime**
Specific Heat [J/kg.K]	20 °C	2136	900	586
	1200 °C	721	1100	905
Conductivity [W/m.K]	20 °C	1.8	1.33	2.0
	1200 °C	0.2	0.55	0.6
Density [kg/m³]	20 °C	1754	2394	1840
	1200 °C	1599	2107	1365
Latent Heat	Latent Heat [kJ/kg]	175.9	63.2	67.7
	Solidus Temp [°C]	90	90	90
	Liquidus Temp [°C]	120	120	120

Table 5-5: The sources and origins of the material properties used in the numerical modelling

	Cob Plaster	Cement Plaster	Lime Plaster	Presented
Specific Heat	Han *et al.*, 2017 adapted	Buchanan & Abu, 2017 adapted	Johanna *et al.*, 2021	Figure 5-4 Table 5-4
Conductivity	Han *et al.*, 2017 adapted	Buchanan & Abu, 2017	Johanna *et al.*, 2021	Figure 5-5 Table 5-4
Density	Han *et al.*, 2017 adapted	Buchanan & Abu, 2017 adapted	Johanna *et al.*, 2021	Figure 5-6 Table 5-4
Latent Heat	Derived from the measured moisture content	Derived from the measured moisture content	Derived from the measured moisture content	Figure 5-4 Table 5-4

5.1.4 Modelling Procedure

Once the material properties from Section 5.1.3 (summarised in Table 5-4) are applied to the solid, homogeneous plaster, infill and ecobrick 2D planar, deformable parts, the assembly is merged to create a single ecobrick wall with the relevant material properties. The part is meshed with a standard, quadratic, triangular heat transfer element using a free technique for both the horizontal and vertical orientated ecobrick wall models as shown in Figure 5-7. The global seed size for the horizontal and vertical models are 0.019 m and 0.02 m respectively. A list of the modelling parameters are available in Appendix C.



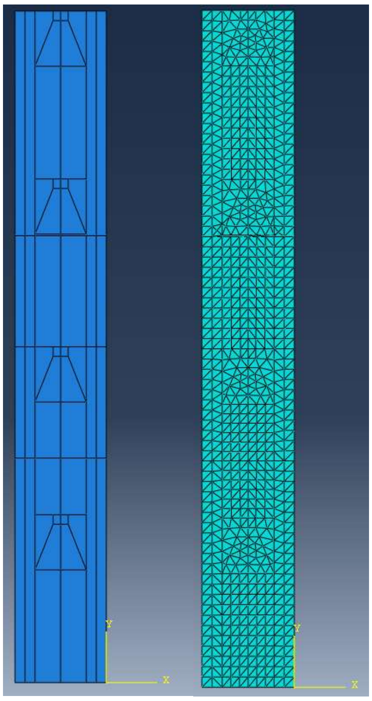


Figure 5-7: Modelled part along with its respective mesh. (Left) Horizontal orientated ecobrick wall, (Right) Vertical orientated ecobrick wall

5.2 Numerical Results

The gas temperatures from the experimental test data of the horizontal and vertical wall samples, with their cob, cement and lime plasters, are applied to each model for 60 minutes to simulate the fire exposure. The predicted numerical results from each model are discussed in the following section.

5.2.1 Furnace Gas Temperatures

The gas temperatures applied to the exposed surface are the same temperatures recorded from the furnace gas temperatures during the experiments. A graph of these temperatures may be found in Section 4.3.3 in Figure 4-17. Using the experimental gas temperatures instead of the standard fire curve, allows for a better comparison between the model and the experimental results. This is to allow for the model results to correlate better with the results from the experimental data as the gas temperature in the furnace had fluctuations caused predominantly by the burners.

5.2.2 Surface Temperatures

Figure 5-8 shows the FEA surface temperatures of the different models alongside the standard fire curve. After 30 minutes, the horizontal samples surface temperatures are slightly elevated compared to the vertical samples. This is due to the cob infill having a lower conductivity at higher temperatures, as shown in Table 5-4. Therefore, the heat does not penetrate the sample as readily as it does in the vertical samples. This is shown by the surface temperature of the horizontal samples being higher than the surface temperature of the vertical samples. The experimental gas temperatures which are used in the model are shown in Appendix D, along with the corresponding numerical surface temperature.

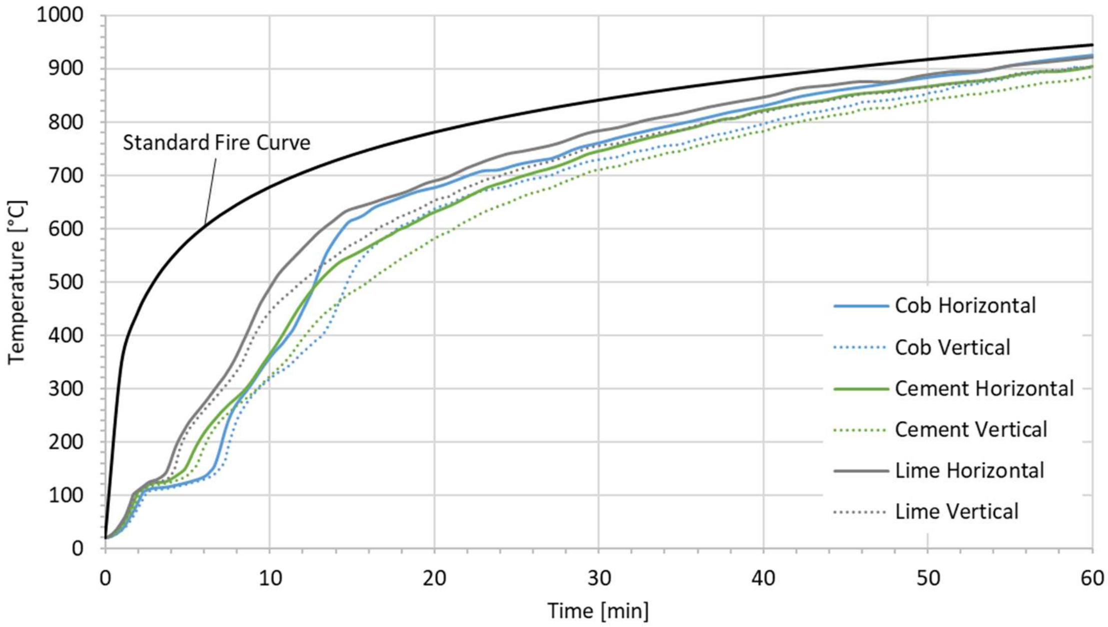


Figure 5-8: Time-temperature graph showing numerical exposed surface temperatures of the samples during a simulation

5.2.3 Mid-plaster Temperatures

At the mid-plaster depth of 20 mm, it is expected that the vertical and horizontal temperatures will follow similar trends for each type of plaster layer, as the plasters are the same for vertical and horizontal, compared to the infill which may vary. The results shown in Figure 5-9, reveal that the cob, cement and lime plaster each have their distinct curve shapes due to the material properties of the plaster types.

Initially, the horizontal samples' mid-plaster temperature is higher, but after 28 min, 39 min and 46 min for the lime, cement and cob plaster, respectively, the mid-plaster on the vertical samples are higher.

This is due to the horizontal orientated ecobrick walls having a higher conductivity as there is a greater volume of cob between the ecobricks.

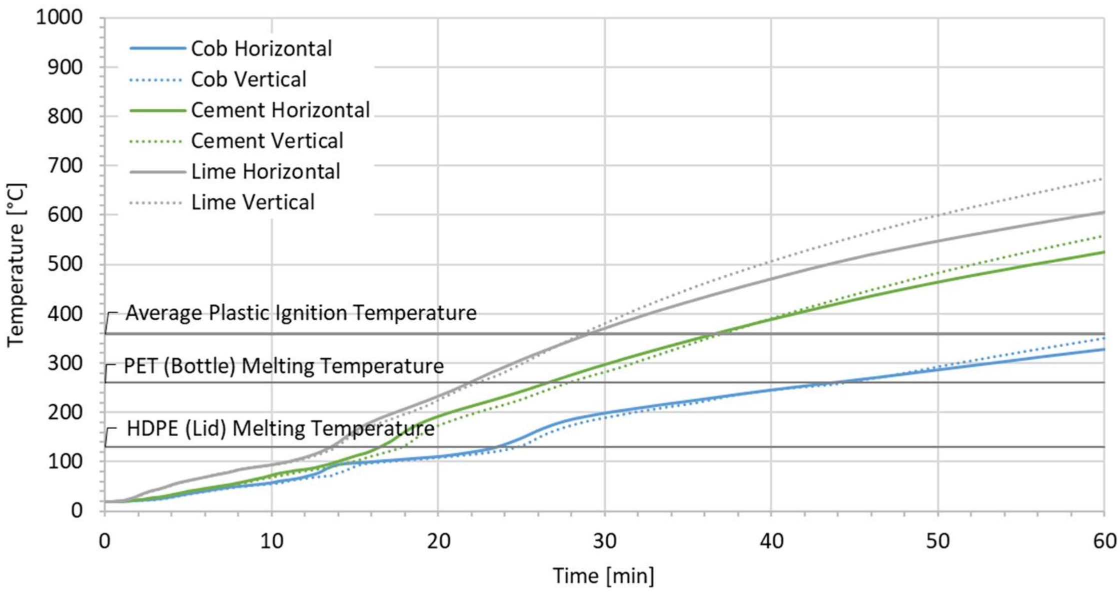


Figure 5-9: Time-temperature graph showing numerical temperature in the middle of the plaster at 20 mm during a simulation. (A comparison of the experimental and numerical data is available in Appendix D)

5.2.4 Temperatures at Back of Plaster

As the time increases and as temperature data further into the samples are analysed, the difference between the vertical and horizontal sample temperatures are more distinct as can be seen in Figure 5-10 which is the time-temperature curves at the back of the plaster at 40 mm. The horizontal wall sample temperatures are lower than the vertical due to the thicker walls, along with the lower conductivity of the cob infill as expected along the graph. The horizontal temperatures of all 3 plaster types are slightly higher than the vertical temperatures near the latent heat solidus (90 °C) and liquidus (120 °C) temperatures. This is due to the greater latent heat of the cob infill compared to the cement and lime plasters. The latent heat required for the phase change is from the lower (solidus) to upper (liquidus) bound.

