Evaluating the potential impact of adding waste glass to clay bricks: An experimental study

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ABSTRACT

In the ever-changing business environment, staying ahead of the competition is crucial, creating a pathway for a new industry, that is entrepreneurial. Embarking on the unbeaten track is immensely challenging and will likely be difficult for most who accept the challenge, therefore, by conducting thorough research and preparing for the challenges, will improve the probability of success for any entrepreneur.

The objective of this research project was to evaluate the impact of adding waste glass to clay bricks, during the manufacturing process, firstly, to determine if various admixtures will yield measurable differences in the quality of the products and secondly, to determine whether the admixtures will improve the quality of the products. The research began with a literature study on the waste generated in South Africa and if there was a need to reduce the waste on landfills. Statistics revealed that there was an alarming imbalance between the amount of waste produced in South Africa versus the amount recycled.

This prompted procuring the necessary material to conduct laboratory-scale testing to establish if the concept was possible and to identify a facility where the physical testing could have been concluded. Laboratory scale testing ensued and proved that producing clay brick samples containing admixtures of glass was possible and full-scale testing was initiated. An investigation was conducted to determine the appropriate equipment required to do the crushing of waste glass on a large scale and appropriate equipment was identified.

A total of 108 samples containing 2% and 3% admixtures were manufactured for the tests and final results proved that the glass admixtures did in fact, improve the quality and durability of the clay bricks. Further recommendations were made to enable an aspiring entrepreneur to use the information in this research project to generate a profitable business that can benefit the economy as well the environment of South Africa.

Keywords: Waste, flux, quality, durability, strength, cullet, manufacturing, firing, drying, extrusion, particle-size-distribution.

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DEFINITION OF KEY TERMS

Abbreviations used in this document

Abbreviation	Meaning
BMC	Business model canvas
C	Control samples containing 0% glass admixture
FBA	Face brick aesthetic
FBS	Face brick standard
FBX	Face brick extra
GDP	Gross domestic product
NDP	National Development Plan
NFP	Non-facing-plaster
NFX	Non-facing extra
PA	Clay pavers (1:1, 2:1 or 3:1)
PB	Clay pavers
POC	Proof of concept
RDP	Reconstruction and Development Programme / Government subsidised housing
SANAS	South African National Accreditation System
SABS	South African Bureau of Standards
SANS	South African National Standards
S1	Samples with 2% glass admixture
S2	Samples with 3% glass admixture
TPH	Tonnes per hour
TVA	Transverse Arch kiln
VSBK	Vertical Shaft Brick Kiln

LIST OF DEFINITIONS

Acceptable: Acceptable to the authority administered in this standard (SANS, 2007).

Bar: Bar is a unit of pressure defined as 100 kilopascals (KPa).

Bed-face: One of the surfaces (of a test unit or sample) that are normally placed in a wall (SANS, 2007).

Burnt clay masonry unit: A masonry unit made basically from clay or shale (with or without an admixture of other materials) moulded or extruded into a rectangular form, hardened by firing, and with or without frogs, perforations or cavities (SANS, 2007).

Cullet: Recycled or refuse glass used in glass-making, suitable for remelting.

Durability: The ability of a material to withstand the combined effects of the weathering agents of moisture, soluble salts and thermal changes to which it is exposed (SANS, 2007).

Efflorescence: Soluble salts that have crystallized on or near the surface of the unit (SANS, 2007).

Face unit: A unit especially made or selected as being acceptable for use without plaster (SANS, 2007).

Flux: A flux is used to promote flowing or fluidity and to remove impurities, fluxes are also used to reduce the melting temperature of materials.

Frog: Depression formed in one or both bed faces of a unit, the total volume of which does not exceed 25% of the gross volume of the unit (SANS, 2007).

Moisture expansion: The unrestrained linear irreversible expansion of a unit at normal temperatures, caused by the absorption of moisture (SANS, 2007).

CHAPTER 1

NATURE AND SCOPE OF THE STUDY

1.1 INTRODUCTION

The focus of this study is limited to exploring the construction industry in South Africa, specifically the clay brick manufacturing industry and exploring potential opportunities for entrepreneurs in adding waste material (specifically waste glass) to the production process and evaluating the effects thereof. Laboratory trials were conducted to prove the concept of extruding, drying and firing clay bricks with an admixture of fine glass particles. Final product testing was conducted on a number of samples to evaluate the impact fine glass material has on fired clay bricks. The optimal crushing methods are investigated and the cost of establishing a plant to do the processing was calculated

1.2 BACKGROUND

This study will focus on evaluating the potential impact resulting from adding waste glass particles to the clay brick manufacturing process, firstly to prove/disprove the hypotheses that the glass will act as a flux which may aid in reducing the firing temperature of the bricks (lowering the energy consumption in the production process). Secondly, to evaluate the change in properties (workability, green shrinkage, water absorption, fired shrinkage, breaking strength and compressive strength) of the clay brick bodies before and after firing. "The possible benefits are threefold: economic benefits due to a reduction in volume of raw material required per unit produced, as well as a reduction in the firing temperature required: environmental benefits due to the diversion of solid waste from landfills, and placement of waste in a sound, inert and useful medium: strength benefits due to the possibility of increased strength and durability of the fired bricks by using appropriate waste material to act as a fluxing agent within the brick" (Frederico *et al.*, 2005). Data will be gathered through conducting laboratory experiments, concluded by a SANAS accredited materials testing laboratory in Pretoria, South Africa. Laboratory tests will be conducted to determine the optimal particle size to enable the glass particles to penetrate open pores inside the clay mixture which will further reduce water absorption of the fired product. Furthermore, physical testing will be concluded on clay brick samples with added glass fines, evaluation of fired products according to SANS 227:2007 specifications and requirements. Optimal processing of the glass will enable an entrepreneur to market the new material as a sellable raw material to be used in the industry. If the primary laboratory experiments prove to be successful, secondary experiments will be concluded to determine the process that can be replicated on a large scale for mass processing. Further investigations will determine the optimal processing methods and capital investment required to establish a plant to satisfy the market. The following impacts will be evaluated (economical, environmental, financial, final product) to determine if this may well be a potential new business venture for entrepreneurs in South Africa.

1.3 PROBLEM STATEMENT

The problem this study aims to address is to increase the overall percentage recovered/recycled waste glass from landfills by beneficiating (processing) waste glass into new raw material. Glass waste is not biodegradable and creates a problem for solid waste disposal, therefore it is vital to provide an alternative, environmentally friendly solution to minimise landfill waste (Abdeen & Shihada, 2017). It is believed that the processed material potentially has beneficial properties that can improve the quality of fired clay bricks. This study aims to develop a business model by reducing waste and generating profit through effective processing methods. Firstly, a technical feasibility study will be conducted in order to determine the properties of introducing processed waste glass to clay bricks, the results will be measured and if successful, will enable the researcher to further investigate the requirements to supply the market with the process raw material. Secondly, the cost of processing waste glass will be calculated by determining the optimal layout, output and approximate running cost of a small-scale processing plant with the appropriate machinery for processing to determine whether it is feasible to use waste glass as a replacement for other fluxes available on the market such as feldspar. This information will contribute to the development of a business model for entrepreneurs who may use the information provided to start a business venture where it involves the construction of a processing plant to supply clay brick manufacturers with processed waste glass to improve their clay brick products.

1.4 OBJECTIVES

1.4.1 PRIMARY OBJECTIVES

- Prove/disprove hypotheses that glass particles will act as a flux in clay bodies.
- Determine the strengths and weaknesses of clay bricks containing waste glass.
- Determine whether waste glass can be a substitute for other fluxes on the market, i.e. feldspar.
- Determine the economic impact of the profitability of a processing plant.
- Determine the capital investment cost of waste glass processing plant.

1.4.2 SECONDARY OBJECTIVES

- Conduct testing and compare results with samples containing glass and samples without glass.
- Interpret the results of the laboratory experiments.
- Gather information on the cost of equipment and machinery required to process waste glass into new raw material.
- Gather information on the cost of building a processing plant including civil works and installation of equipment as well as monthly overhead costs and profitability.

1.5 SCOPE OF THE STUDY

This study will be concluded on experimental design, using scientific methods to prove or disprove the hypotheses that waste glass will have a significant improvement in the physical properties of fired clay bricks. The nature of the study will mainly be of a technical nature including methods and experiments concluded in a laboratory to extract information to be used to develop a business plan, although financial information will be presented, the intention is not to do a financial feasibility study but to focus on technical information. The research will include an investigation and evaluation of existing studies to find and determine the relationship between the findings in the studies concluded in other countries around the world to the findings and results in this study.

1.6 RESEARCH METHODOLOGY

A quantitative research approach will be conducted for the purpose of this study. The quantitative approach will be used to generate and analyse data generated from laboratory experiments on concluding the proof of concept evaluation and real-world simulations. Data generated during the laboratory experiments will allow the researcher to compare results. The one-factor-at-a-time method will be followed. Variants of different additions of glass (i.e. 0% (control), 2% and 3% glass addition will be measured against the control), samples will be fired at a pre-determined firing temperature and applicable SABS 227:2007 test procedures will be carried out to compare the results of samples vs the control. The optimal particle size will be determined by crushing glass particles into different sizes and firing samples containing the different sizes of glass particles until no substantial visual difference is visible between the control samples and samples containing glass particles. The optimal particle sizes will be determined by sieve analyses to determine the particle size distribution of crushed glass powder. The laboratory tests will determine the potential of the proposed products and to evaluate the potential benefits and limitations the new product may/may not have. Industry analysis will determine the potential cost of establishing a processing facility and a capital expenditure determination will be designed to evaluate a budget cost for the aspiring entrepreneur.

The Osterwalder business-model canvas will be used to develop the business model for the prospective entrepreneur in a logical structure, also to allow the entrepreneur to visualise ways to determine how to complete and manage activities of the new venture.

1.7 DESCRIPTION OF RESEARCH DESIGN

This matrix (see Table 1) will serve as the basis on which all results from laboratory experiments will be compared. The matrix will be expanded to indicate results from every sample batch tested. Averages will be calculated from the total number of samples which will be used to compare with the averages from the other batches, i.e. average breaking strength of the control will be compared against the average breaking strength of sample 1 and so forth.

Table 1-1: Matrix to compare test results

	Parameter	Control 1 (0% glass)	Sample 1 (2% glass)	Sample 2 (3% glass)
Fired temperature	Workability			
	Water absorption			
	Green Shrinkage			
	Moisture content			
	Fired Shrinkage			
	Breaking strength			
	Crushing strength			

Furthermore, test work is divided into two phases namely, the laboratory phase in which the proof of concept of manufacturing clay bricks containing glass particles will be completed and secondly, real-world simulations will follow the laboratory phase where a large number of samples will be manufactured to be fired in an industrial tunnel kiln, thereafter tests will be conducted on the samples to measure the change in properties of the samples containing variations of glass admixtures.

1.8 SAMPLING

This study, being experimental by nature required a substantial number of test samples to accurately determine a measurable difference in the properties of the samples versus the control. The controlled samples consisted of raw clay material, procured from two different existing clay brick manufacturers (control) in the Gauteng region. The raw material was prepared and extruded into equal size samples which were numbered for the purpose of the experiments. Test samples were made with the same clay material (to maintain consistency) but with a pre-determined addition of glass powder (2% and 3% respectively). 108 samples were manufactured for the purpose of the experiments (control=36 samples, sample 1=36 samples, sample 2=36 samples).

The following units of analysis (parameters) will be compared between the test specimens:

- Workability
- Water absorption
- Green Shrinkage
- Moisture content

- Fired Shrinkage
- Breaking strength
- Crushing strength

1.9 DELIMITATIONS AND ASSUMPTIONS

1.9.1 DELIMITATIONS

This study was conducted in the vicinity of the Gauteng province, South Africa as this region is home to the largest flat glass manufacturing company in South Africa, the SANAS accredited materials testing laboratory where all testing procedures took place and 23 clay brick manufacturers (6 of which use tunnel kiln technology for firing). The laboratory tests were conducted on clay samples received from an industrial clay brick manufacturer who utilises tunnel kilns for the firing of the bricks as sufficient temperature management in tunnel kilns is achievable and replicable on small (laboratory) and large-scale (real-world environment) environments.

1.9.2 ASSUMPTIONS

It is assumed that raw materials (clay) required for this study will be available from clay brick manufacturers in Gauteng and useable for the purpose of this study. Another assumption is that laboratory experiments will provide results that will be replicable on a large scale to conclude the real-world simulations. Furthermore, an assumption is made that existing literature will support the findings gathered from the testing and research concluded in this study. Lastly, the assumption is that the technology required to effectively process the waste material is available on the market and the capital investment required is calculable to enable an entrepreneur to use the information in this research project to acquire and install the appropriate equipment to conduct the processing of glass.

1.10 RIGOUR AND RELIABILITY

All tests and experiments were conducted under the supervision of a competent representative from a reputable, independent SANAS accredited materials testing laboratory based in Pretoria, Gauteng, South Africa, who has been in the material testing industry for more than 16 years. Tests were conducted and executed against the SANS 227:2007 standard methods and procedures (see units of analysis for test methods). The test results pertain only to the specimens tested and all test results will be filed in the archives of the laboratory for five years as per the requirements of the South African National Accreditation System. Therefore, the test results will be of high quality as the reputation of the materials testing laboratory is at risk. All laboratory tests were conducted on-site, on the premises of the materials testing laboratory.

1.11 RESEARCH ETHICS

1.11.1 ETHICAL CONSIDERATIONS

The following ethical principles will be followed throughout the duration of the study:

- Data collection and analysis will be done without any interference or manipulation of results.
- The information of the clay brick factory where the clay raw materials were procured will be kept confidential.
- The name and information of the glass manufacturing company will be kept confidential.
- The results pertain only to the samples tested.

1.12 LAYOUT OF THE STUDY

Chapter 1: Nature and scope of the study

This chapter is focused on the context and background of the study. It introduces the reader to the topic(s) being researched, the problems and the reason for the research. Research design, the scope of the study, delimitations and assumptions are presented in this chapter.

Chapter 2: Literature review

In this chapter, the construction industry in South Africa is discussed, the clay brick manufacturing process is explained, waste and glass waste in clay bricks are also discussed.

Chapter 3: Research design

The measures of tests and analyses are discussed in this chapter, the different phases of the study are explained, the South African National Standard on which different tests were conducted on is expressed, data collection methods are discussed, crushing methods are outlined and the theory behind the Osterwalder business model canvas is described.

Chapter 4: Results and findings

All of the results from the different tests are revealed, results from similar research are compared, the capital investment required to establish a processing plant is given and the application of the Osterwalder business model canvas for the processing plant is explained. Data were arranged in tables, graphs and figures to illustrate the findings of the test results.