At 30 minutes, both the horizontal and vertical orientated ecobrick wall samples of the cob and cement plaster samples are below the melting temperature of the HDPE lid. Whereas from the experimental data, only the horizontal ecobrick wall samples with cob or cement plaster are below the melting temperature.

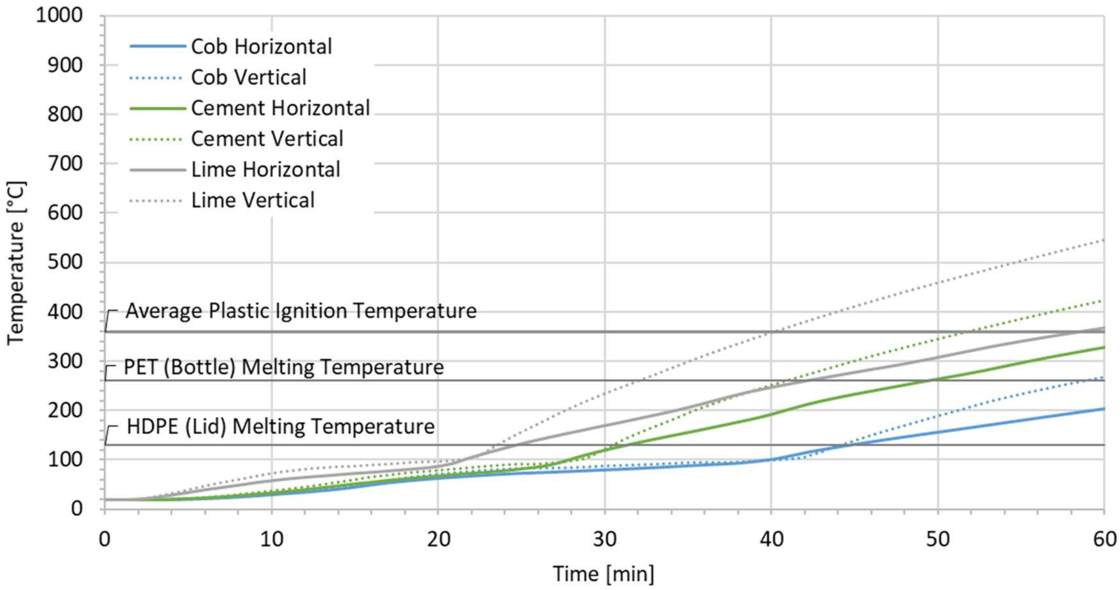


Figure 5-10: Time-temperature graph showing numerical temperature at the back of 40mm plaster during a simulation. (A comparison of the experimental and numerical data is available in Appendix D)

5.2.5 Wall Mid-section Temperatures

The mid-section depth of the horizontal and vertical wall samples are 207.5 mm and 92.5 mm, respectively. The thermal mass capacity and the depth analysed in the wall sample have a clear correlation, as can be seen in Figure 5-11, where the horizontal wall sample temperatures at the mid-section depth are relatively similar as the initial ambient temperature of 20 °C at 60 minutes, looking at the vertical scale of 300 °C. Comparing the results to the insulation criteria, even though the temperatures are at the mid-section depth, the horizontal samples have remained below the 160 °C average insulation criteria.

The vertical wall sample temperatures at the mid-depth have significantly increased from the ambient temperature at 60 minutes. Figure 5-11 shows that the cob and cement plaster on the vertical orientated ecobrick wall samples remain below average insulation criteria although have increased by 70 °C and 123 °C respectively. The vertical orientated ecobrick wall with lime plaster exceeded both the average and maximum insulation criteria, as it reached 277 °C at 60 minutes.

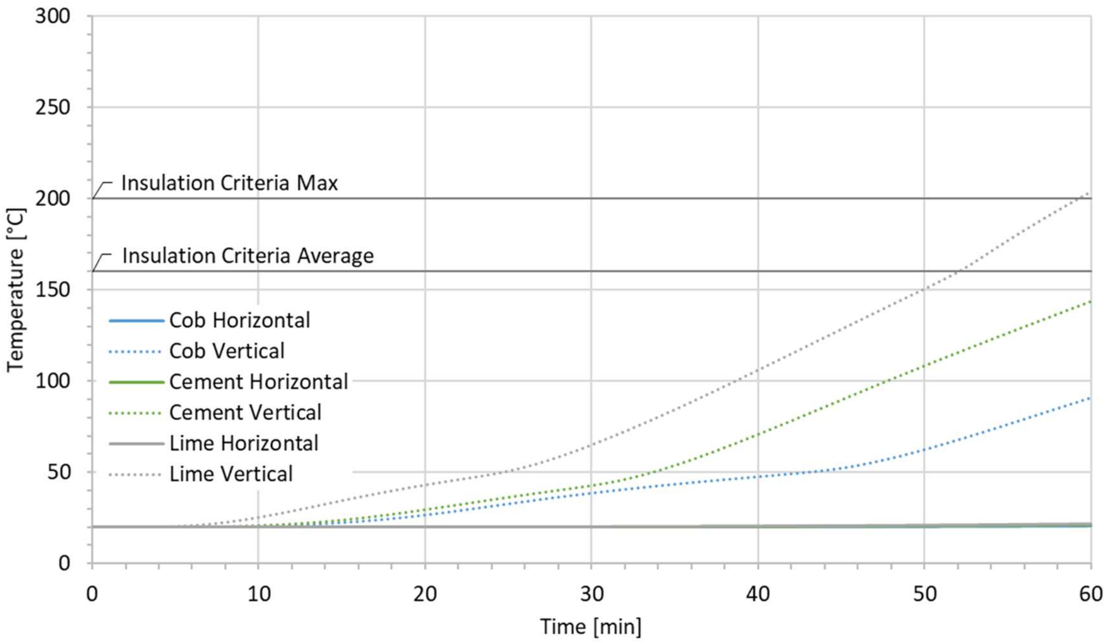


Figure 5-11: Time-temperature graph showing numerical temperature mid-section of the wall samples during a simulation (Note: The scale on the graph has been adjusted to a maximum of 300 °C, A comparison of the experimental and numerical data is available in Appendix D)

5.2.6 Unexposed Surface Temperatures

The ambient gas temperature of the unexposed surface of the finite element model are all set to 20 °C. Figure 5-12 illustrates that the horizontal samples all remain at 20 °C, whereas the vertical wall sample temperatures all increased by a fraction of a degree (note the graph y-axis scale). The vertical orientated ecobrick wall sample with the cob plaster temperature increased the least, whereas the cement and lime plaster on the vertical orientated ecobrick wall samples increased by 0.7 °C. This increase is relatively insignificant when analysing the temperatures, but it does identify that the vertical wall samples have less of a thermal capacity than the horizontal wall samples.

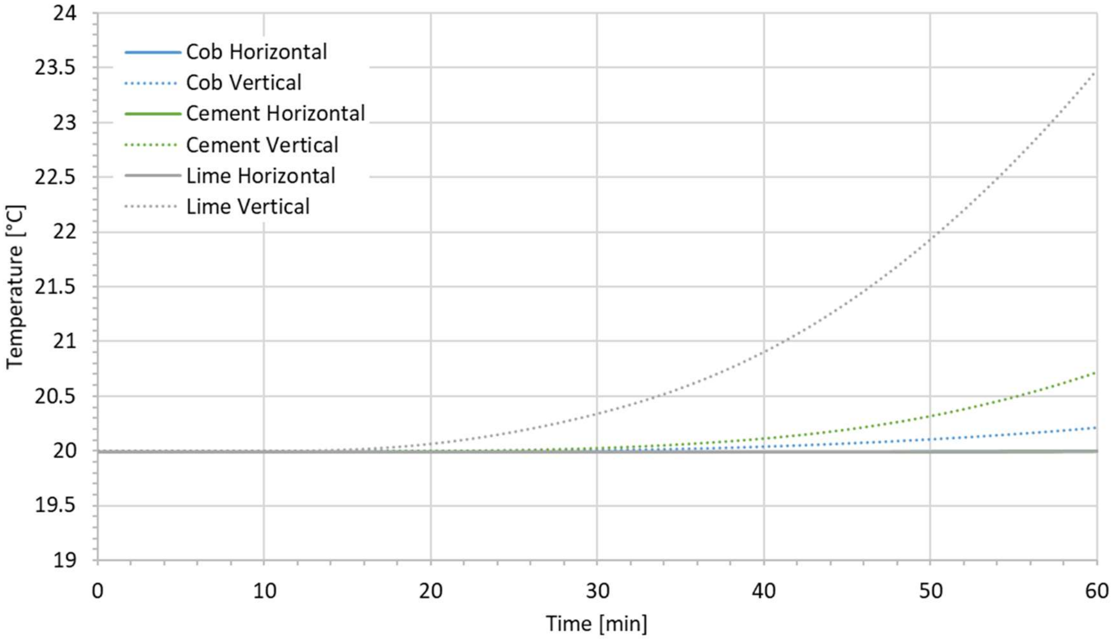


Figure 5-12: Time-temperature graph showing numerical temperature of the unexposed surface gases during a simulation (Note: The scale on the graph has been adjusted to a maximum of 22 °C, (A comparison of the experimental and numerical data is available in Appendix D)

5.3 Comparison and Summary

A tabular summary of the time taken to reach critical plastic temperatures at the back of the plaster at 40 mm are shown in Table 5-6. The cob plaster performed optimally with regards to the plastic melting and ignition temperatures followed by the cement. The numerical lime samples, horizontal and vertical, exceeded the plastic melting temperatures of both the lid and bottle within the first 30 minutes of the analysis. The numerical model does not predict cracking, so large differences in results between experimental and numerical results highlight when cracking occurs.

Table 5-6: Numerical and experimental time taken to reach critical plastic temperatures at the back of the plaster at 40 mm against the ecobricks. Green, yellow and red cells indicate fire resistance ratings of above 60 minutes, below 60 minutes and below 30 minutes respectively (A negative difference indicates that the numerical time is greater than the experimental time)

		Cob Plaster		Cement Plaster		Lime Plaster	
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
HDPE Lid Melting Temperature Reached 130 °C	Numerical	45 min	44 min	31 min	30 min	20 min	18 min
	Experimental	37.7 min	18.5 min	31.4 min	15.7 min	12.3 min	
	% Difference	-16.2 %	-58.0 %	1.27 %	-47.7 %	-38.5 %	
PET Bottle Melting Temperature Reached 260 °C	Numerical	> 60 min	59 min	49 min	41 min	29 min	29 min
	Experimental	64.6 min	39.6 min	55.1 min	21.3 min	13.2 min	
	% Difference	7.1 %	-32.9 %	11.10 %	-48.1 %	-54.5 %	
Plastic Ignition Temperature Reached 360 °C	Numerical	> 60 min	> 60 min	> 60 min	52 min	36 min	34 min
	Experimental	90.9 min	63.8 min	> 72 min	26.7 min	16.3 min	
	% Difference	34.0 %	6.0 %	16.70 %	-48.7 %	-54.7 %	

A bar graph in Figure 5-13 illustrates the different times taken to reach the critical plastic temperatures and compares the times of the experimental tests in Table 4-3 to the numerical models in Table 5-6. Note that a maximum time of 60 minutes was analysed in the FEA, due to modelling time constraints and as well as the author felt that after the experimental analysis, that ecobrick walls should not be used with a fire rating longer than 60 minutes. Therefore Figure 5-13 only illustrates 60 minutes of the experiments. As a guide to the bar graph in Figure 5-13, the longer the bar the better. It illustrates that the sample took longer to reach that temperature, which in turn would give it a higher fire rating.

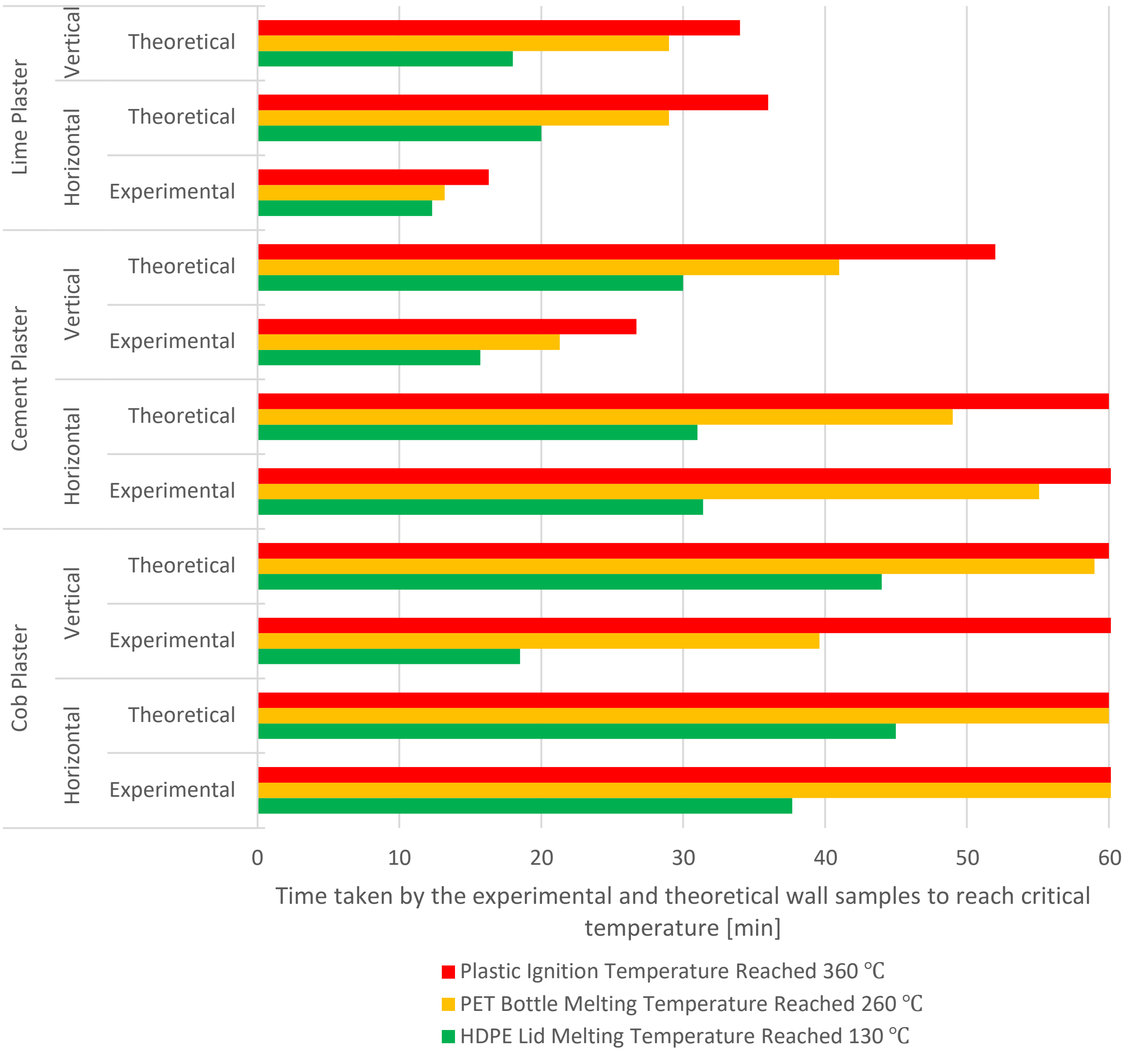


Figure 5-13: Experimental and numerical time taken to reach critical plastic temperatures at the back of the plaster at 40 mm against the ecobricks (Read graph from bottom to top)

To understand the difference in the time taken to reach the critical plastic temperatures in Figure 5-13, a percentage difference comparison is shown in Figure 5-14. If the finite element model captures the behaviour well, the difference between the experimental time and numerical time is less. If the material properties across the different temperatures are correct, the percentage difference will be similar.

Similarities and large differences are viewed in Figure 5-14. The cement plaster with the vertically orientated ecobricks have a similar percentage difference in the time taken to reach all 3 critical temperatures. Whereas for the cob horizontal and vertical, the percentage difference varies significantly. This is shown in the horizontal cement plaster as well. This may be a good indication that the cob material properties need to be investigated and improved on to have an improved numerical understanding of the cob material properties.