Chapter 5: Conclusions and recommendations

This chapter provides the reader with a summary of all of the findings from the tests, it provides conclusions and recommendations motivated by the facts obtained from the data collected from the analyses.

CHAPTER 2
LITERATURE REVIEW

2.1 LITERATURE REVIEW

2.1.1 SOUTH AFRICA AND IT'S ECONOMY – AN OVERVIEW

South Africa, situated at the most southern tip of Africa, became a republic in 1961 and transitioned into a constitutional democracy in 1994 (PWC, 2019). The country is described as a middle-income, emerging market by investors. South Africa has an abundant supply of natural resources, including gold, platinum, and diamonds. According to PWC (2019), South Africa has well developed financial, legal, communications, energy and transport sectors. The country is known as a "rainbow-nation" due to its cultural diversity and its 11 officially recognised languages. South Africa has a modern infrastructure, supported by the efficient distribution of goods to major centres across the country (PWC, 2019). South Africa's stock exchange is the largest in Africa and among the top 20 in the world (Indexmundi, 2018).

Economically, growth has decreased in recent years, slowing to an estimated 0.7% in 2017 (Indexmundi, 2018). Factors including unemployment, poverty, inequality, and corruption remain among the highest in the world, possibly hampering growth and clouding the perspective of foreign investors. According to Indexmundi (2018), official unemployment is roughly 27% of the workforce, this high unemployment rate is a major concern for South Africans as high unemployment rates contribute to an increase in poverty and inequality of its population. WB (2019) states that the South African economy grew by 1.3% in 2017 and by 0.8% in 2018, furthermore the World Bank projects 2019 growth at 1.3%. This projection can be ascribed to population growth, coupled with the gross domestic product (GDP) per capita growth being close to nil since 2014 (WB, 2018).

2.1.2 INFRASTRUCTURE AND CONSTRUCTION OUTLOOK OF SOUTH AFRICA

The South African construction industry is a strategic sector that supports the South African government's National Development Plan (NDP) (Veitch, 2017). The 2016 nominal expenditure on construction works and related activities totalled approximately

R 420 bn, furthermore, the sector generated an estimated 1,483,000 employment opportunities across the formal and informal sectors of the industry (Veitch, 2017). The South African construction industry has been in a steady decline in recent years with the nominal value of contracts awarded to industry decreasing year on year. A substantial decrease of new contracts awarded by the South African government coupled with increased violence and thuggery on local construction sites caused a state of accelerated decline in the South African construction industry (Venter, 2019). "Public infrastructure spend has been declining", in the 2017/2018 financial year, government's infrastructure budget was R 947,2 bn and in 2018/2019 it was reduced to R 834,1 bn, totalling a nominal decrease of 12% (Venter, 2019). Furthermore, Venter (2019) reports that there was a 15.3% decline in the nominal value of contracts awarded, with the building industry being hit the hardest.

South Africa's beleaguered construction industry faces a trio of major risks this year from the general election, failing state-owned entities (SOEs) and the Budget, according to construction market intelligence firm Industry Insights (Cokayne, 2019). Fitch Solutions expects that 2019 will be the year the sector will finally emerge from the recession (Mavuso, 2019), stating that growth will remain tepid at 2.4%. It is clear that the South African construction sector is in turmoil with some reporting that it is at the lowest position it has been for more than 20 years. On the other hand, others are arguing that the industry will improve and grow once again.

2.1.3 BUILDING MATERIAL INDUSTRY IN SOUTH AFRICA

"The total building materials market was worth R 191,3 bn in 2016 according to Statistics South Africa (StatsSA)" (Bekker, 2017). Wholesale trade in construction/building materials such as cement, aggregate, concrete and steel totalled R 122,9 bn, while retail sales of hardware, paint and glass were worth R 68,3 bn (Bekker, 2017). The South African building materials industry outlook has been more positive in recent years, though being reliant on the construction sector. "Companies like Afrimat and Corobrik have been thriving despite a weak economy" (Bridge, 2016). Bekker (2017) further states that building materials account for up to 6.2% of total South African wholesale trade, while the retail of hardware, paint, and glass makes up 7.5% of all retail in the country.

2.1.4 FOCUS: CLAY BRICK INDUSTRY IN SOUTH AFRICA

The clay brick industry in South Africa is an essential sector in the larger building materials industry. The building and construction industry recorded an income of R 395 bn in 2014 and that informal and formal clay brick sectors employed approximately 20 000 people (Bosman, 2016). Bosman (2016) also reported that since 2016, there had been a need for more than 1.5 million RDP houses (government subsidised housing) which were to be constructed between 2016 and 2020 at a cost of R 30 bn per annum, creating a significant demand for bricks to be manufactured. It is estimated that the total number of formal clay brick manufacturers have declined from approximately 112 in 2014 to approximately 105 in recent years.

The first clay bricks in South Africa were produced in 1652 and the first house constructed with fired clay bricks was built in August 1654 (Swisscontact & CBA, 2016). Furthermore, it is reported that the mass production of clay bricks began in 1655. Swisscontact (2016) also reports that clay bricks assisted in meeting the growing need for housing in mining towns across the Witwatersrand after 1900. At present, it is estimated that 3500-3600 million bricks are produced annually in South Africa in industrial (formal) factories across the country. Clay bricks factories vary in production size as some produce an average of 0.5 million bricks per month while other factories are capable of producing more than 20 million bricks per month. Clay bricks have a market share of 45% in South Africa versus other building materials.

Figure 0-1: Market share of building materials in South Africa

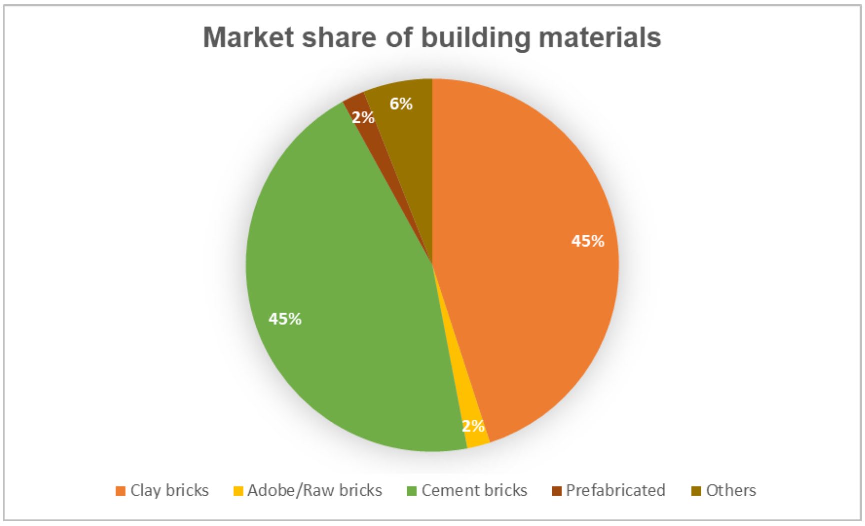


Figure source: Swisscontact and CBA (2016)

The production output of clay brick factories is dependent on technologies incorporated in production coupled with the fuel sources used to fire the bricks.

2.1.5 CLAY BRICK – AN OVERVIEW

Clay bricks are regarded as the simplest and oldest of all building materials. The multitude of uses of clay bricks is quite extensive as clay bricks can be used for load-bearing construction, decorative application or any combination thereof. Clay can be moulded into virtually any shape or form and requires little to no maintenance if properly constructed. The flexibility this gives to design and construction makes building with clay bricks most cost-effective (CBA, 2012). “Secondary clay materials are compounds of alumina, silica with minor amounts of lime, magnesia, soda or potash. Iron compounds, usually the oxides, hydroxides or carbonates, are nearly always present as impurities in brick clays” (du Toit & van Vuuren, 2016). These impurities contribute to most of the wide range of colours available in the finished product. Iron oxides that range between 8-10% will have a pinkish-to-red finish while manganese dioxide content or addition of 1-4% will create a range of colours from grey to brown. The chemical composition of clay bricks plays a critical role in the manufacturing process. The following facts should not be ignored:

- The addition of water to clay increases plasticity and workability, allowing the user to shape/mould the clay into the desired shape.
- Controlled evaporation of free water surrounding the particles in “plastic” clay minimises excessive shrinkage during drying in the structure of the brick.
- Heat affects the physical properties of the clay body, controlled flow of heat between 100 – 400 °C will assist in the drying process, whilst heat ranges between 1000 – 1200 °C fuse the clay particles into a cohesive mass of exceptional strength.

2.1.6 CLAY BRICK MANUFACTURING PROCESS

Modern clay brick factories are capable of extrusion rates of at least 25 000 bricks per hour. Before firing, “green” bricks are much heavier due to increased water content and should be dried before firing. The traditional South African clay brick has the following dimensions 222 mm (l) x 106 mm (b) x 73 mm (h) and weighs between 3-3.5 kg as a final product.

Figure 0-2: Standard brick dimensions

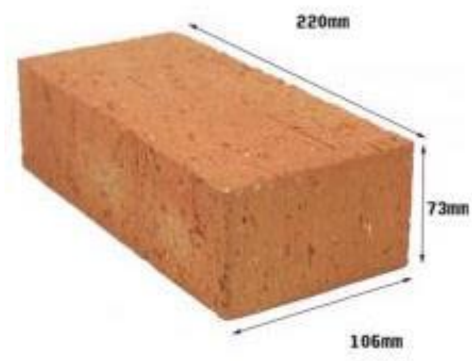


Figure source: (Nova, 2019)

2.1.7 MINING AND STOCKPILING OF CLAY

Mining of clay is conducted using the open cast mining method (quarrying), i.e. topsoil and overburden (unusable material) is removed by means of heavy machinery (earth-moving equipment). Heavy machinery may include hydraulic excavators, mechanical scrapers or bulldozers. The excavated material is removed from the pit and transported by dump truck or conveyor system to stockpiles. Clays and shales removed from the pit may have different properties (compositions) and will influence the mining procedures, furthermore quarry samples should be evaluated regularly to maintain quality and uniformity of the material in the quarry. Stockpiling of the clay can be done in various ways, clays can be stockpiled either as individual material or blended in layered stockpiles. Stockpiles function as blending, conditioning or storage piles. The main aim of stockpiles is to maintain uniformity of material over extended periods of time (CBA, 2012).

Figure 0-3: Mining of clay material

Figure source: (Ziegelindustrie, 2011)

2.1.8 CLAY PREPARATION

Once the clay is mined from the quarry it may be in the form of fine to coarse clay particles to lumps of clay (shale). At present, different methods are used in the industry for the preparation of raw materials, of which the main process includes reducing particles to pre-determined sizes. The size reduction process can include up to three crushing stages (depending on the type of bricks). Primary crushers are suitable for primary crushing or grinding of clay and minerals directly from quarries and for reducing irregular sizes to uniform sizes below 80 mm (Verdes, 2019).

Figure 0-4: Primary crusher (Roller type)

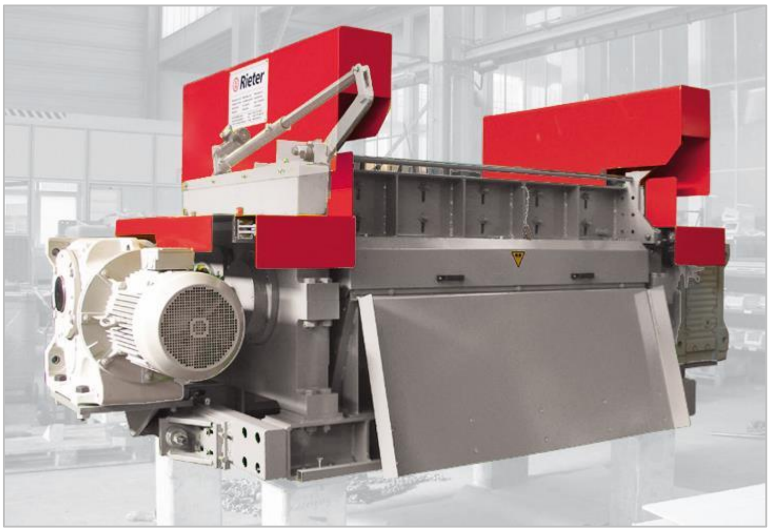


Figure source: (RieterMorando, 2019)

Secondary crushing includes further reduction of material from 80 mm to less than 8 mm, equipment used in secondary crushing includes refining rolls, disintegrators or pan mills.

Figure 0-5: Wet pan mill

Figure source: (Verdes, 2019)

Tertiary crushing involves the further reduction of particles to an average size of 0,8 mm. Softer materials will require fewer types of crushing or crushing stages. Traditionally, South African manufacturers use roll crushers, hammer mills, pan mills, and refining rolls. The preparation process further involves transporting (conveying) the crushed material through screens for size determination and once optimal sizes are achieved, additives such as coal, manganese, sand, grog (crushed bricks) and ash are added, depending on the process of the manufacturer as some additives influence colour and strength or function as a fuel source inside the clay body to aid in the firing process. Lastly, the fine mix can be stored under shelter (souring) or moved directly to the next step in production, known as forming. Souring is recommended for South African conditions. During this period of rest, the water spreads by means of capillary attraction and the clay undergo the necessary changes, eventually becoming a homogeneous mass ready for the shaping process (BioKeram, 2019).

2.1.9 THE SHAPING OF CLAY BRICKS

The shaping of clay bodies can be done in a multitude of ways including soft-mud hand moulding, semi-dry pressing, and extrusion. Fort the purpose of this study, the focus on forming methods will be conducted on extrusion as all formal South African manufacturers use the extrusion method for forming/shaping of bricks in the manufacturing process. Before the clay mixture is extruded, the clay is mixed by means of industrial mixers, typically single or double-shaft mixers are placed before the extruders to aid in mixing the clay before extrusion.

2.1.10 EXTRUSION

Extrusion can be described as passing a water and clay mixture through a suitable orifice or die to create a continuous column. The clay is forced through the die under pressure by means of an auger and a vacuum is created in the die chamber to remove air from the column so that a stiffer column of extruded clay is created. The extrusion process can be further defined into two types of extrusion, soft - and stiff extrusion. Depending on the plasticity of and the water content of the clay, stiff extrusion is defined as clay containing between 12-20% of moisture at the point of extrusion, while soft extrusion columns are extruded with 20-30% moisture in the column. Very few South African clay factories use soft extrusion methods as the majority of clays in the South African regions are coarse and difficult to extrude without the addition of water. The process (See below, Figure: 6) can be described in the following steps:

- **I.** Clay is deposited into the mixture and mixed thoroughly.
- **II.** The clay mixture is forced by an auger towards the die of the extruder.
- **III.** The clay column is forced through the die of the extruder and takes the shape of the die, the clay column can be perforated or unperforated, depending on the shape of the die.

Figure 0-6: Extruder

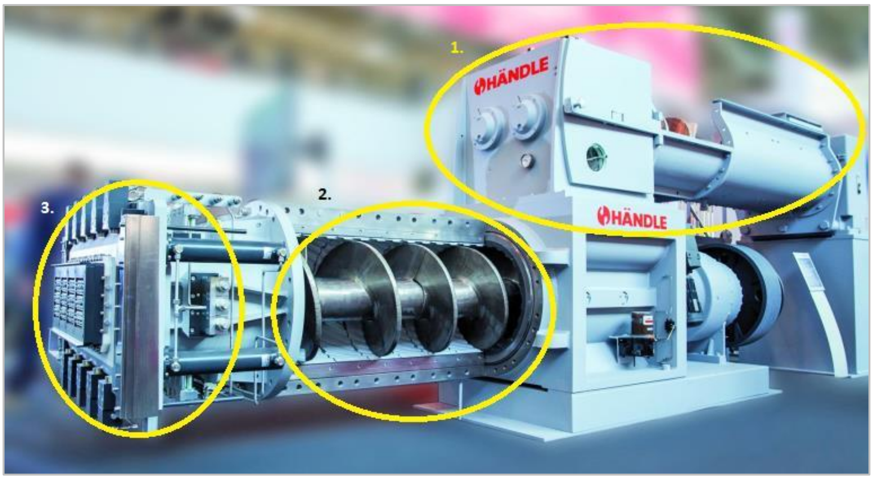


Figure source: (Ziegelindustrie, 2016)

Figure 0-7: Extrusion of clay column

Figure source: (Tecnofiliere, 2019)

Extruded columns are cut into brick-sized pieces by an arrangement of wires using a reel-cutter or push-through-cutter.

Figure 0-8: Push-through-cutter

Figure source: (Araipiasa, 2019)

The process is mechanised and automated to increase uniformity and efficiency as the high production capacity demands continual production. Extruded bricks may be patterned or textured. Extruded bricks can be perforated or solid (depending on the design of the die). Perforation improves drying, firing and cooling times as air (hot or cold) can pass through the bricks with less resistance.

2.1.11 DRYING OF CLAY BRICKS

Before forming, water is added to the clay mixture to assist in shaping, however, after shaping, the water is extracted from the clay bodies by evaporation. There are many ways to dry bricks, however, all methods are classified into one of the following types:

- Intermittent: Intermittent drying refers to a batch process in which bricks are placed in a dryer where they remain until sufficiently dry, after frying they are removed and replaced with fresh, moist products (CBA, 2012; du Toit & van Vuuren, 2016).
- Continuous: Stacked bricks pass continuously through a dryer, entering wet on one side and exiting, dried at the other side of the dryer (also known as tunnel drying).

Intermittent drying can be done outside in the open air (also known as hack drying) or wet products can be placed in chambers (chamber drying) designed to keep a limited number of wet bricks where the air is forced through the chambers to effectively dry out the bricks inside.

Tunnel driers are commonly used in factories where tunnel kilns are built as hot air generated in the kilns are channelled into the tunnel passages of the drier at different intersections as the wet bricks move continually through the dryer on wheeled structures called kiln cars. The total drying process can take 40-50 hours, from “green” to dry.

2.1.12 FIRING OF CLAY BRICKS

Dry bricks are now ready to be fired at temperatures ranging between 1000 – 1200 °C, however, the process is not as simple as adding heat to bricks. Upon firing, chemical and mineralogical changes occur in the clay body of the brick. Furthermore, physical changes also occur as changes in density, porosity, volume, strength and hardness appear in the clay material. The chemical changes can be divided into three distinct stages:

2.1.12.1 CHEMICAL AND MINERALOGICAL CHANGES DURING FIRING

I. **Dehydration stage (100 °C - 650 °C):** "Dried" bricks still have moisture, called combined water (always present under normal circumstances) when placed in the kiln. It's not until around 650 °C that all combined water is removed, i.e. water that is part of the crystal lattice (du Toit & van Vuuren, 2016).
II. **Oxidation stage (300 °C - 800 °C):** Oxidation takes places as water is removed and the vitrification process starts. Typically, oxidation of carbon, sulphur compounds and iron-bearing minerals react and oxidise.
III. **Vitrification stage (800 °C upwards):** Vitrification of the clay refers to the process in which the clay (ceramic) body can withstand high temperatures without serious distortion, secondly vitrification is the stage in which reactions occur that produce the glass phase of production.

2.1.13 PHYSICAL CHANGES IN FIRING

A number of physical changes occur during the firing process of clay bricks:

- **Porosity:** Bricks manufactured for building/construction should be moderately porous, however, pores should not be too large to enable water to be absorbed into the pores (cause of damp spots on walls), at the same time, the brick should be porous enough to absorb mortar and create a strong bond in the wall. Water absorption is classified as:
  - 16% - 20% as high but acceptable for stock bricks
  - 12% - 16% as medium but satisfactory for stocks and face bricks
  - 8% - 12% as low for stock but acceptable for face bricks (du Toit & van Vuuren, 2016)
- **Permeability:** Bricks should be as permeable to air as possible, but only partially permeable to water. High temperature during firing decreases permeability.
- **Change in volume:** Parts of the ceramic materials melt during the vitrification stage, resulting in the remaining crystals migrating closer together. Shrinkage is limited up to the vitrification stage. During vitrification, however, rapid changes in volume (shrinkage) occur until the completion of the vitrification stage. Volume changes are important to evaluate as they are a determinant of the final size of the brick.

- **Strength and hardness:** Typically, higher fired bricks tend to have higher strength. As the strength increases, so too does the porosity decrease proportionally (du Toit & van Vuuren, 2016). Similarly, the higher the firing temperature, the harder the product becomes although hardness is not evaluated during final product testing.
- **Weight:** Generally, all bricks show a measurable decrease in weight during and after firing as a result of all the physical changes as outlined above. Weight loss can be attributed to a loss in moisture, oxidation of minerals or decomposition of organic matter inside the ceramic body.

2.1.14 TYPES OF KILNS

Clay bricks can also be fired intermittently or in a continual process. Intermitted firing is done in kilns called "clamp kilns".

2.1.14.1 CLAMP KILNS

Clamp kilns are constructed every time a batch of bricks is to be fired, therefore they are not permanent structures. This is because the "clamp" is constructed with the bricks that are to be fired. A solid pack of dried bricks are placed on a grid base. The grid consists of the fuel that is to be used for firing (typically coal nuts) and is the basis of the kiln that supplies the initial energy required to ignite the kiln. The bricks in the clamp contain fuel in the clay body to assist in the firing process to enable thorough firing of the brick. Firing times of clamp kilns can range from ten days up to four weeks, depending on weather conditions as clamp kilns are fired outside, in the open air.

Figure 0-9: Grid formation of clamp kiln

Figure source: (Naude, 2018)

Figure 0-10: Coal placed inside the grid

Figure source: (Naude, 2018)

Figure 0-11: Fully constructed clamp kiln

Figure source: (Nova, 2019)

Clamp kilns do have the ability to function continually as well, however, it involves setting bricks in front of the firing zone whilst de-hacking (unpacking) behind the fire. This method creates difficulties in controlling the firing process and can be dangerous for the packers and unpackers. With the additional problem of temperature management of the firing zone, under-firing or over-firing can occur.

2.1.14.2 CONTINUOUS FIRING KILNS

Continual firing kilns are designed to fire the bricks continually from dried to fired, without the need to shut off the heat supply. More modern and advanced brickworks in South Africa are making use of continuous firing methods (du Toit & van Vuuren, 2016).

2.1.14.2.1 CHAMBER KILNS

Continuous chamber kilns include Transverse Arch (TVA) or Hoffmann kilns, both designed to circulate the air required for combustion through the firing zone. The firing zone moves from chamber to chamber as it follows that path of combustible material throughout the chambers, effectively firing the bricks as the fire moves.

Figure 0-12: Hoffmann kiln design

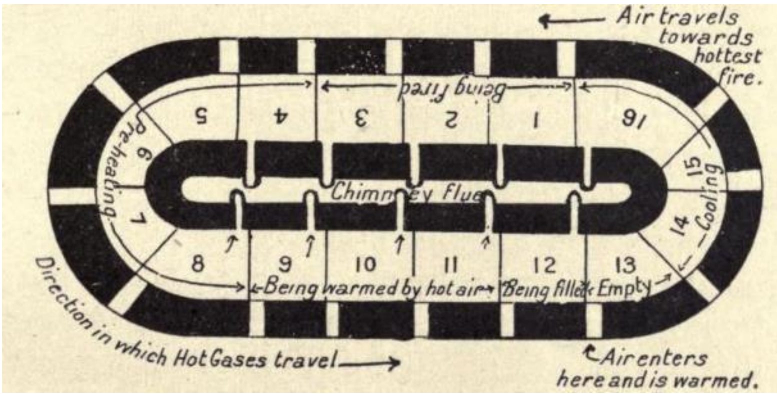


Figure source: (De Decker, 2009)

TVA kilns have become quite popular in South Africa, mainly to ensure compliance with the Air Qualities Act of 2004 (amended in 2014). Chamber kilns have been around for hundreds of years with a number of different designs but functioning on the same principle. Open roof Hoffman kilns, Zigzag and Bull's Trench kilns function on the same firing principles as the Transverse Arch (TVA) kilns but differ as they do not have a fixed roof. After the green bricks are placed inside of the kiln, the top of the setting is sealed off, normally with a layer of reject fired bricks, soil and mud. Natural or forced drafts are used to control the firing process in the kiln (du Toit & van Vuuren, 2016).

2.1.14.2.2 TUNNEL KILNS

Tunnel kilns were originally designed to only use coal as a source for heat but technological improvements in recent years created the possibility of oil and gas being used as fuel sources respectively. Tunnel kilns consist of three main zones, pre-heat, firing and cooling zones. In short, kiln cars (driven by hydraulic pullers) travel through the tunnel through zones of different temperatures and atmospheres as air (of low and higher temperatures) is forced through the kiln. The firing zones have burners where coal, gas or oil are burned continuously, while bricks pass by the firing zone slowly, being fired in the process. Tunnel kilns are traditionally used to produce large volumes of face bricks as tunnel kilns are more manageable, products of higher quality and consistency are usually manufactured in tunnel kilns.

Figure 0-13: Schematic representation of a tunnel kiln

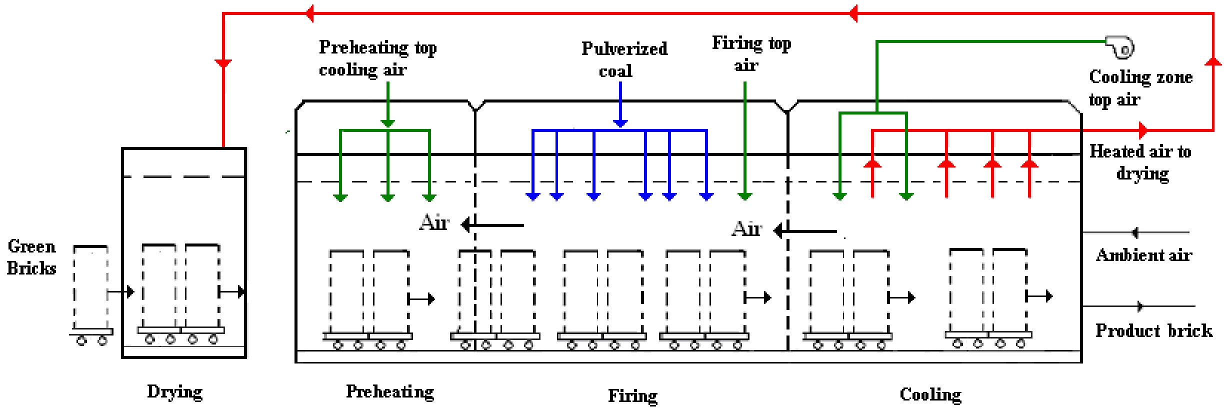
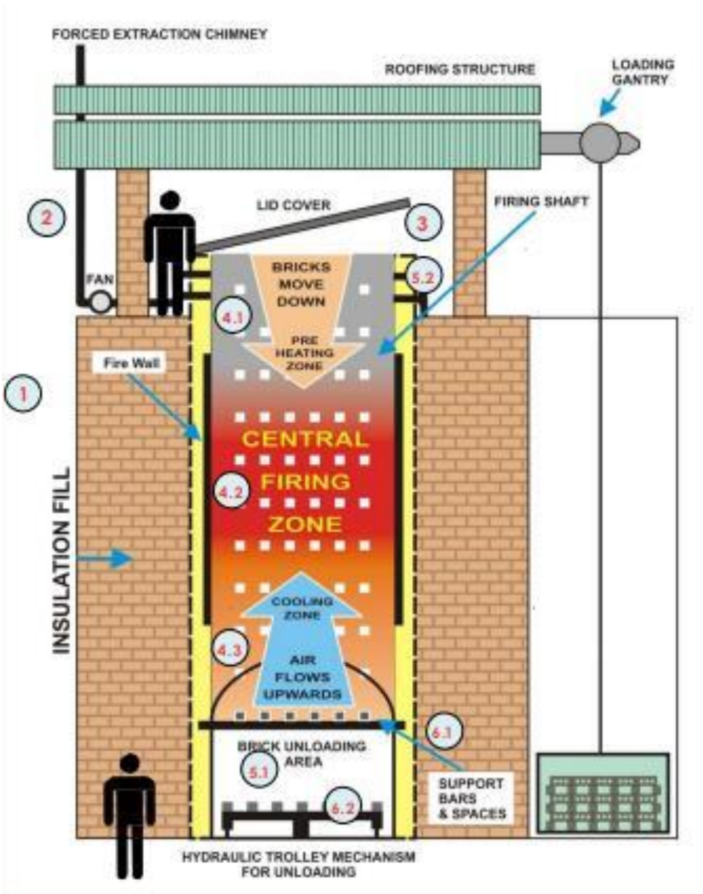


Figure source: (Mancuhan et al., 2011)

2.1.14.2.3 VERTICAL SHAFT BRICK KILNS (VSBK)

The VSBK kiln has only been in the South African brickmaking industry in recent years. It is known as being one of the most environmentally friendly kiln technologies available today. VSBK kilns consist of a vertical shaft size of 1 m² and approximately 6.5 m in height (du Toit & van Vuuren, 2016). At the base of the shaft is an unloading tunnel running through the centre of the kiln. This design allows access from two sides, used for unloading fired bricks whilst loading unfired bricks at the other end. Bricks and coal are loaded, one batch at a time, with the coal being fired as it passes through the combustion zone continuously. Green bricks are loaded while fired bricks are unloaded. The design is so effective as the packing of the bricks restricts air to the point where no excess air is required for firing. The cooling bricks below the firing zone assist in heating the air enough to create combustion, the hot air from combustion moves up to the preheating zone to pre-heat bricks before firing. Once the kiln reaches the required temperature, all the heat from the coal fines goes into the firing of the bricks" (du Toit & van Vuuren, 2016). "

Figure 0-14: VSBK kiln



1. Kiln
2. Exhaust
3. Loading
4. Firing zones
5. Counter current principle
6. Unloading

Figure source: (VSBK, 2016)

2.1.15 SORTING AND DELIVERY

After bricks are fired and cooled down, bricks are unloaded and sorted according to colours and quality then packed on pallets or cube packs of ±500 units and ready for dispatch to depots or directly to customers. Automation in unpacking, packing and handling of bricks has been a familiar sight in South Africa and around the world. Robot technology has also been implemented in handling, stacking and packing of bricks as it increases efficiency and effectivity of the process versus human input.