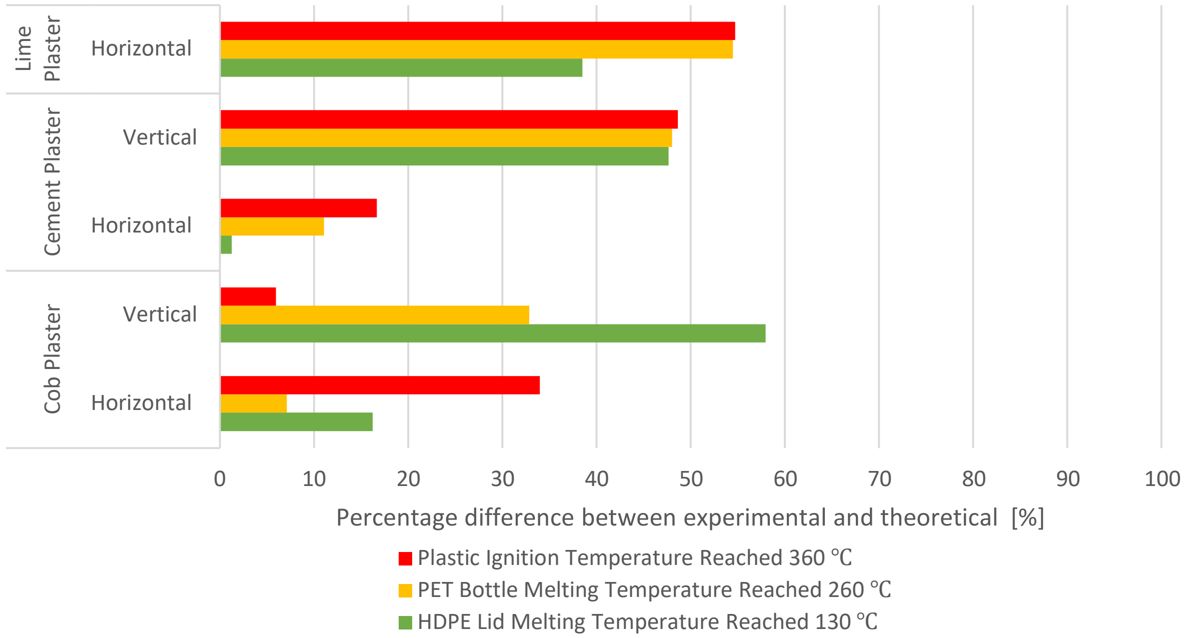


Figure 5-14: Percentage difference of the time taken to reach critical plastic temperatures at the back of the plaster at 40 mm between the experimental and numerical data (Read graph from bottom to top)

5.4 Conclusion

The six ecobrick wall samples were modelled with the gas temperatures measured from the experimental data in Section 3. The correlation between the experimental and numerical results indicate that the material properties should be investigated before the FEA could replace the physical testing of the wall samples. Once the material properties and interaction between the plaster and ecobricks are better understood, a FEA could provide a faster and cheaper method of analysis. Mechanisms such as cracking and delamination seem to be the main failure of the wall samples. However, these are not analysed by the finite element model. The numerical modelling may be useful in analysing the temperatures of the wall sample to ensure that the melting and ignition temperatures of the ecobricks are not reached in an ideal scenario. Results such as the horizontal orientated ecobricks with a cement plaster show good correlation with variations of 1.3 – 16.7%, whilst the vertical orientated ecobricks with a cob plaster shows poor correlation with variations of -58 - 6%.

6 Conclusions and Recommendations

This chapter presents the summary of results from the objectives of this study, the main conclusions and recommendations. Firstly, insight into the use of ecobricks, not covered in this study, are highlighted for the reasonable use of this technology for housing by end users.

6.1 Discussion on the Research Focus of this Study

As stated in Section 1.2, the aim of this thesis was to determine if constructing with ecobricks as an infill building material is safe where fire is concerned. This has been addressed through the experimental testing and numerical modelling of ecobricks when exposed to high temperatures following a standard fire curve. The highlights from the objectives are discussed in the following sub-sections.

6.1.1 Behaviour of ecobrick walling systems with a variety of construction and plaster types exposed to fire

Two main methods of building with ecobricks that are commonly used have been investigated and reported in this study. Ecobricks can be orientated horizontally between layers of cob with a plaster covering the ecobrick ends and vertically, encased with a mesh and plaster. The plaster types tested are cob, cement and lime plasters. The experimental and numerical testing illustrated that the cob layers between the horizontal ecobricks provided a better thermal resistance than the plaster placed against the vertical ecobricks with mesh. Similarly, the cob plaster performed better than the cement plaster, with both the vertical and horizontal orientations.

Due to the high clay percentage of the cob, it acted as a good thermal insulator. Therefore, it is suggested to be used as the plaster layer along with a horizontal orientated ecobrick structure. This construction method yielded a 60-minute fire rating with the physical testing, in terms of total wall thickness integrity and insulation resistance, but a 30-minute rating when smoke production and from the numerical models when the criterion of bottle tops melting is considered. Therefore a 30-minute fire rating is recommended to be used.

6.1.2 Thickness of plaster required for the protection of ecobricks

This study found that a 40 mm cob plaster layer was sufficient for the horizontal and vertical orientated ecobrick wall to provide a 30-minute fire rating along with the construction method mentioned in Section 6.1.1. The cob plaster kept the temperature below 130 °C for both the vertical and horizontal orientated ecobrick walls up to 44 and 45 minutes respectively. It is critical that the plaster is mixed and applied correctly that it will not crack or delaminate when exposed to fire as this severely influences the temperatures and behaviour.

6.1.3 Design fuel loads and energy contribution of ecobricks in fire

As large amounts of combustibles are stored in ecobrick walls, it will be appropriate to increase the design fuel loads for these structures as discussed in Section 3.6, if ecobricks will be ignited. The fire load density of an informal settlement dwelling of approximately 2.4 m wide, 3.6 m long and 2.3 m high (Cicione *et al.*, 2020), would increase by a lower range of 654 MJ/m² and an upper range of 2865 MJ/m² of floor area from the ecobricks walls if they were to be all exposed and add to the fuel load of the structure.

6.1.4 Quality control for ecobrick walls

The issue of quality control for homes built with ecobricks in low-income area is a concern. However, the objectives addressed in this thesis do not cover all the topics required to compile a comprehensive building guideline to build safely with ecobricks as the wall infill material. Further research needs to be done as stated in Section 6.3 to provide quality control guidelines for the usage of this technology. From the lime plaster wall test it was shown that poor quality materials greatly diminish the ability of the plaster to thermally protect the ecobricks within.

6.2 Summary and Conclusion

This research seeks to determine the fire performance of ecobrick walls through experimental and numerical modelling. The numerical results support the summary of the experimental findings provided in Table 6-1, as it is still a relatively unknown building method with a significant number of unknown variables. As discussed in Section 4.4.2, if a back plaster layer can be used to prevent smoke emissions then the issue of smoke emissions may be addressed. This could increase the fire resistance rating, as shown in Table 4-2. Although the horizontal cob emitted smoke at 35 minutes, the amount of smoke was negligible. Therefore, the cob with a 40 mm plaster thickness on both the horizontal and vertical orientated ecobrick wall sample achieved a 60-minute fire rating in terms of fire propagation and wall resistance. However, if the smoke emitted will hinder evacuation and endanger lives, it is recommended that an ecobrick structure is given a maximum fire rating of 30 minutes, as it is still a relatively unknown building method with a significant number of unknown variables. As discussed in Section 4.4.2, if a back plaster layer can be used to prevent smoke emissions then the issue of smoke emissions may be addressed. This could increase the fire resistance rating, as shown in Table 4-4.

Table 6-1: Summary of the important times for critical temperatures to be reached based on thermal images, and visible events on the unexposed side of the test sample. Green, yellow and red cells indicate fire resistance ratings of above 60 minutes, below 60 minutes and below 30 minutes, respectively

	Cob Plaster		Cement Plaster		Lime Plaster
	Horizontal	Vertical	Horizontal	Vertical	Horizontal
Plastic Ignition Temperature Reached 360 °C	90.9 min	63.8 min	> 72 min	26.7 min	16.3 min
Insulation Criteria Average 160 °C	90 min	90 min	-	30 min	35 min
Smoke Visible	35 min	-	44 min	27 min	9 min
Estimated Fire Resistance (excl. smoke emissions)	**60 min**	**60 min**	**30 min**	**None**	**None**
Recommended Fire Resistance	**30 min**	**30 min**	**30 min**	**None**	**None**

It is of vital importance that the ecobricks are prevented as far as possible from adding to the fuel load of a structure. As shown in Table 6-2 the upper range that the ecobricks could increase the fuel load of a dwelling of approximately 2.4 m wide, 3.6 m long and 2.3 m high, is 2865 MJ/m^2 if a 2 l ecobrick is filled with 600g of PE.

Table 6-2: Summary of the lower and upper fuel load if the ecobricks are filled with PVC and PE respectively for a vertically and horizontally orientated ecobrick wall assembly, of a dwelling of approximately 2.4 m wide, 3.6 m long and 2.3 m high

	Lower Range (PVC)	Upper Range (PE)
Vertical Orientated Ecobrick	654 MJ/m^2	2292 MJ/m^2
Horizontal Orientated Ecobrick	817 MJ/m^2	2865 MJ/m^2

From this work it does appear that ecobricks can be used for single storey homes as a 30 minute fire resistance can be obtained. Homes built properly from such systems would typically be a significant improvement in relation to many informal settlement homes which have no fire resistance. The use of the system for multi-storey homes still needs further consideration as the production of smoke could potentially endanger lives once plastic starts melting. Also, if walls collapse during a fire large quantities of plastic could suddenly become exposed and severely influence fire behaviour.

6.3 Recommendations for Future Research

The following sections discuss topics for future research which were observed to be a limitation of the current work.

6.3.1 How should joints be designed such that they do not open up during a fire?

During the experimental testing of the ecobrick wall samples, it was found that the frames which housed the sample were charring during the testing even though they had a plaster cover. It was found that if, or when, the plaster delaminated, that the frame was exposed to the gas temperatures of the furnace. The width of the exposed timber frame, 20 mm or 40 mm, depended on if a single or both plaster layers delaminated respectively. Further research should be done to ensure that the plaster covering the joint between the wooden or reinforced concrete does not delaminate and expose the ecobricks.