2.1.16 QUALITY CONTROL AND TESTING

Quality control of and testing of fired bricks are critical in supplying good products to the market. Fired clay bricks can be tested according to the SABS 227 standard (SANS 227:2007 Burnt clay masonry units). Testing according to SABS 227:2007 includes the following inspection and test methods (SANS, 2007):

- Inspection

- Methods of taking samples
- Test specimens
- Test for dimensions
- Test for warpage
- Compressive strength test
- Efflorescence test
- Soundness test
- Water absorption test
- Water-soluble salt test
- Moisture expansion test

2.1.17 TYPES OF CLAY BRICKS

There are three standard brick types in South Africa, namely bricks for rendered or plastered use, bricks with no rendering as well as engineering units, each with its own grades/types.

2.1.17.1 BRICKS FOR RENDERED OR PLASTERED USE

These bricks are designed as a backing to an external face brick leaf, or as a single leaf interior wall. Rendering/plastering of the bricks is essential to protect the brick from weather or to provide a surface for tiling/cladding. These bricks are generally known as NFPs (non-face plaster) or "stock bricks" as well as "commons" or "common bricks" (du Toit & van Vuuren, 2016).

2.1.17.2 BRICKS WITH NO RENDERING

Bricks with no rendering are designed to face the environment without the need for plastering or covering of the surface of the brick as it provides an aesthetic value through colour, texture, accuracy, size and uniformity. These bricks are classed as FBA (Face brick aesthetic), FBS (Face brick standard) and FBX (Face brick extra). Non-face extra bricks are designed for building work below damp proof course (DPC), under damp conditions or below ground level (foundation bricks) where aesthetics are unimportant (du Toit & van Vuuren, 2016). NFX bricks may be plastered or left unrendered (un-plastered).

2.1.17.3 ENGINEERING UNITS

These bricks are produced for structural or load-bearing purposes, they may be facing or non-facing brick types, as long as it conforms to the relevant requirements of the building regulations.

All of the above types of bricks can further be distinguished by surface finishes and textures, textures and finishes include clinker, rockface, rustic, coral, satin and travertine.

2.1.18 WASTE IN SOUTH AFRICA

It is estimated that 59 million tonnes of general waste were produced during the year 2011 in South Africa (StatsSA, 2018a). This is an alarming statistic as this amounts to more than 1 million tonnes of waste per person in the country. Secondly, suitable space for waste disposal is rapidly decreasing as the ever-growing heaps of waste are reaching a point where there will not be areas available for general waste to be dumped in across the country. As landfills are reaching maximum capacity throughout South Africa, progressive closure of landfills is becoming critically important. According to Mavuso (2018), landfills need to be closed for various reasons, including unacceptable environmental impacts namely groundwater pollution, unmanageable air pollution or odours. Stats SA (2018) reported that only 5.2% of households in South Africa recycled waste during 2015. Foodreview (2018) indicated that South Africa has more than 1200 landfills across the country, which receive approximately 90% of all solid waste. Another alarming statistic as published by the South African Department of Environmental Affairs in the article, “South Africa produces a shocking amount of waste” (DEA, 2018), reported that “more than 17 million tons of waste was disposed of across 120 landfills in 2017”. “Reduce, reuse, recycle” is a common catch-phrase known to many around the world, however it seems that not everyone is taking part in reducing the amount of waste produced. Appropriate recycling aids in conserving energy, reducing the use of natural resources and reduces pollution (StatsSA, 2018b).

2.1.18.1 GLASS WASTE IN SOUTH AFRICA

“Glass is essentially a transparent material produced when materials such as silica, soda ash, feldspar, $CaCO_3$ and other fluxes are mixed, melted at high temperature, blown into different shapes and sizes then cooled to solidify without crystallizing" (Abuh *et al.*, 2019). Glass waste accounts for approximately 4.5% of all waste (Consol, 2019). The South Africa State of Waste Report (2018) states that in the year 2017, 1 395 103 tonnes of waste glass was generated and only 320000 tonnes (23%) were recycled, this means that 1 723 506 tonnes of waste glass remained landfilled (DEA, 2018). Fortunately, an increase in glass recycling has occurred in recent years as The Glass Recycling Company reports that more than 80% of glass were diverted from landfill (TGRC, 2019). Glass is traditionally made by heating silica sand, limestone and soda ash up to 1500 °C in a furnace, thereby melting the mixture to create a molten mixture of the ingredients (AZoCleantech, 2008).

2.1.18.2 BENEFICIATION OF WASTE GLASS

"Recycling glass has huge environmental benefits as it saves landfill space, minimises the use of raw materials, lessens the demand for energy, and reduces CO2 emissions (Unknown, 2018). "Cullet" is recycled, crushed glass that can be added to the mixture by as much as 40% (AZoCleantech, 2008). However, there is a limit to the amount of cullet that can be used as increased quantities of cullet may impact the quality of manufactured flat glass (Butler, 2019). Unfortunately, not all glass can be readily recycled. All glass bottles and containers can and should be recycled repeatedly. Window glass (also called flat glass), lightbulb glass, mirrors and ceramic materials like cups, saucers and plates, cannot be readily recycled and should not be added to the glass recycling stream. Even a very small addition of unsuitable material to a large batch of recyclable glass can result in the whole batch becoming contaminated (AZoCleantech, 2008). Furthermore, recycling facilities cannot recycle glass contaminated with food or dirt, this contamination deems the product "not recyclable" (Averda, 2018).

2.1.18.3 WASTE GLASS AS AN ADDITIVE TO CLAY BRICKS

Beneficiation of waste glass is possible by crushing non-recyclable glass into fine sand which can be used as fillers or aggregate in cement or concrete, finely crushed glass can also be combined with foam to create a lightweight filler for insulation and foundation construction (Averda, 2018). Currently, "South Africa does not have mandatory punitive legislation in place regulating the separation of waste materials at the source", says Shabeer Jhetam (TGRC, 2019). This may prove challenging to entrepreneurs who are focused on beneficiating only one part of the general waste generated throughout the country. Glass beneficiating plants do exist around the world; however, they do differ depending on the requirements of the final product. The CQ Glass Beneficiation Plant in Australia utilizes new implosion technology which allows the glass to be broken down to less than 3 mm to be used as a sand replacement in construction (MacKenzie, 2015). "Recent advancements in living standards and development of technology have brought a significant increase in the consumption of glass material" (Hameed *et al.*, 2018). This increase in consumption demands new solutions in the recycling and repurposing of waste materials in an economical and feasible manner.

2.1.18.3.1 INTERNATIONAL STUDIES ON WASTE GLAS IN CLAY BRICKS

A study conducted by Hameed *et al.* (2018) from Pakistan focused on the effect of waste glass in burnt clay bricks, concluded that clay bricks showed a continual increase in flexural and compressive strength with a higher content of waste glass used. Furthermore, the study indicates that water absorption and efflorescence decreased with increased additions at higher fired temperatures. Lastly, the study concluded that specimens burned in industrial kilns exhibited similar trends for increased waste glass content as the specimens fired in the laboratory environment. A study from Turkey indicates that the viability of producing building bricks with waste glass as an additive was verified (Demir, 2016). Test mixtures of up to 10% were evaluated to be strong enough that it could be used in building brick production. Secondly, the Turkish study determined that at a firing temperature of 950 °C, the bricks produced proved to be strong enough for construction purposes, however an increase in strength was detected in bricks fired at 1050 °C. A researcher from Canada stated that upon firing the brick containing glass particles, it is believed that the glass inside the brick softens into a glass form, which bonds the remaining particles to one another where they are in contact in a process known as sintering (Frederico *et al.*, 2005). This was confirmed by a study from Thailand, "the clay bodies containing waste glass, as a consequence, became denser with increasing glass content (Loryuenyong *et al.*, 2009). The raw mixture of clay and waste glass also minimised the physical damage that occurred during brick production. Lastly, Demir (2016) also stated that the reuse of waste glass material in brick production provides an economic contribution and also helps to protect the environment. The feasibility of bricks containing glass was confirmed by the study from Thailand as the researcher stated: Based on the results of this study, it is feasible to use wasted glasses from structural glass walls as a mixture for the manufacture of clay bricks. Wasted glasses can be mixed with clay in different proportions to prepare good quality bricks" (Loryuenyong *et al.*, 2009). See Annexure A8 for results on research on similar experiments from Turkey, Russia, Pakistan and Palestine. On the issue of energy consumption during production, it is believed that adding waste glass to clay may play a part in, by acting as a fluxing material, less energy being consumed during firing of the clay material. "The good news is that bricks can be made using one-third less energy, and within 12 hours from dry clay to finished brick" (Kirby, 2006).

CHAPTER 3
RESEARCH DESIGN

3.1 INTRODUCTION

The experimental design of this study includes a number of different phases. The initial phase of the research will be concluded on small, laboratory-scale testing of clay samples extruded containing 2% and 3% glass fines. The reason for adding such a small amount of glass is to determine whether there is a measurable difference in the properties of the final product and secondly, flux levels in clay bricks generally range between 1-5%. The experimental phases in this research project include laboratory phase testing and real-world simulations. Additionally, further research will involve determining the optimal methods in refining/processing waste glass into the desired particle size, the required equipment and or machinery required and the determining the running cost of processing waste glass including maintenance, the abrasiveness of glass and the optimal arrangement of the equipment for sustainable processing.

3.1.1 LABORATORY PHASE TESTING

The laboratory phase will be completed to prove the concept (POC) of extruding, drying and firing clay brick samples containing an admixture of glass particles. The following steps will be regarded as part of the laboratory testing phase:

- Clay procurement and preparation
- Glass procurement and reduction (crushing) to optimal particle size
- Addition of glass particles and extrusion of samples
- Proof of concept results

3.1.2 REAL-WORLD SIMULATIONS

If the laboratory testing as stated above proves the concept of extruding clay brick samples containing an admixture of glass particles, real-world simulations will be carried by extruding 108 samples with different admixtures of glass which will be dried in the laboratory but fired in an industrial tunnel kiln. The fired samples will then be tested according to SANS 227:2007 specifications and the results reported to determine the difference in properties between the control samples and the samples containing glass. The following steps are included in the real-world simulations:

- Particle size reduction in industrial equipment
- Final product testing:
    - Workability
    - Green shrinkage
    - Moisture content
    - Fired shrinkage
    - Water absorption
    - Compressive strength
    - Breaking strength

3.2 LABORATORY PHASE

3.2.1 CLAY PROCUREMENT AND PREPARATION

Two bags of clay consisting of approximately 50 kg of raw material were procured from a clay brick factory in the Gauteng region. The material from the clay brick factory is known to be very strong and exceeds the specifications according to SANS 227:2007. The purpose of using this material is, however, to determine if there is a measurable difference in the fired products and if a potential benefit may arise from a reduction of firing temperature as the glass is expected to act as a flux.

Figure 0-1: Clay removed from the stockpile

Figure source: (Bloem, 2019)

Clay materials were mixed in a laboratory pan mixer with the minimum quantity of water required to allow adequate extrusion. Extrusion was carried out in a de-airing (under vacuum) laboratory extruder with 20% of maximum extruder speed with a vacuum of 0.80 bar. Briquettes of extruded samples were cut from the clay column with the dimensions of 40 mm (b) x 25 mm (h) x 155 mm (l).

Figure 0-2: Extruded clay samples

Figure source: (Bloem, 2019)

3.2.2 GLASS PROCUREMENT

A bulk bag of approximately 500 kg contaminated waste cullet was collected from a flat glass manufacturing company based near Johannesburg, South Africa. The contaminated cullet consisted of flat glass, coloured glass and glass containing silver coatings (mirrored glass). The types of waste cullet typically contain measurable levels of iron (Fe), silver coatings and other contaminants. For the purpose of this study, levels of contaminants are considered to be insignificant as the contaminants will not have an impact on the fired material as the addition of glass in clay bricks are minimal (2% and 3%). Generally, being low values contaminants, this is not viewed as a barrier or obstacle. Still, if higher levels of contamination are expected, chemical and mineralogical analysis will provide the level of contamination. This means that most types of waste glass (except windscreen cullet as it contains polyvinyl butyral) can be treated as one waste stream. This is important as the most waste glass can be processed at one facility.

Figure 0-3: Contaminated cullet before crushing

Figure source: (Naude, 2018)

3.2.3 PREPARATION OF WASTE GLASS FOR LABORATORY TESTS

Different processing technologies were evaluated to establish the appropriate technologies to be used to enable full-scale replication of laboratory tests. Firstly, broken shards of waste glass were put through a sieve of 2 mm in a hammer mill to reduce the fragments into a powder form. The sieve size in the hammer mill was 2 mm to allow particles of less than 2 mm to pass through for secondary crushing. Initially, it was believed that particles smaller than 1 mm will be sufficient for the purpose of this test. Secondary crushing consisted of manually crushing the glass powder with a pestle and mortar, while continually conducting sieve analyses to measure particle sizes <1 mm. Once the material was less than 1 mm, it was ready for addition into clay mixtures for extrusion and further testing.

Figure 0-4: Glass powder after crushing

Figure source: (Naude, 2018)

3.2.4 ADDITION OF GLASS PARTICLES AND FIRING OF SAMPLES IN A LABORATORY ENVIRONMENT

The milled material was then mixed in with the clay and mixed in a laboratory pan mixer exactly as the control to ensure consistency in the preparation of samples for testing. Clay columns with 2% and 3% glass additions were extruded and dried. There was no visual difference between the extruded samples containing 0% glass and samples containing an admixture of 2% and 3% glass powder.

3.2.5 PROOF OF CONCEPT (POC)

Clay brick samples containing glass particles were extruded, dried and fired at 950 °C to prove the feasibility of the final products. 108 samples were tested according to applicable SANS 227:2007 specifications to prove whether the samples can be used for the intended purpose and if the final products are comparable to standard clay brick samples (control). See Annexures A 1-6 for the raw data from the tests. The results were positive and the POC was proven to be successful and this result allowed further testing of samples in industrial kilns under real-world conditions.

3.3 REAL-WORLD SIMULATIONS

Before real-world simulations can be conducted, it is important to understand to what specifications the samples will be tested and measured against. The SANS 227:2007 standard is the benchmark to which all clay brick manufacturers measure the quality and durability of their products. Sections 3.3.1-3.3.6 explain the requirements and specifications to which clay bricks (burnt clay masonry units) can be tested in order to comply with the standard. The samples used for the purpose of this study will be measured against FBS (face brick standard) specifications as the clay used for this project is used by the manufacturer to create FBS bricks to be sold to the public.

3.3.1 SANS SPECIFICATIONS

SANS 2207:2007 have the following requirements and tests methods, all tests conducted on the fired samples were done according to SANS 227:2007 methods and specifications. For the purpose of this study, the samples will be tested against the requirements of FBS bricks. The following requirements are applicable to the tests on FBS bricks:

3.3.1.1 SHAPE, APPEARANCE, TEXTURE AND COLOUR

The shape, appearance, texture and colour specifications refer to the visual inspection of the samples tested.

3.3.1.1.1 SHAPE

All units may be with or without frogs, perforations or cavities and (except FBA) shall be true to the appropriate acceptable pattern. They shall have rectangular faces, and units to be used in facing and structural applications shall have uniform arises (SANS, 2007).

3.3.1.1.2 APPEARANCE

All units shall be well burnt and shall be acceptably free form deep or extensive cracks, damage to edges and corners, and pebbles and expansive particles of lime. When a cut surface of a unit is examined, it shall show an acceptably uniform texture (SANS, 2007).

3.3.1.1.3 TEXTURE AND COLOUR

Unless otherwise specified, the texture and colour of masonry units shall be uniform. For the purpose of assessing the uniformity of colour and texture, the manufacturer shall, by agreement with the purchaser, submit for the purchaser's approval a sample of 20 units, 10 of which are to be retained by the purchaser and 10 by the manufacturer (SANS, 2007).

3.3.1.1.3 DIMENSIONS

a) For any class of unit, the work size shall be as stated by the manufacturer.
b) When determined in accordance with section 6.4 of the standard
   1) The dimensions of an individual unit shall not differ from the stated work size by more than the relevant tolerances given in columns 2-4 (inclusive) of table 5; and
   2) The average dimensions of 32 units shall not differ from the stated work size by more than the relevant tolerances given in columns 5-7 (inclusive) of Table 5.

Table 3-1: Tolerances on work sizes

1	2	3	4	5	6	7
Class	**Individual units** mm			**Average dimensions of 32 units** mm		
	Length	**Width**	**Height**	**Length**	**Width**	**Height**
FBS	± 7	± 4	± 4	± 3,5	± 2	± 2

3.3.2 WARPAGE

When determined in accordance with section 6.5 of the standard, the warpage of FBS shall be within the following units:

- The warpage of any individual unit shall not exceed 5 mm.

3.3.3 COMPRESSIVE STRENGTH

Compressive strength measures the maximum load per unit area that a product will withstand before failure occurs at ambient temperature under specified conditions and compression (Abuh *et al.*, 2019). The average compressive strength of 12 units shall not be less than the nominal compressive strength and, when tested in accordance with section 6.6 of the standard, the individual compressive strength of units shall comply with the appropriate values given in column 3 of Table 3-2, relative to the nominal strength given in column 2 (SANS, 2007).

Table 3-2: Compressive strength (SANS, 2007).

1	2	3
Class of unit	**Nominal compressive strength** **MPa**	**Individual compressive strength** **MPa min**
FBS	12,0	9,0

3.3.4 EFFLORESCENCE

When units are tested in accordance with section 6.7 of the standard, the number that exhibits efflorescence shall not exceed the limits given in Table 3-3, for a special or normal grade, appropriate to the class of units (SANS, 2007). Efflorescence is a visible salt-like deposit that can occur on the surface of the body. Efflorescence occurs when sulphur, either being present in the clay itself, or in the coal used for firing the bricks, is oxidised thus forming sulphur dioxide gas. The sulphur dioxide gas passes through the kiln and reacts with water vapours released by the bricks to form sulphuric acid. The sulphuric acid then reacts with carbonates and other calcium salts in the clay brick units to form calcium sulphate (Hameed *et al.*, 2018).

(Note: The samples used in this study were not tested for efflorescence as glass added is expected to assist in improving strength and durability. Additions of glass will have no impact on reducing efflorescence in clay bricks, therefore efflorescence testing was deemed not necessary for the purpose of this research project.)

Table 3-3: Degree of efflorescence

1	2	3	4	5
Grade	Class of unit	Number of units that exhibit efflorescence		
		Degree of efflorescence		
		Slight	**Moderate**	**Heavy**
Normal	FBS	10	10	-

3.3.5 SOUNDNESS

When units are tested in accordance with section 6.8 of the standard, the following surface pop-outs shall be allowed (SANS, 2007):

a) A maximum of two pop-outs of mean diameter 2-5 mm in each of only two of the six units tested and none in the remaining four; or
b) A maximum of two pop-outs of mean diameter 5-10 mm in only one of the six units tested and none in the remaining five.

(Note: The test for soundness was not conducted on the samples used in this study as this test is done when the bricks show defects from lime-popping. Adding glass to the samples will not reduce or improve pop-outs, therefore soundness tests were not conducted on the samples used in this study.)

3.3.6 WATER ABSORPTION, WATER-SOLUBLE SALTS AND MOISTURE EXPANSION

Water absorption is a crucial indicator for assessing the durability of clay bricks (Abdeen & Shihada, 2017). When limitation of, or any combination of the following properties is required, the values of the properties, determined in accordance with the applicable tests, shall be such that they lie within limits agreed upon between the supplier and the purchaser (SANS, 2007):

a) Water absorption (determined in accordance with 6.9 of the standard);
b) The total water-soluble salts content, the quantities of selected radicals, and the pH value of the water extract (determined in accordance with 6.9 of the standard); and
c) Moisture expansion of refired units or of units as received (determined in accordance with 6.11 of the standard)

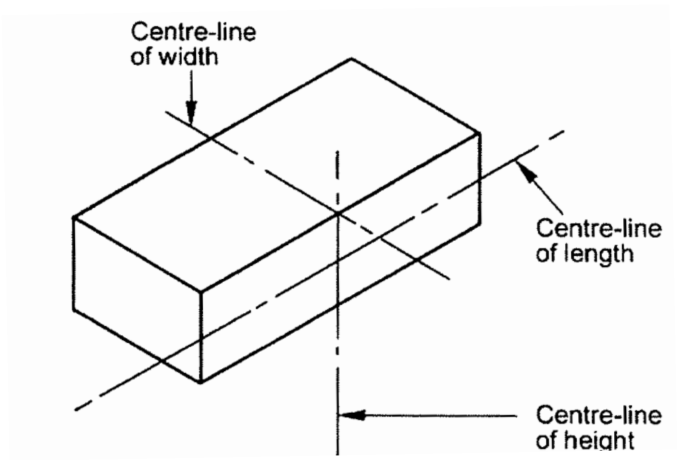
3.4 DATA COLLECTION

The following inspections and methods of testing were completed on the samples in this study.

3.4.1 INSPECTION

Inspection of each unit in the sample batch was completed for and measured with the following dimensions: 40 mm (b) x 25 mm (h) and 155 mm long. The test for dimensions was carried out by using a steel rule with increments of 1 mm and an end stop with a vertical plane face as per the requirements of the SANS 227:2007 requirements. The procedure used to test for dimensions was done by measuring to the nearest 1 mm, the overall length and height of each unit along the appropriate centre-line of each stretcher face, and the overall width along the transverse centre-line of each bed face (see Figure 21 below), in each case by placing the appropriate face of the unit against the end stop and measuring the distance from the end stop to the opposite face of the unit. The mean of each pair of measurements was recorded and the average was calculated of each sample batch.

Figure 0-5: Procedure to measure dimensions



3.4.2 TEST SPECIMENS

3.4.2.1 PARTICLE SIZE DISTRIBUTION OF GLASS

Before the samples were prepared, glass particles were crushed to <1 mm, see Table 3-4 for results of crushing glass in the laboratory environment.

Table 3-4: Particle size distribution after laboratory communition

Sieve Size (mm)	Sieve weight	Material + sieve	Glass	Fraction (%)	Cumulative
3,15	559,1	559,7	0,6	0,1	100,0
2,36	474,9	475,1	0,2	0,0	100,0
1	505,1	520,0	14,9	3,0	100,0
0,6	414,7	433,2	18,5	3,7	96,3
0,4	472,4	541,6	69,2	13,8	82,5
0,3	323,0	367,6	44,6	8,9	73,5
0,2	310,7	417,3	106,6	21,3	52,2
0,106	363,4	519,4	156,0	31,2	21,0
0	415,6	505,0	89,4	17,9	3,1
		Total	**500**	**100**	

3.4.2.2 FORMING PROPERTIES

The minimum amount of water was added to the clay mixes until adequate extrusion of samples was possible. Samples were extruded using a de-airing laboratory extruder at a rate of approximately 20% of the maximum speed and a vacuum of 0.80 bar. A total of 108 samples were extruded for each sample batch (C – Control, S1 – Sample 1 (2% glass particles), and S2 – Sample 2 (3% glass particles)).

Table 3-5: Workability of samples with and without glass

Properties	C	S1 (2%)	S2 (3%)
Mixing water (%)	21,2	21,0	21,0
Workability	Good	Good	Good

Figure 0-6: A collection of dried samples

3.4.2.3 MOISTURE CONTENT

The moisture content of the samples was measured before drying to determine how effective the clay (in its raw form) is in absorbing and retaining moisture. Moisture content refers to the total moisture absorbed by the clay body before drying as opposed to the water absorption tests, which measure the total weight of water absorbed by the fired body after firing. 9 Samples from each batch were tested for its moisture content and the results for the moisture content tests can be viewed below:

Table 3-6: Moisture content of samples before drying

Samples	C (0%)	S1 (2%)	S2 (3%)
Moisture Content (%)	23,45	22,82	22,77

3.4.2.4 GREEN SHRINKAGE

Before the final drying of the brick samples, green shrinkage was measured on all samples. It was expected that the samples containing an admixture of glass particles would have lower shrinkage as the glass is an inert material, meaning that the particles will retain its shape during the drying process. Green shrinkage refers to the physical shrinking of the clay body during the drying phase of the bricks, where moisture is drawn out of the brick and released into the atmosphere. The dimensions of the "wet" samples were recorded before drying and after drying. The samples were then air-dried at room temperature, followed by overnight drying at 110 °C, after green shrinkages were calculated.

The average for each sample batch (9 samples per batch) was calculated and the results are visible below:

Table 3-7: Green shrinkage of the samples after drying

Samples	C	S1 (2%)	S2 (3%)
Green Shrinkage (%)	3,59	3,46	3,34

3.4.4.5 TEST FOR WARPAGE

The test for warpage was conducted on all samples measured in the moisture content and green shrinkage tests. The equipment required for the test for warpage was a steel straight edge, a steel rule (as used for measuring dimensions) and four steel measuring wedges, graduated in increments (indicating increments of thickness) of 1 mm. The test for warpage was carried out on a flat surface of the glass. Each unit was placed on the flat surface on one of the bed faces. The samples chosen for the test for warpage were found to be within the acceptable range, which indicated that the samples were adequately extruded and dried.

After completion of the test for warpage, the clay samples were fired under real-world conditions inside a tunnel kiln at an existing clay brick factory. In total, 108 samples of each sample batch were divided according to the ratio of glass particles contained inside the clay body and stacked on a kiln car between full-sized clay bricks to determine if there will be a difference in properties of the fired bricks in different zones of the kiln car.

Figure 0-7: Packing of samples in the kiln before (left) and after (right) firing

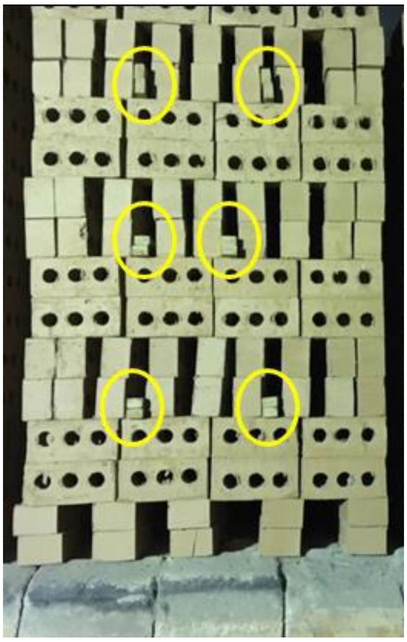


Figure source: (Bloem, 2019)

Figure 0-8: A collection of fired samples

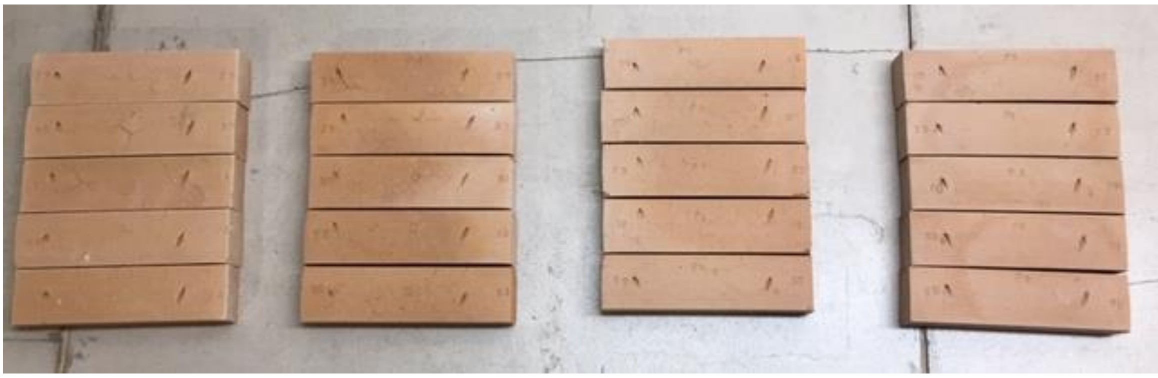


Figure source: (Naude, 2018)

3.4.4.6 WATER ABSORPTION TEST

After firing the samples in an industrial tunnel kiln, the selected samples were weighed on a laboratory balancing scale (accurate to determining 0.1%, the mass of the unit). The samples were weighed and the dry mass (m1) was recorded for each sample. After determining the dry mass, the samples were placed in a tank fitted with a lid. The samples inside the tank were placed on a grid and immersed in clean water which was controlled between 22-25 °C for 24 hours. After immersion, the samples were then wiped down with a damp cloth and the mass (m2) of each sample was recorded.