6.3.2 How should penetrations through walls be designed?

Similarly, to Section 6.3.1, a method should be designed to ensure that the joint between the penetration and ecobrick wall does not become compromised. An example of this may be to use a heat resistant liner to join two walls or a corner which has plaster applied over it.

6.3.3 How should the insurance industry address ecobrick structures?

Ecobricks are not only being used to build schools and low-income housing, they are being used in high-end homes as well. For example, a question which should be addressed, is how would the insurance industry calculate the potential damage and repair costs for a high-end home which have built additions to the building with ecobricks as the infill material? This would increase the fuel load of that portion of the house significantly. Further research may be done to understand the implications this may pose and whether it is possible to repair, reuse or replace the ecobrick structures.

6.3.4 Can design codes be developed for ecobrick homes?

Yes, a design code could be developed to build with ecobricks as an infill material. Although a thorough understanding of the material is needed, not only in fire but all physical properties relating to using it as a building material. Thermal protection can be achieved through the correct application and a sufficient plaster thickness and type to ensure that the ecobricks do not melt nor add to the fuel load of a structure.

References

Antico, F.C., Wiener, M.J., Araya-Letelier, G. & Retamal, R.G. 2017. Eco-bricks: A sustainable substitute for construction materials. *Revista de la Construccion*. 16(3):518–526.

Beyler, C.L. 2014. *Ignition Handbook*. Vol. 40. Issaquah, WA, USA: Fire Science Publishers.

Buchanan, A.H. & Abu, A.K. 2017. *Structural Design for Fire Safety*. 2nd ed. Chichester, West Sussex, United Kingdom: John Wiley & Sons Inc.

Byron, P. 2013. The Assessment of Alternate Building Technologies. *NHBRC Magazine*. (June). [Online], Available: https://www.sans10400.co.za/alternate-building-technologies/ [2021, September 29].

Cafe, T. 2007. *Physical Constants for Investigators*. [Online], Available: http://www.tcforensic.com.au/docs/article10.html [2019, February 26].

CEN. 2002. *Eurocode 1991: Actions on structures: Part 2: General actions - Actions on structures exposed to fire*. Brussels: European Committee for Standardization.

Çengel, Y.A. 2004. *Heat Transference a Practical Approach*. 2nd ed. New York, United States: MacGraw-Hill. [Online], Available: http://dx.doi.org/10.1007/978-3-642-20279-7_5.

Cicione, A. & Walls, R. 2019. Estimating time to structural collapse of informal settlement dwellings based on structural fire engineering principles. In CRC Press *SEMC Conference*.

Cicione, A., Walls, R., Sander, Z., Flores, N., Narayanan, V., Stevens, S. & Rush, D. 2020. The Effect of Separation Distance Between Informal Dwellings on Fire Spread Rates Based on Experimental Data and Analytical Equations. *Fire Technology*. (July).

Cobute. 2016. *Delft | Environmental beauty — Cobute precast concrete solutions*. [Online], Available: https://www.cobute.co.za/things-we-like/2016/12/12/ecobricks-delft [2021, September 28].

Cullen, D. 2017. What On Earth is An Eco Brick? 14 December. [Online], Available: https://greenpop.org/what-is-an-eco-brick/ [2020, October 11].

Dassault Systèmes. 2018. *ABAQUS CAE*. Vélizy-Villacoublay, France: Dassault Systèmes Simulia Corp.

Devasahayam, S., Bhaskar Raju, G. & Mustansar Hussain, C. 2019. Utilization and recycling of end of life plastics for sustainable and clean industrial processes including the iron and steel industry. *Materials Science for Energy Technologies*. 2(3):634–646.

Dieleman, A. & Maier, R. 2018. *The Andrew Report*. Cordillera Administrative Region of the Philippines.

Drysdale, D. 2011. *An Introduction to Fire Dynamics*. 3rd ed. Chichester, West Sussex, United Kingdom: John Wiley & Sons, Ltd.

Gales, J., Chorlton, B. & Jeanneret, C. 2021. The Historical Narrative of the Standard Temperature–Time Heating Curve for Structures. *Fire Technology*. 57(2):529–558.

Global Ecobrick Alliance. 2019. *What are Ecobricks? | Ecobricks.org*. [Online], Available: https://www.ecobricks.org/what/ [2019, February 19].

Global Ecobrick Alliance. 2020. *10 Step Guide to Making an Ecobrick | Ecobricks.org*. [Online], Available: https://www.ecobricks.org/how/ [2020, October 05].

Gontsana, M.-A. 2020. Life in a shack when you're in a wheelchair. *Groundup.org.za*. 4 June. [Online], Available: https://www.groundup.org.za/article/life-informal-settlement-when-youre-wheelchair/ [2020, October 05].

Green, E. 2018. Why do informal settlements get cluttered with litter? *Groundup.org.za*. 29 June. [Online], Available: https://www.groundup.org.za/article/why-do-informal-settlements-get-cluttered-litter/ [2020, October 06].

Han, C., Xu, Q., Liu, Q., Chen, Z. & Xu, Z. 2015. Experimental research and FEA of fire resistance of RC continuous T-beam. *Jianzhu Jiegou Xuebao/Journal of Building Structures*. 36:142–150.

Han, J., Sun, Q., Xing, H., Zhang, Y. & Sun, H. 2017. Experimental study on thermophysical properties of clay after high temperature. *Applied Thermal Engineering*. 111:847–854.

Han, L.-H., Zhou, K., Tan, Q. & SONG, T. 2016. Performance of Steel-Reinforced Concrete Column after Exposure to Fire: FEA Model and Experiments. *Journal of Structural Engineering*. 142:4016055.

Hayhoe, W.C. & Youssef, M.A. 2013. Structural behaviour of concrete walls during or after exposure to fire: A review. In Montréal, Québec *CSCE 2013 General Conference*. 2854–2863.

Heckman, J.J., Pinto, R. & Savelyev, P.A. 1967. *Fire Properties of Polymer Composite Materials*. Dordrecht, The Netherlands: Springer.

Hopkins, R. 2014. EcoBricks and education: how plastic bottle rubbish is helping build schools. *The Gaurdian*. 29 May. [Online], Available: https://www.theguardian.com/lifeandstyle/2014/may/29/ecobricks-and-education-how-plastic-bottle-rubbish-is-helping-build-schools [2020, October 11].

Hug It Forward. 2013. *The Bottle School Manual | WHAT ARE BOTTLE SCHOOLS*. [Online], Available: https://bottleschools.org/chapter-1/what-are-bottle-schools/ [2021, August 30].

Hug It Forward. 2019. *Hug It Forward*. [Online], Available: https://hugitforward.org/ [2019, May 16].

Hug It Forward. 2021a. *Hug It Forward | Donate*. [Online], Available:

http://hugitforward.org/donate/ [2021, September 27].

Hug It Forward. 2021b. *Hug It Forward | What We Build*. [Online], Available: http://hugitforward.org/what-we-build/ [2021, September 28].

Iris Coatings. 2021. *Structural steelwork fire protection*. [Online], Available: https://www.iriscoatings.it/structural-fire-protection [2021, October 14].

Johanna, L., Judith, K., Alar, J., Birgit, M. & Siim, P. 2021. Material properties of clay and lime plaster for structural fire design. *Fire and Materials*. 45(3):355–365.

Johansson, E. & Svenningsson, A. 2018. Delamination of cross-laminated timber and its impact on fire development. Focusing on different types of adhesives. *Report 5562. Division of Fire Safety Engineering, Lund University, Sweden.*

Karlsson, B. & Quintiere, J. 2000. *Enclosure Fire Dynamics*. A.K. Gupta et al. (eds.). London, New York, Washington D.C.: CRC Press.

Klitzke, R.A. 1959. Roman Building Ordinances Relating to Fire Protection. *The American Journal of Legal History*. 3(2):173.

LaMinx, S. 2018. How to make EcoBricks. 13 February. [Online], Available: https://skinnylaminx.com/2018/02/13/how-to-make-ecobricks/ [2020, October 11].

LeFevre, C. 2021. *Ecobricks: An Answer to Plastic Waste?* [Online], Available: https://www.buildwithrise.com/stories/ecobricks-an-answer-to-plastic-waste [2021, September 27].

Lenkiewicz, Z. 2016. *This Is Not A Leaf: The Story Of Plastic Bottle Schools*. [Online], Available: https://zlcomms.co.uk/this-is-not-a-leaf-the-story-of-plastic-bottle-schools/ [2019, February 21].

Lenkiewicz, Z. 2018. *This Is Not A Leaf: The Story Of Plastic Bottle Schools - WasteAid*. [Online], Available: https://wasteaid.org/this-is-not-a-leaf-the-story-of-plastic-bottle-schools/ [2021, September 28].

Lutge, G. 2009. *Clay block compression requirements and tests*. Scarborough, Cape Town, South Africa: G.M.LUTGE Pr Eng.

Maier, R., Angway, I., Stodgel, J. & Grande, I.T. 2015. [Online], Available: https://www.ecobricks.org/pdfs/Vision EcoBrick Guide - v3.2.pdf [2019, February 15].

Maree, F. 2015. Fire Loads and Burn Characteristics of Shacks in Informal Settlements. *University of Stellenbosch*.