Calculation of cold-water absorption:

$$\textbf{24h cold water absorption, \% (m/m)} = \frac{\textbf{m2-m1}}{\textbf{m1}} \quad \textbf{x 100}$$

The average water absorption of 36 samples from each sample batch was tested, see test results below:

Table 3-8: 24 Hr Water absorption results

Samples	C (0%)	S1 (2%)	S2 (3%)
24 Hr Water Absorption (%)	4.30	5.05	3.11

3.4.4.7 FIRED SHRINKAGE

Fired shrinkage was measured after the samples from each batch was collected from the clay brick factory where the firing of the samples was concluded under real-world conditions. Generally, bricks must have a firing linear shrinkage lower than 8% in order to retain good mechanical performance (Abdeen & Shihada, 2017). It was expected that the fired shrinkage would be more profound in samples containing more glass. The glass inside the clay body is expected to melt at a lower temperature than the clay and depending on the fineness, melt into the pores of the clay body to reduce water absorption but increase shrinkage. The results of the shrinkage before and after firing were recorded and are indicated below:

Table 3-9: Average fired shrinkage of samples

Samples	C (0%)	S1 (2%)	S2 (3%)
Fired Shrinkage (%)	4,483	4,490	4,53

3.4.4.8 COMPRESSIVE STRENGTH

The compressive strength test was conducted using a King Test crushing machine, which complies with the requirements of ISO 7500-1. Abdeen & Shihada, 2017 states that: "compressive strength is the most important index for assuring the engineering quality of building material because, with higher compressive strength, other properties also improved". Extruded samples were placed in the centre, between the steel plates of the testing instrument. The capping method as stated in the SANS 227 standard was not used as the samples used for this test was smaller than normal burnt clay masonry units as they were extruded using a laboratory extruder. The procedure on the testing instrument was, however, followed by positioning the samples in the device. Pre-load of 5 kN was applied to each sample, without shock and the load was increased by 15 MPa/min. The device measured compression until the point of failure of each sample when the readings on the instrument were recorded. The purpose of this test was to determine if there was a measurable difference between the samples with and without glass addition. The resulting force was measured for each sample and averages were calculated for all samples and the results are visible below:

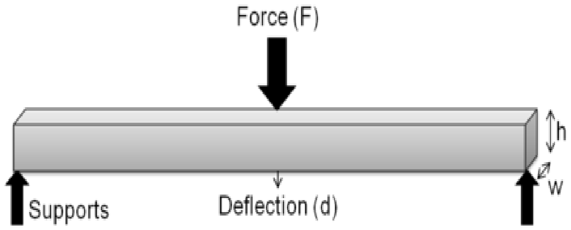
Table 3-10: Average compressive strength

Samples	C (0%)	S1 (2%)	S2 (3%)
Strength (MPa)	35,38	36,89	45,59

3.4.4.9 BREAKING STRENGTH (MODULUS OF RUPTURE)

The breaking strength of the brick samples was measured using an Instron tensile testing instrument. The flexural strength (or modulus of rupture) is determined by calculating the amount of force an object can take without breaking or permanently deforming (Johnson, 2018). Modulus of rupture is calculated based on the maximum stress at failure. The samples were placed on supports (see Figure 3-9) with a central force pushing downward until failure occurred. The total force was calculated at the point of failure.

Figure 0-9: Modulus of rupture test



The averages of all samples were calculated, and the results can be seen below:

Table 3-11: Fired breaking strength

Samples	C (0%)	S1 (2%)	S2 (3%)
Strength (MPa)	9,78	9,85	11,13

3.5 OPTIMAL PROCESSING METHODS OF WASTE GLASS

3.5.1 DETERMINATION OF THE APPROPRIATE EQUIPMENT

Test work was conducted on determining the optimal processing methods, a subcontractor was contacted with the assistance of Cermalab management to determine the optimal configurations, quantities, throughputs and outputs of machines available on the market at present to determine if a viable solution is available for potential entrepreneurs to establish a processing plant to fulfil the needs for brickmakers who opt to use waste glass as an additive (flux) in their manufacturing processes. As little was known of the available machinery on the market and its capabilities, the benchmark for the tests was set at determining the possibility to process up to 3.75 tonnes of glass per hour (tph). This would mean it takes a processing plant to process 660 tonnes of glass per month. The purpose of these tests was to determine the appropriate equipment required to crush large amounts of waste glass into particles <1 mm for the introduction into clay bricks. The following tests on glass processing were performed:

- Machine or machines that would be best suited for processing
- The final product to be produced from the crushing process
- Power consumption at each crushing stage

- Expected wear rate at each crushing stage

The crushing machines used for the purpose of these tests were a Hazemag AP-S 0404 impact crusher and a Novorotor 490/190 hammer mill.

Figure 0-10: Hazemag AP-S 0403 Impact crusher

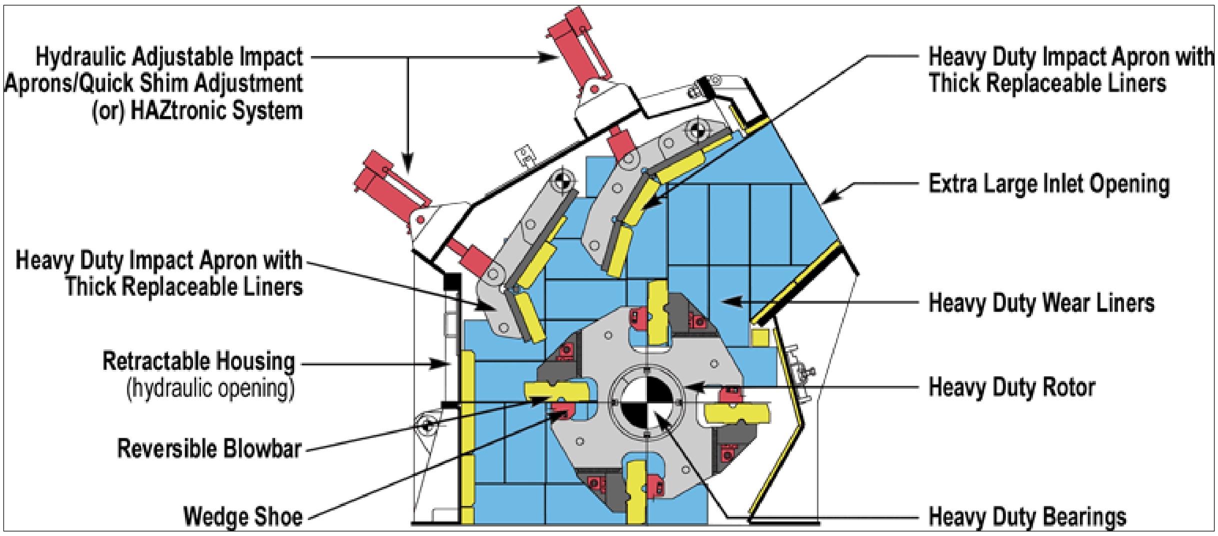
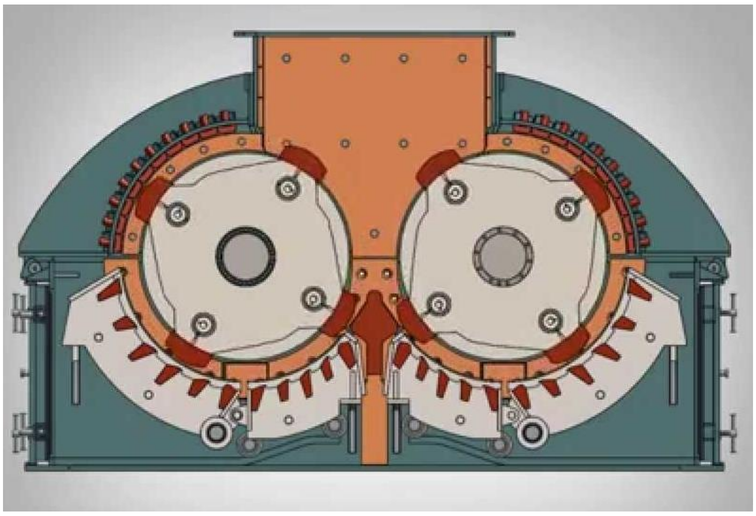


Figure 0-11: Double-rotor Hammermill



Different configurations of the machines were tested to determine if a single-stage process is sufficient or a dual-stage process would yield better results (for pulverisation of irregular glass pieces into finer particles). The single-stage process was configured with the impact crusher as the primary crushing machine, while the dual-stage process was configured as having the impact crusher as the primary crusher and the hammer mill as the secondary crusher, reverse trials were carried out with the hammer mill as the primary crushing machine and the impactor as the secondary crusher. Three bulk bags containing approximately 500 kg of irregularly sized glass pieces were used for the purpose of the tests. A total of seven tests were performed with the machines in different configurations and settings. Important notes on tests performed:

I. The hammer mill was set up in the central feed configuration, using high-chrome hammers.
II. The impact crusher was fitted with high-chrome blowbars.
III. Tests 1,5 and 6 were performed with the impactor to simulate the primary stage of a dual-stage crushing process. Three tests were performed in order to prepare sufficient material for the secondary-stage test.
IV. The products from tests 1,5 and 6 were screened at 1 mm with the +1 mm fraction serving as feed to test 7. These four tests together simulate dual-stage crushing processes, with screening out of the product between the stages (only the +1 mm oversize from the primary stage reports to the secondary stage).

Table 3-12: Summary of crushing tests

Test no:	Test machine	Feed	Arrangements
1	AP-S 0403 (impactor)	Delivered feed	Single-stage impactor crushing
2	NOVO 490/190 (hammer mill)	Delivered feed	Primary crushing
3	NOVO 490/190 (hammer mill)	Delivered feed	Single stage hammer mill crushing
4	NOVO 490/190 (hammer mill)	Delivered feed	Primary of dual-stage crushing
5	AP-S 0403 (impactor)	Delivered feed	Primary of dual-stage crushing
6	AP-S 0403 (impactor)	Delivered feed	Primary of dual-stage crushing
7	NOVO 490/190 (hammer mill)	>1 mm material from tests 1,5,6	Secondary stage of dual-stage crushing

Configurations in tests 2 and 4 are problematic as using the hammer mill for primary crushing to effect single or dual-stage crushing is a high-risk arrangement because of the potential high-wear expected from crushing an abrasive material such as glass.

Further tests using Test 2 and 4 arrangements were abandoned for the remaining tests on the basis that the potential high-wear rate if utilised in an industrial process, would likely result in substantial financial implications due to high maintenance costs. This decision was made as a result of advice received from the subcontractor used to perform the crushing tests, therefore only data from tests 1, 3, 5, 6 and 7 will be visible from this point onwards.

Table 3-13: Crusher settings for each test

Test no:	Machine	Tip speed (m/s)	Gap size (impact crusher) [mm]	Grid opening (hammer mill [mm]	Grid configuration
1	AP-S 0403 (impactor)	50	Apron 1: 30 Apron 2: 16		
3	NOVO 490/190 (hammer mill)	62		2	50% grinding bars 50% grids
5	AP-S 0403 (impactor)	50	Apron 1: 30 Apron 2: 16		
6	AP-S 0403 (impactor)	50	Apron 1: 30 Apron 2: 16		
7	NOVO 490/190 (hammer mill)	62		2	50% grinding bars 50% grids

3.5.2 THROUGHPUTS OF CRUSHING TESTS

Table 3-14: Throughputs of test feeds

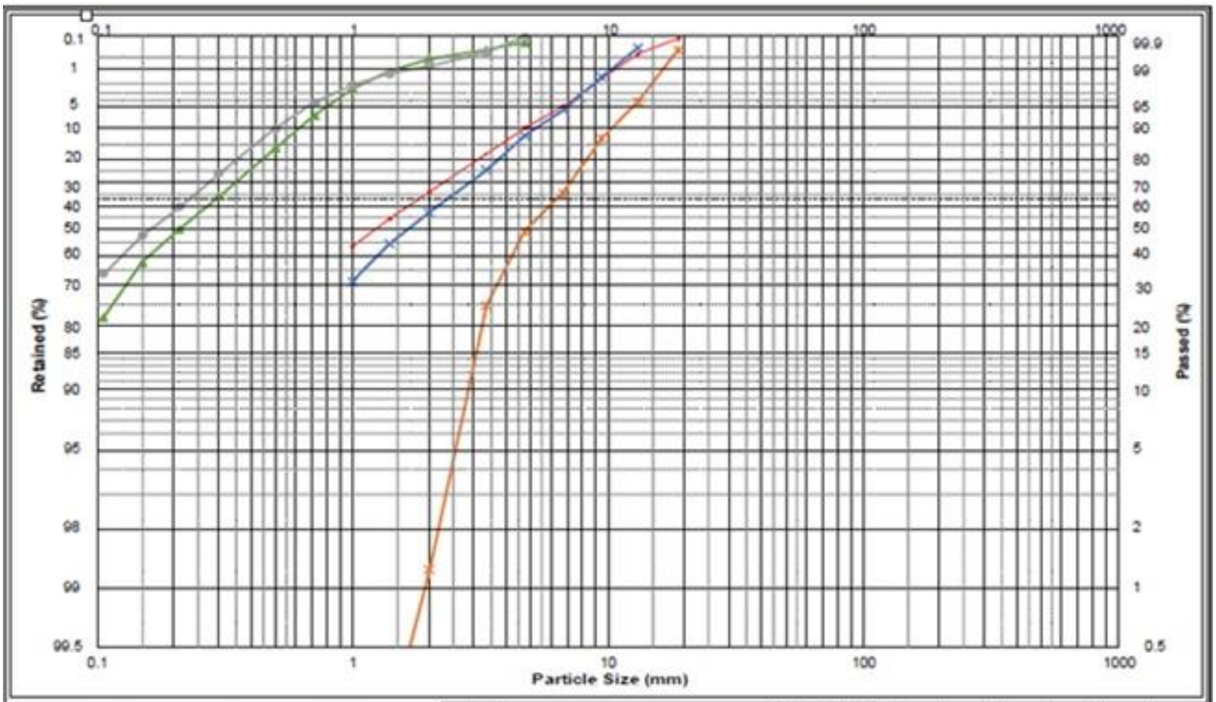
Test no:	Test machine	Throughput [tph]
1	AP-S 0403 (impactor)	11.5
3	NOVO 490/190 (hammer mill)	5.9
5	AP-S 0403 (impactor)	11.2
6	AP-S 0403 (impactor)	-
7	NOVO 490/190 (hammer mill)	3.1

The throughputs of the tests will assist in determining the optimal configuration of the processing plant, the total quantities that could be processed at 100% efficiency and the necessary equipment to be utilised. This information will also contribute to determining an accurate capital investment required to establish the ideal processing plant.