Mokhtar, M., Sahat, S., Hamid, B., Kaamin, M., Jahaya Kesot, M., Wen, L.C., Xin, L.Y., Ling, N.P., et al. 2016. Application of plastic bottle as a wall structure for green house. *ARPN Journal of Engineering and Applied Sciences*. 11(12):7617–7621.

Moller, T. 2019. *The Folly Chapel. Yellowwood Forest. Morgan Bay*. [Online], Available: https://www.facebook.com/The-Folly-Chapel-Yellowwood-Forest-Morgan-Bay-

560688374455950/ [2021, September 28].

Morris, J. 2014. *West Country cob houses: The man building a house out of mud*. [Online], Available: https://www.bbc.com/news/uk-england-devon-25689764 [2021, October 14].

Mostert, C. 2019. *It all started with a plastic bottle and some non recyclables*. [Online], Available: https://waste-ed.co.za/about/.

Mowrer, F.W. & Emberly, R.L. 2018. Structural Performance: An Overview of Fire Protection for Structural Engineers Part 1. *Structure Magazine*. (January):22–25.

Pace, A. 2020. Unique Eco-Brick home offers sustainable living. *cape town etc*. 12 February. [Online], Available: https://www.capetownetc.com/cape-town/unique-eco-brick-home-offers-sustainable-living/ [2020, October 05].

Quintiere, J.G. 2017. *Principles of Fire Behavior*. 2nd ed. New York: CRC Press.

Rahn, T. 2017. *NMSBA Project Report: Tests for potential degassing of hazardous organics from alternative recycled insulating materials Prepared For Mr. Jo Stodgel, Upcycle Santa Fe*. [Online], Available: https://upcyclesantafe.files.wordpress.com/2017/02/upcycle_2016_finalreport.pdf [2019, February 15].

Rodic-Wiersma, L. & Bethancourt, J. 2012. Rehabilitation of Waste Dumpsite in Guatemala City. *ISWA World Solid Waste Congress*. (September).

SABS. 2005. *SANS 10177-2:2005 - Fire testing of materials, components and elements used in buildings Part 2: Fire resistance test for building elements*. Pretoria: South African Bureau of Standards.

SABS. 2011. *SANS 10400-T: 2011 - The application of the National Building Regulations Part T: Fire protection*. Vol. 9098. Pretoria: South African Bureau of Standards.

Suzuki, J. ichi, Mizukami, T., Naruse, T. & Araki, Y. 2016. Fire Resistance of Timber Panel Structures Under Standard Fire Exposure. *Fire Technology*. 52(4):1015–1034.

Taaffe, J., Sullivan, S.O., Ekhlasur, M. & Pakrashi, V. 2014. *Experimental characterisation of Polyethylene Terephthalate (PET) bottle Eco-bricks*. Elsevier Ltd.

Tewarson, A., Abu-Isa, I.A., Cummings, D.R. & Ladue, D.E. 1999. *Characterization of the Ignition Behavior of Polymers Commonly Used in the Automot,ive Industry*. [Online], Available: http://iafss.org/publications/fss/6/991/view/fss_6-991.pdf [2019, May 28].

Vivier, T.L. 2020. *800 EcoBricks later, Noordhoek beach has a beautiful new bench*. [Online], Available: https://www.goodthingsguy.com/lifestyle/800-ecobricks-noordhoek-bench/ [2021, September 27].

Walford, C. 1877. Fires and Fire Insurance Considered Under their Historical, Financial, Statistical, and National Aspects. *Journal of the Statistical Society of London*. 40(3):347–432. [Online], Available: https://www.jstor.org/stable/2339074.

Walls, R., Olivier, G. & Eksteen, R. 2017. Informal settlement fires in South Africa: Fire engineering overview and full-scale tests on "shacks". *Fire Safety Journal*. 91(April):997–1006.

Yakut, A. 2011. [Online], Available: https://www.world-housing.net/wp-content/uploads/2011/06/RC-Frame_Yakut.pdf.

Appendix A : Fuel Load

Fuel load of floor area:

Eco-brick arrangement:

$Bottles_{vertical} := \frac{28}{m^2}$

$Bottles_{horizontal} := \frac{35}{m^2}$

Eco-brick weight:

$Bottle\_weight_{lower} := 400\ g$

$Bottle\_weight_{upper} := 600\ g$

Heat of combustion: From Table 1.2 (Drysdale)

$\Delta H_{c\_PVC} := 19,9\ \frac{kJ}{g}$

$\Delta H_{c\_PE} := 46,5\ \frac{kJ}{g}$

Typical small home dimensions:

$height := 2,3\ m$

$width := 2,4\ m$

$length := 3,6\ m$

$door_{height} := 2,05\ m$

$door_{width} := 0,85\ m$

$Area_{door} := door_{height} \cdot door_{width} = 1,742\ m^2$

$window_{height} := 0,6\ m$

$window_{width} := 0,85\ m$

$Area_{window} := window_{height} \cdot window_{width} = 0,51\ m^2$

$Area_{walls} := 2 \cdot height \cdot width + 2 \cdot height \cdot length - Area_{door} - Area_{window} = 25,348\ m^2$

$Area_{floor} := width \cdot length = 8,64\ m^2$

Mass of the walls:

$M_{vert\_lower} := Bottles_{vertical} \cdot Area_{walls} \cdot Bottle\_weight_{lower} = 283,892\ kg$

$M_{vert\_upper} := Bottles_{vertical} \cdot Area_{walls} \cdot Bottle\_weight_{upper} = 425,838\ kg$

$M_{hori\_lower} := Bottles_{horizontal} \cdot Area_{walls} \cdot Bottle\_weight_{lower} = 354,865\ kg$

$M_{hori\_upper} := Bottles_{horizontal} \cdot Area_{walls} \cdot Bottle\_weight_{upper} = 532,298\ kg$

Maximum possible energy:

$E := M \cdot \Delta H_c$ Eq (3,2) Buchanan

Polyvinylchloride: PVC

$E_{vert\_lower\_PVC} := M_{vert\_lower} \cdot \Delta H_{c\_PVC} = 5649,451\ \mathrm{MJ}$

$E_{vert\_upper\_PVC} := M_{vert\_upper} \cdot \Delta H_{c\_PVC} = 8474,176\ \mathrm{MJ}$

$E_{hori\_lower\_PVC} := M_{hori\_lower} \cdot \Delta H_{c\_PVC} = 7061,814\ \mathrm{MJ}$

$E_{hori\_upper\_PVC} := M_{hori\_upper} \cdot \Delta H_{c\_PVC} = 10592,72\ \mathrm{MJ}$

Polyethylene: PE

$E_{vert\_lower\_PE} := M_{vert\_lower} \cdot \Delta H_{c\_PE} = 13200,978\ \mathrm{MJ}$

$E_{vert\_upper\_PE} := M_{vert\_upper} \cdot \Delta H_{c\_PE} = 19801,467\ \mathrm{MJ}$

$E_{hori\_lower\_PE} := M_{hori\_lower} \cdot \Delta H_{c\_PE} = 16501,2225\ \mathrm{MJ}$

$E_{hori\_upper\_PE} := M_{hori\_upper} \cdot \Delta H_{c\_PE} = 24751,8338\ \mathrm{MJ}$

Fire Load Energy Density per square meter of floor area:

$e_f := \frac{E}{A_f}$ Eq (3,3) Buchanan

Polyvinylchloride: PVC

$$e_{f\_vert\_lower\_PVC} := \frac{E_{vert\_lower\_PVC}}{Area_{floor}} = 653,872\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

$$e_{f\_vert\_upper\_PVC} := \frac{E_{vert\_upper\_PVC}}{Area_{floor}} = 980,807\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

$$e_{f\_hori\_lower\_PVC} := \frac{E_{hori\_lower\_PVC}}{Area_{floor}} = 817,34\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

$$e_{f\_hori\_upper\_PVC} := \frac{E_{hori\_upper\_PVC}}{Area_{floor}} = 1226,009\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

Polyethylene: PE

$$e_{f\_vert\_lower\_PE} := \frac{E_{vert\_lower\_PE}}{Area_{floor}} = 1527,891\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

$$e_{f\_vert\_upper\_PE} := \frac{E_{vert\_upper\_PE}}{Area_{floor}} = 2291,836\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

$$e_{f\_hori\_lower\_PE} := \frac{E_{hori\_lower\_PE}}{Area_{floor}} = 1909,864\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

$$e_{f\_hori\_upper\_PE} := \frac{E_{hori\_upper\_PE}}{Area_{floor}} = 2864,796\ \frac{\mathrm{MJ}}{\mathrm{m}^2}$$

Appendix B : Concrete Validation

Concrete Validation

$f_y := 450\ \text{MPa}$ $d_1 := 20\ \text{mm}$

$d_2 := 40\ \text{mm}$

$d_3 := 206{,}5\ \text{mm}$

Standard Fire Curve:

$$T_g\left(t_{min}\right) := 20\ °C + 345\ K \cdot \log10\left(\frac{8}{1\ min} \cdot t_{min} + 1\right)$$

Temperature in concrete: Wickstrom's

Given:

$depth := 1\ mm$

$time_{SFC} := 60\ min$

$t_{min} := time_{SFC}$

$T_g\left(t_{min}\right) = 945{,}3401\ °C$

$t_h := t_{min} = 1\ hr$

$x := depth = 0{,}001\ m$

$T_f := T_g\left(t_{min}\right) = 945{,}3401\ °C$

Buchanan Ch7

$$\eta_w := 1 - 0{,}0616 \cdot \left(\frac{t_h}{60\ min}\right)^{-0{,}88} = 0{,}9384 \qquad \text{Eq (7.2)}$$

$$T_w := \eta_w \cdot T_f = 870{,}2811\ °C \qquad \text{Eq (7.1)}$$

$$\eta_x := 0{,}18 \cdot \ln\left(\frac{\frac{t_h}{60\ min}}{\left(\frac{x}{1\ m}\right)^2}\right) - 0{,}81 = 1{,}6768 \qquad \text{Eq (7.3)}$$

$$\therefore\ T_c := \eta_x \cdot \eta_w \cdot \left(\frac{T_f - 273{,}15\ K}{1\ K}\right) = 1487{,}494 \text{ degrees Celcius}$$

Abaqus Model: 2D Section 375mm x 1110mm

Steady State

Concrete conductivity $k := 1{,}33\ \frac{W}{m\ °C}$

specific heat $c_p := 900\ \frac{J}{kg\ °C}$

density $\rho := 2394\ \frac{kg}{m^3}$

Convection heat transfer coeff

Ambient $h := 9$ $T := 20\ °C$

Furnace $h := 25$ $T := 945{,}34\ °C$

Radiation Furnace:

Emissivity $\varepsilon := 0{,}8$ $T = 945{,}34\ °C$

Transient see excel for material

Abaqus Results:

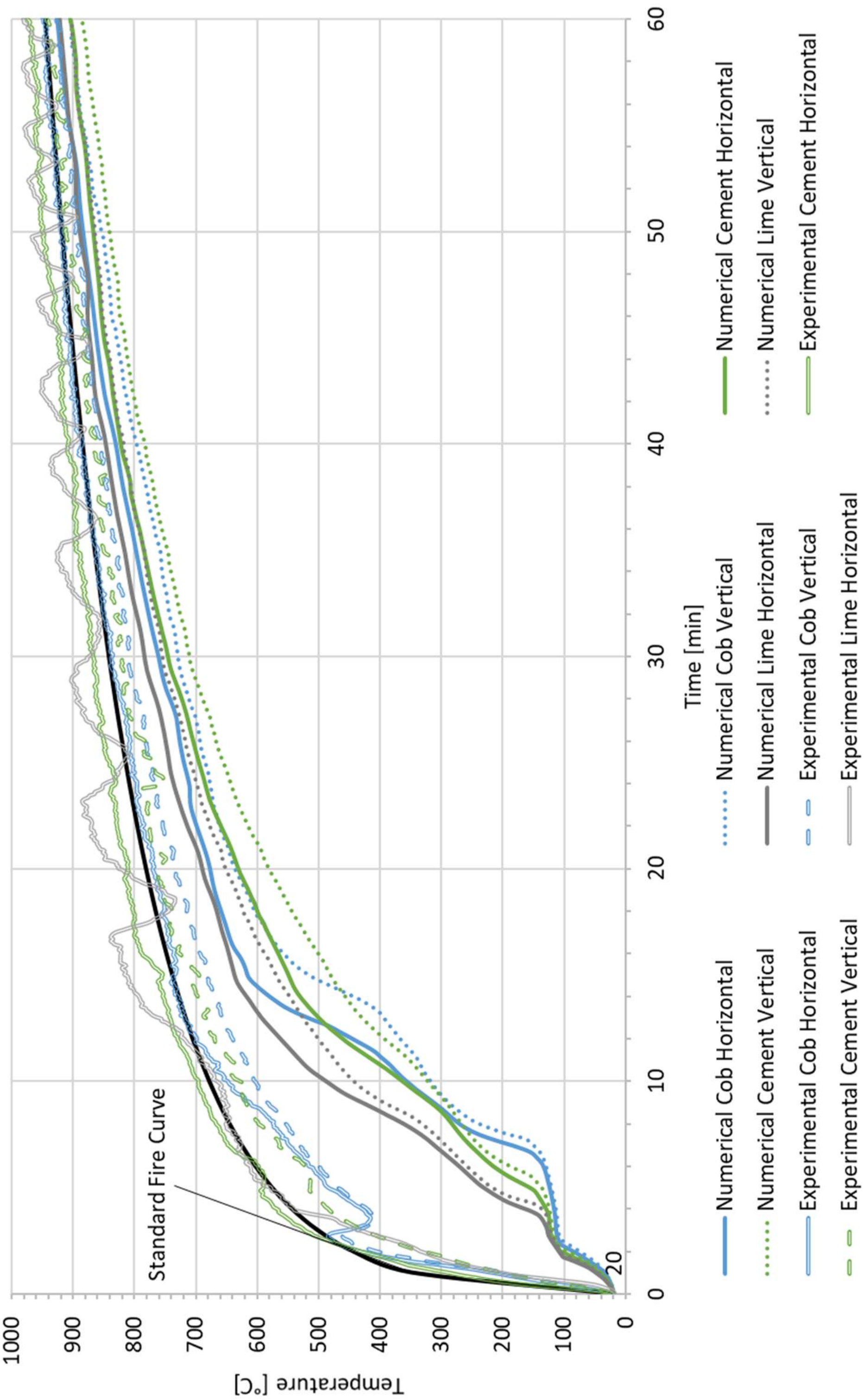
Steady-state	Transient
$T_{20mm} := 903{,}53\ °C$	$T_{20mm} := 526{,}05\ °C$
$T_{40mm} := 868{,}38\ °C$	$T_{40mm} := 310{,}31\ °C$

Appendix C : Finite Element Model Parameters

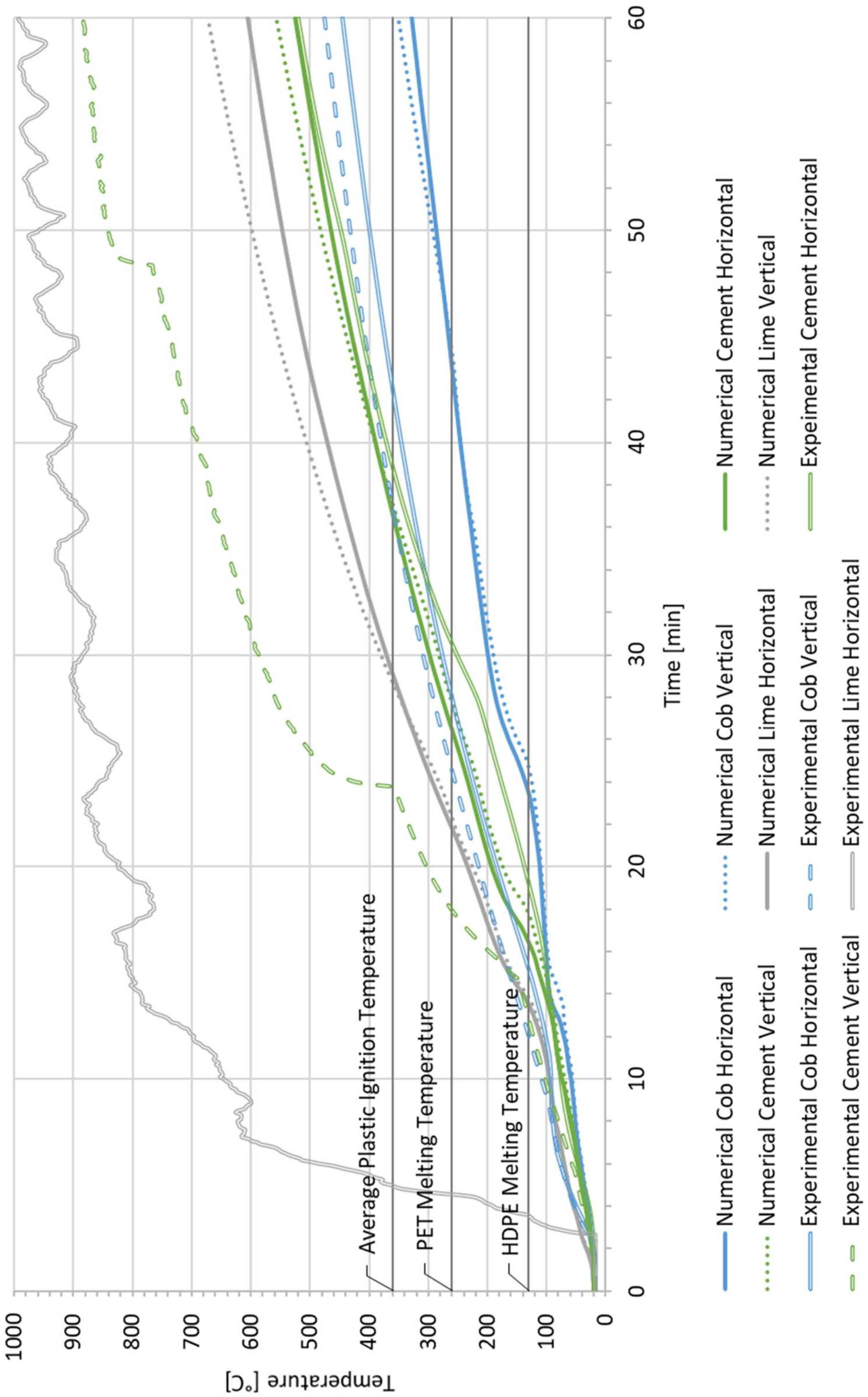
- Parts - Merged
  - 2D Planar
  - Deformable
- Materials
  - Conductivity
  - Density
  - Latent Heat
  - Specific Heat
- Sections
  - Solid, Homogeneous
- Steps
  - Initial
  - Transient Heat Transfer
    - Time period 3600
- Interactions
  - Surface Film Condition (Convection): Ambient temperature applied to unexposed surface
  - Surface Film Condition (Convection): Gas temperatures applied to exposed surface
  - Surface Radiation: Radiation caused by gas temperatures applied to exposed surface
- Predefined Fields
  - Initial temperature applied in initial step to the whole sample