3.5.3 PARTICLE SIZE DISTRIBUTION

The particle size distribution of each test configuration was measured after each test to determine the particle sizes of the glass after crushing. Figure 33 (below) illustrates the particle size distribution results of each test based on the amount of glass retained (%), the amount passed through the sieves (%) and the size of the particles (mm). Test 1 (Red), Test 3 (Green), Test 5 (Blue), Test 7 Feed (>1 mm material from tests 1, 3, 5 (Orange)) and Test 7 Product (Grey).

Figure 0-12: Particle size distribution of test feeds



No		Material	Setting (mm)	F.Rate t/h	F_{80}	$F_{63.2}$	P_{80}	$P_{63.2}$	$R_{(P80)}$	$R_{(P63.2)}$
1		TEST 1 PRODUCT					3.1	1.8		
2		TEST 3 PRODUCT					0.4	0.3		
3		TEST 5 PRODUCT					3.7	2.3		
4		TEST 7 FEED (+1mm MATERIAL)					8.2	6.3		
5		TEST 7 PRODUCT					0.3	0.2		

3.5.4 POWER CONSUMPTION OF TEST CONFIGURATIONS

The power consumption of the crushing machines in different configurations was measured to assist in calculating the operational cost of a processing plant over a period of time. This information is valuable as it is an important variable in estimating the capital investment and operating costs of a glass processing plant.

3.5.4.1 TEST 1 POWER CONSUMPTION

Power consumption of Test 1 was calculated by measuring the power consumed by the impact crusher only as the impact crusher is used as the primary crusher in this arrangement.

Figure 0-13: Power consumption of Test 1

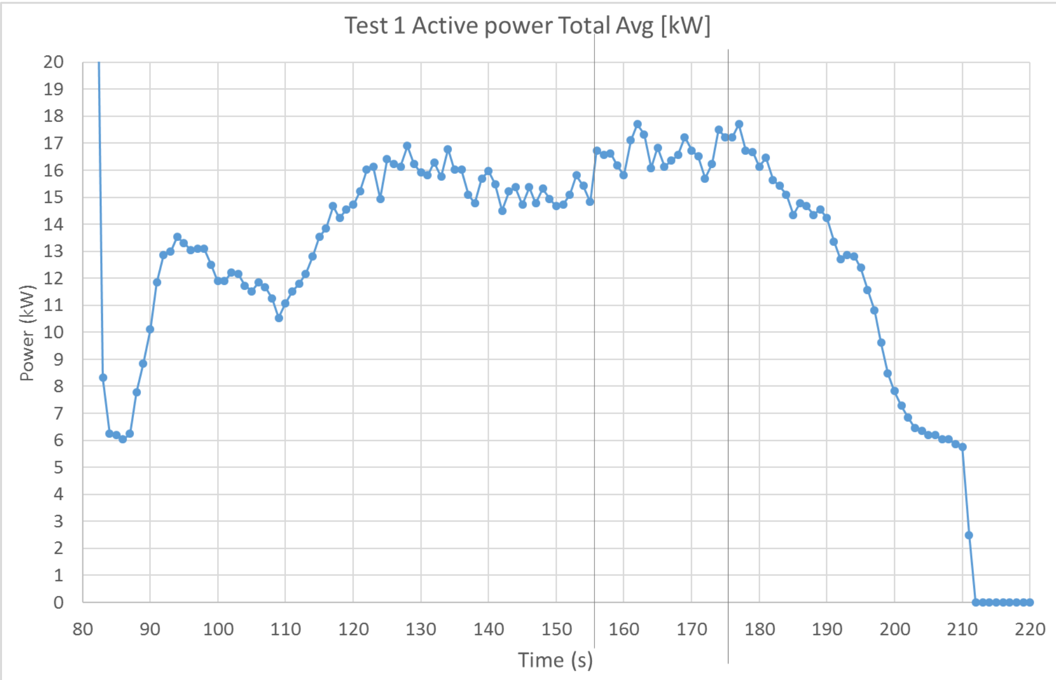


Table 3-15: Specific power consumption for Test 1

Throughput (tph)	11,5
No-load power (kW)	4,4
Average power consumption for Test 1 (kW)	16,7
Specific power consumption for crushing (formula below) = Average power consumption - No load power Throughput	1,070

3.5.4.2 TEST 3 POWER CONSUMPTION

The power consumption for Test was calculated by measuring the total power consumed by both motors in the Novorotor 490/190 hammermill. The expectation was that the hammermill required more power as it used two motors to mill material.

Figure 0-14: Power consumption of Test 3

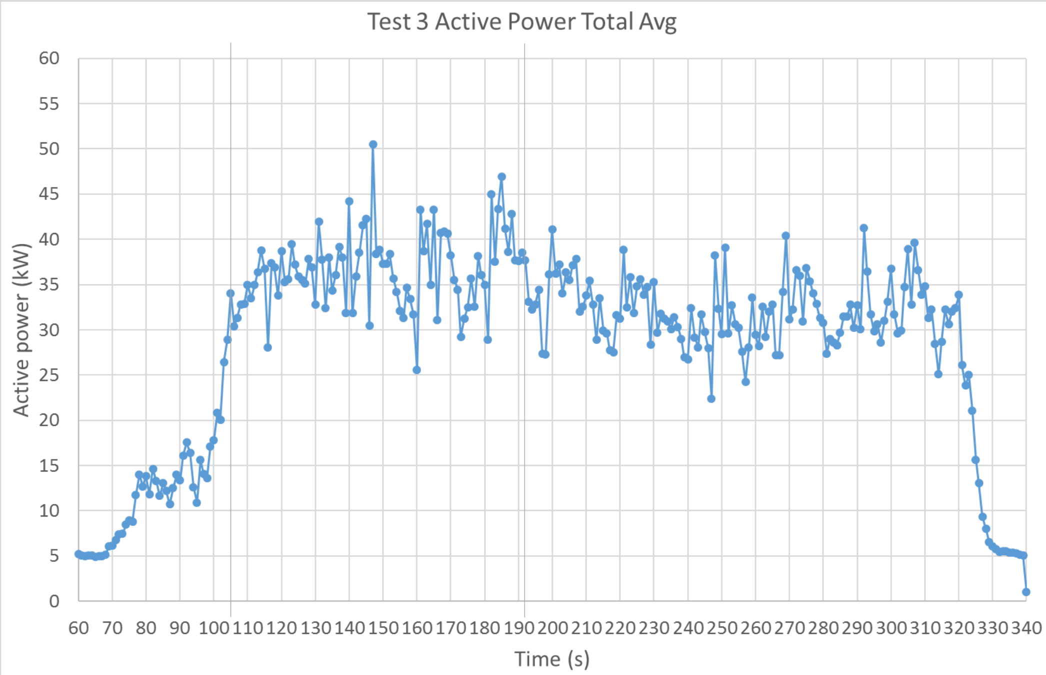


Table 3-16: Specific power consumption of test 3

Throughput (tph)	5.9
No-load power (kW)	5.03
Average power consumption for Test 3 (kW)	37.5
Specific power consumption for crushing (formula below) = $\frac{\text{Average power consumption - No load power}}{\text{Throughput}}$	5.503

3.5.4.3 TEST 7 POWER CONSUMPTION

The power consumption for Test 7 was calculated by crushing the material left over from the tests where the impact crusher was used as the primary crusher. The feed was the material exceeding 1 mm. The material was crushed using the hammer mill with both motors running.

Figure 0-15: Power consumption of Test 7

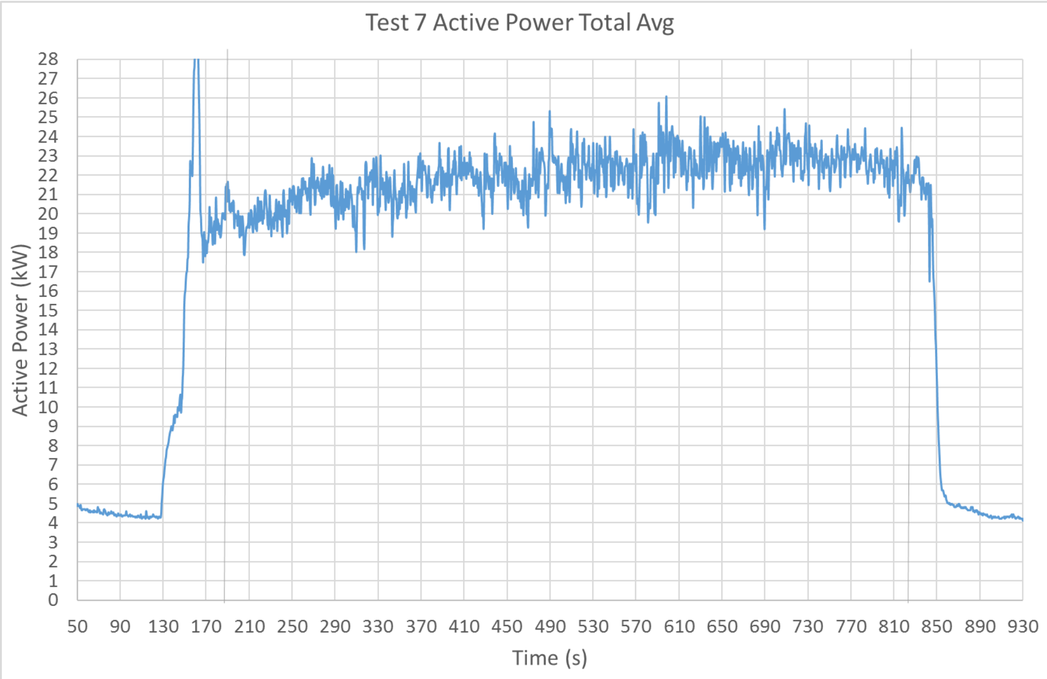


Table 3-17: Specific power consumption of test 7

Throughput (tph)	3.1
No-load power (kW)	4.37
Average power consumption for Test 7 (kW)	22.7
Specific power consumption for crushing (formula below) = Average power consumption - No load power Throughput	5.919

3.5.5 WEAR RATES

The wear rates of the machines were calculated by weighing the blowbars of the impact crusher before and after a test run. Accurate wear rates of the hammer mill could not be calculated as the material provided for testing did not cause excessive wear on the hammers. A subject matter expert on crushing equipment estimated that the wear rate on the hammermill can be up to five times more than the impactor due to its milling action and the abrasiveness of the glass.

Table 3-18: Blowbar wear rate calculation

Mass of blowbars before the test (g)	Mass of blowbars after the test (g)	Mass of materials processed (tonnes)	Specific wear rate (g/ton)
23458	23432	1,735	14,99

All results of the tests will be discussed in more detail in chapter 4.

3.6 OSTERWALDER BUSINESS MODEL CANVAS

The Osterwalder business model canvas (BMC) will be used to develop a business plan for a potential entrepreneur or venture capitalist to realise the potential of beneficiating waste products and creating products of superior quality when introduced into the manufacturing process. For the purpose of this study, all nine essential components as identified by Alexander Osterwalder will be expressed in the context of the potential business opportunity dependent on the results from the test results encapsulated in this research project. The following components will be used to develop a business plan to generate the entrepreneurial spirit of the reader and to set the foundation of a potentially profitable business venture as explicated below.

3.6.1 KEY PARTNERSHIPS

Key partnerships can be described as an alliance of entities such as other business, government or non-consumer entities that assist in making your business model work (Anastasia, 2015). Partnerships have become and are still becoming an essential component of many business models. Strategic alliances between businesses can be utilised to be a mutually beneficial component in industries in optimising business models, reducing risks and assist in the acquisition of important resources. There are four types of partnerships, such as strategic alliances between non-competitors, coopetition: strategic partnerships between competitors, joint ventures to develop new businesses, and buyer-supplier relationships to assure reliable supplies (Strategyzer, 2019).

3.6.2 KEY ACTIVITIES

Key activities are regarded as the business's most important actions, which must be performed to operate successfully. Key activities are used to generate and offer a value proposition, enter markets, maintain sustainable customer relationships and earn revenues for the business. Different types of activities are managed that depend on the nature of the business, core issues of key activities are production, problem-solving, financial, supply chain management, networking and platforms (Eppenhart, 2015).

3.6.3 KEY RESOURCES

Key resources are regarded as vitally important elements of a business. Resources allow businesses to function. Resources are needed to create value for your customers (Empowerwomen, 2016). Resource management promotes sustainability, reaches new markets, expands on existing markets, offers value proposition and maintains relationships in different customer segments. Types of resources include physical resources such as assets, facilities, machines, distribution networks and infrastructure and financial resources, which include cash and cash flows, credit lines, stocks or shares and capital. Human resources are the backbone of any business as all ideas and creativity inside a business stem from humans, secondly, a skilled sales force has the potential to grow a business exponentially depending on the product offering and skills network of the employees. Intellectual property resources can be described as proprietary knowledge, patents, copyrights, brands, partnerships and customer databases. The resources discussed above are becoming increasingly important components of strong business models (Strategyzer, 2019).

3.6.4 COST STRUCTURE

The cost structure component or building block describes the most important costs incurred while operating under a particular business model (Strategyzer, 2019). It is relatively easy to define the cost structure of business after key resources, key activities and key partnerships are defined. Delivering value, maintaining customer relationships and buying resources all incur costs (Altexsoft, 2018).The main spectrum in which cost structures fall is between cost-driven business models and value-driven business models. In-between these classes of cost structures different attributes contribute to the types of cost structures: economies of scale refer to cost advantages business benefits from during expansion and growth. Economies of scope refer to cost advantages companies benefit from due to a larger scope of operations. Fixed cost structures refer to costs that remain constant despite the volume of products or services produced. Variable cost structures refer to costs that vary proportionally with the volume of products or services produced.

3.6.5 VALUE PROPOSITIONS

The value proposition of a business refers to the “pulling power” the business has over its competitors, it is the reason why customers choose one business over another. It creates revenue by solving a problem the customer has (or believes they have) or satisfies the need the customer may feel they experience. Each value proposition refers to a specific requirement or customer segment and can be described as a bundle of benefits a business offers its customers. Value propositions can be innovative or disruptive, depending on the product or service and the market of the said product or service. Value propositions are the added features or attributes linked to a product or service that separates the business achieving the sale versus the business that does not. Types of value propositions are identified as being performance-based, the newness of the product or service, customisation capabilities of a product or service, product design, status or brand value, price competitivity, convenience for customers and the level of accessibility are examples of value propositions.