Appendix D : Experimental and Numerical Results

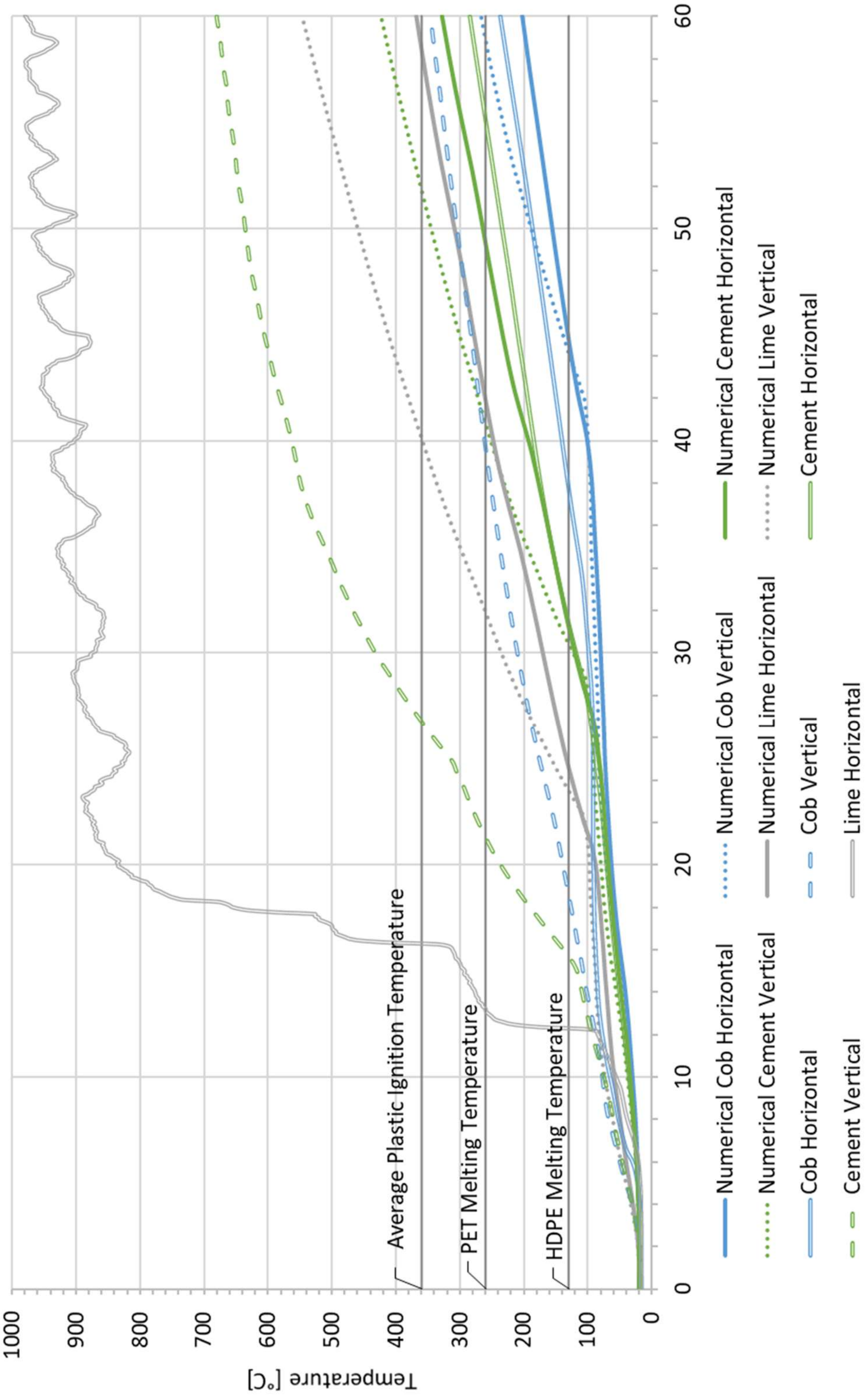
<u>Numerical Surface Temperatures Associated with Experimental Gas Temperatures</u>



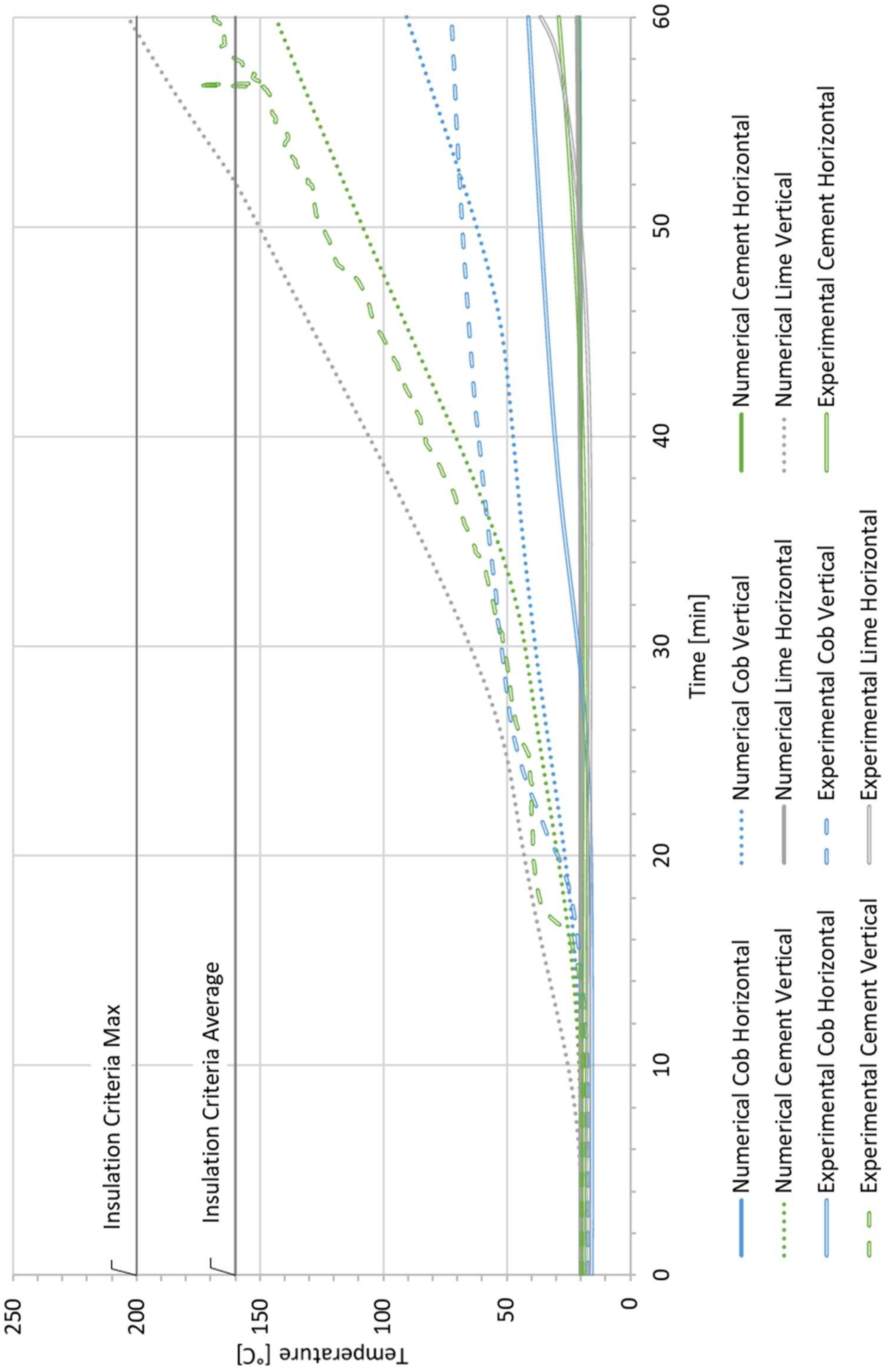
Mid-plaster Temperatures



Back of plaster Temperatures


Temperature [°C]
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Average Plastic Ignition Temperature
PET Melting Temperature
HDPE Melting Temperature
Numerical Cob Horizontal
Numerical Cement Vertical
Cob Horizontal
Cement Vertical
Numerical Cob Vertical
Numerical Lime Horizontal
Cob Vertical
Lime Horizontal
Numerical Cement Horizontal
Numerical Lime Vertical
Cement Horizontal

Mid-section Temperatures



Unexposed Surface Temperatures