3.6.6 CUSTOMER RELATIONSHIPS

Customer relationships are defined as the type of relationship a business has with its customers or the type of relationship it wants to establish with each customer segment. Customer relationships can be transactional (impersonal or once-off interactions) or long-term relationships that are built over time and can have a level of customer loyalty connected to it. There are many types of customer relationships which can co-exist in a customer segment, such as transactional or long-term relationships as described above, self-service relationships, automated service relationships (digital interactions), co-creation (where customers and a business can create content or reviews for public consumption) and communities, where communities are formed for businesses to become more involved with customers on a platform used to facilitate interactions between the business and community members.

3.6.7 CHANNELS

Channels in a business plan are regarded as the communication, distribution and sales channels in the business. Essentially, channels refer to the interface between the business and its customers, the pathways aimed at delivering value proposition to customer segments (Altexsoft, 2018). Channels in business serve several functions such as the delivery of a value proposition provided by the business, customer support, evaluation of customer support after sales, promotion of business activities and brand awareness. Different types of channels are owned-direct, referring to all channels being owned and administrated by the business, or partner-indirect, referring to wholesale distribution, retail, or partner-owned networks (Strategyzer, 2019).

3.6.8 REVENUE STREAMS

Revenue streams can be described as all income related to the business, retrieved from various sources. Each revenue stream is a channel where income for the business can be generated (Altexsoft, 2018). Each revenue stream may have varying pricing mechanisms, such as product prices, bargaining, volume- or market-dependencies, yield management or auctioning, which can be transactional (once-off) or recurring. Different types of revenue streams are sales of assets/products, fees received for services rendered, subscription fees, licensing, brokerage fees, renting of equipment or property and advertising (Strategyzer, 2019).

3.6.9 CUSTOMER SEGMENTS

Customers are generally the main income source for businesses and without profitable customers, businesses cannot survive. A good strategy is to diversify customers into different segments with common needs or attributes. Businesses can have small or large customer segments, depending on the type of products or services. Diversifying customers into segments creates the ability to cater specifically to the needs of the different customer groups. This will enable the business to create a detailed understanding of its customers in a particular group. Some examples of customer segments include mass-market segments (all customers with similar needs and problems are placed into a large segment), niche market segments (catering for customers with specific needs), segmented customer groups (focused on customers with slightly different needs and problems) diversified segments (catering for customers with very different needs and problems) and multi-sided platforms (serving two or more interdependent customer segments).

Figure 0-16: Osterwalder business model canvas

Osterwalder business model canvas (BMC)				
Key Partners	Key Activities	Value Propositions	Customer Relationships	Customer Segments
	Key Resources		Channels	
Cost Structure		Revenue Streams		

3.7 CHAPTER 3 SUMMARY

- The laboratory phase and the real-world simulation phases of the study were explained.
- The materials required for the purpose of the study were procured, namely the clay for the manufacturing of clay brick samples and sufficient waste glass for the crushing tests and admixtures for the clay samples.
- The proof of concept for the advancement of the study was completed and successful.
- SANS 227:2007 standard was explained and data from the various tests on clay samples were collected before and after firing of the samples for interpretation.
- The optimal processing methods of the waste glass were determined by measuring different crusher settings, particle-size-distribution, throughputs of glass per hour, power consumption and wear rates on the crushing equipment were analysed.

- The Osterwalder business model canvas was described on which the business model for the aspiring entrepreneur was to be applied for based on the processing plant required to process the waste glass for the clay brick industry.

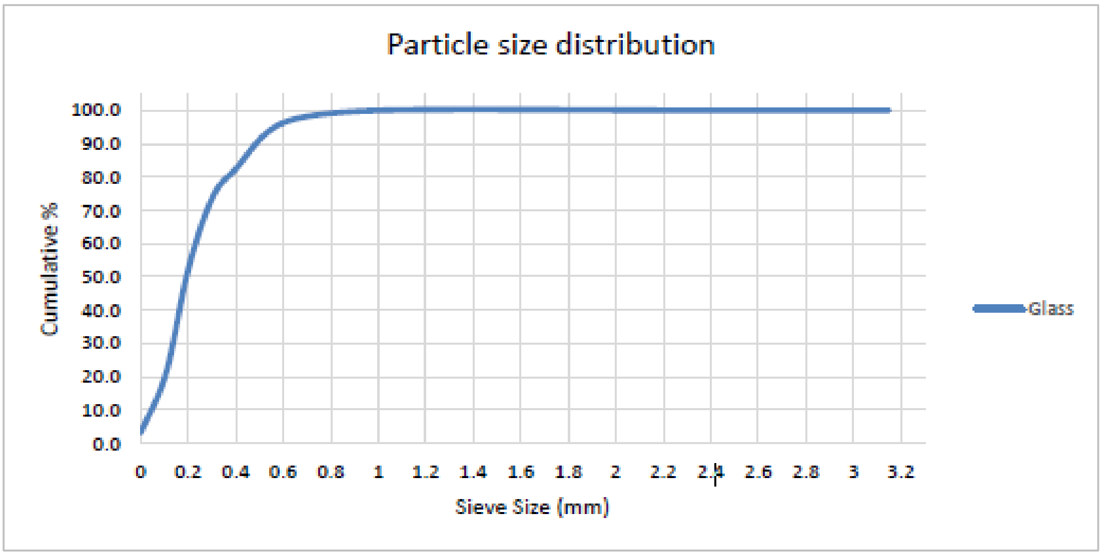
CHAPTER 4
RESULTS AND FINDINGS

4.1 RESULTS OF TEST WORK

4.1.1 LABORATORY PHASE AND TESTING (PROOF OF CONCEPT)

The laboratory phase of the project was necessary to prove whether glass additions in clay bricks was possible and if clay bricks can be manufactured using the same process, only with the additional step of adding glass fines to the production process. Secondly, the laboratory phase included milling or crushing of irregular glass pieces into glass particles fine enough to be introduced into the clay bodies without the need for additional equipment or added fixtures to extruders and the dies used for extrusion. Glass preparation to <1 mm was achieved using standard laboratory scale milling equipment (hammer mill with 2 mm screen) and physical communition using a pestle and mortar. The particle size distribution showed that after communition, all glass material crushed was smaller than 1 mm (the majority of particles being smaller than 0.5 mm). Figure 4-1 shows that the graph has a narrow distribution. The narrow distribution of the glass particles is positive as the particles are the appropriate size with an even distribution of particle size in the majority of the batch.

Figure 0-1: Particle size distribution of glass particles after crushing



The introduction of 2% and 3% mixes was achieved without any difficulty as the glass powder was weighed, introduced and mixed using a laboratory mixer. The glass particles in the clay with 2% or 3% additions were not noticeable in any of the mixes. Extrusion of the clay without and with glass additions was successful as no noticeable wear was visible on the extruder or the die of the extruder. Drying of the clay mixes was successful as no cracks developed during drying and no signs of warpage was found, upon testing warpage of the dried samples, all samples were found to be in the acceptable parameters of the SANS 227:2007 standard. The dried samples containing glass resembled the samples without glass, indicating that the glass was mixed in properly. Firing of the samples in the laboratory kilns at 900 °C was also successful as the samples resembled the samples containing 0% glass, proving that the laboratory phase was successful and the feasibility of manufacturing clay bricks containing glass (up to 3%) is achievable on a small scale and that the project could progress to testing of samples fired in real-world environments.

4.1.2 REAL-WORLD SIMULATIONS AND TESTING RESULTS OF SAMPLES

New samples were manufactured to be fired in an existing clay brick factory kiln at 950 °C to determine if the samples would react similarly to the samples generated for the laboratory phase of the project. A total of 108 samples were manufactured in the laboratory to be fired in the factory kiln, 36 with 0% glass additions (C), 36 with 2% (S1) glass additions and 36 with 3% (S2) additions.

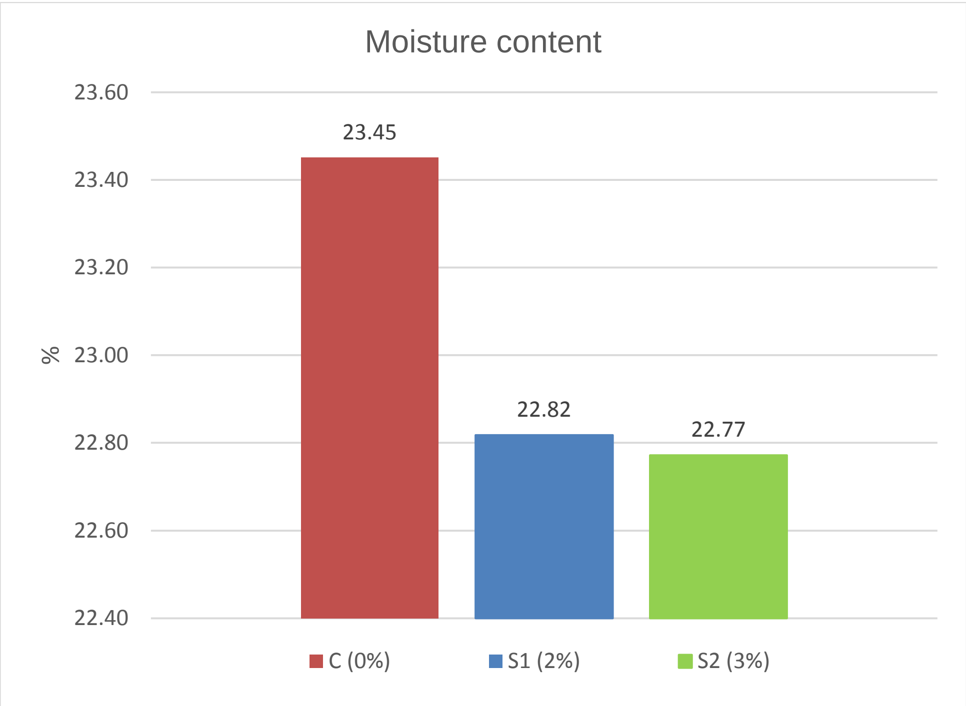
4.1.2.1 FORMING PROPERTIES

The samples containing 0%, 2% and 3% showed good workability without the need for souring and showed no deviations during extrusion. No signs of dog-earing were visible during extrusion, which is an indication that the clay was mixed properly, and that the column was extruded stiff enough for cutting into bricks (or in this case samples). Dog-earing is an extrusion fault found on the edges of a rectangular extruded column of clay. The greater friction at the corners of the die retain the clay relative to the centre of the extruded column and if the friction on the corners is too great, it results in a series of tears along the edges of the column.

4.1.2.2 MOISTURE CONTENT

After samples were extruded, moisture content of 36 (out of the 108) samples from each batch were measured before the drying process was initiated. The average moisture content of the control sample (C) was measured at 23,45%. The average moisture content required for full-size bricks manufactured in South Africa range between 18- and 25% as clays in South Africa are generally extruded using the stiff extrusion process, where less moisture is required for extrusion as soils and clays are coarser and tougher than in other parts of the world. The samples containing 2% glass had an average moisture content of 22,82%, it was expected that the moisture content would be lower in samples containing glass as glass particles are inert and would fill some of the pores where water molecules would normally accumulate. Similarly, samples containing 3% glass had an even lower moisture content on average, measuring at 22,77%.

Figure 0-2: Average moisture content of samples before drying

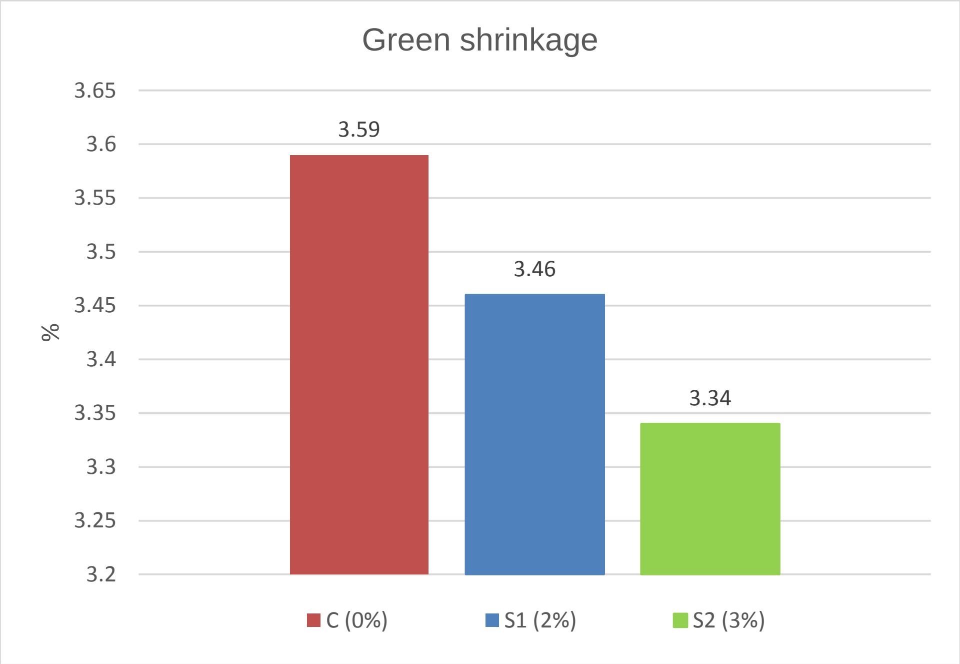


4.1.2.2 GREEN SHRINKAGE

The green shrinkage of 36 samples from each batch was measured after the drying process was completed. Even though the samples were dried in a laboratory drier overnight at 110 °C, the heat was still too low for the glass to melt into the clay body.

The glass remained inert inside the clay bodies and while the moisture was drawn out of the samples during drying, the samples containing glass showed lowered shrinkage during drying.

Figure 0-3: Green shrinkage of test samples



4.1.2.3 WARPAGE

Warpage was measured on the samples used for the moisture content and green shrinkage, equally all other samples were inspected for warpages and all samples were found to be within the acceptable parameters of the SANS 227:2007 standard, indicating that the samples were adequately extruded and dried. All of the other samples were inspected as per the SANS 227:2007 specifications, the shape appearance and texture of the samples were inspected and found to be compliant with the specification of the standard.

After the visual inspections for warpage, shape, appearance, texture and colour was completed, the samples were batched and transported to a kiln owned by an active clay brick manufacturer in Pretoria, South Africa, where all of the samples were fired, along with the bricks being fired by the factory to be sold as facing bricks. The samples were placed in between the other bricks on the kiln cars, at different positions (TL- Top left, TM – Top middle, TR – Top right, ML – Middle left, MM – Middle middle, MR –

Middle right, BL – Bottom left, BM – Bottom middle and BR – Bottom right, See Annexures A 1-6 for specific results of tests from each sample in various positions).

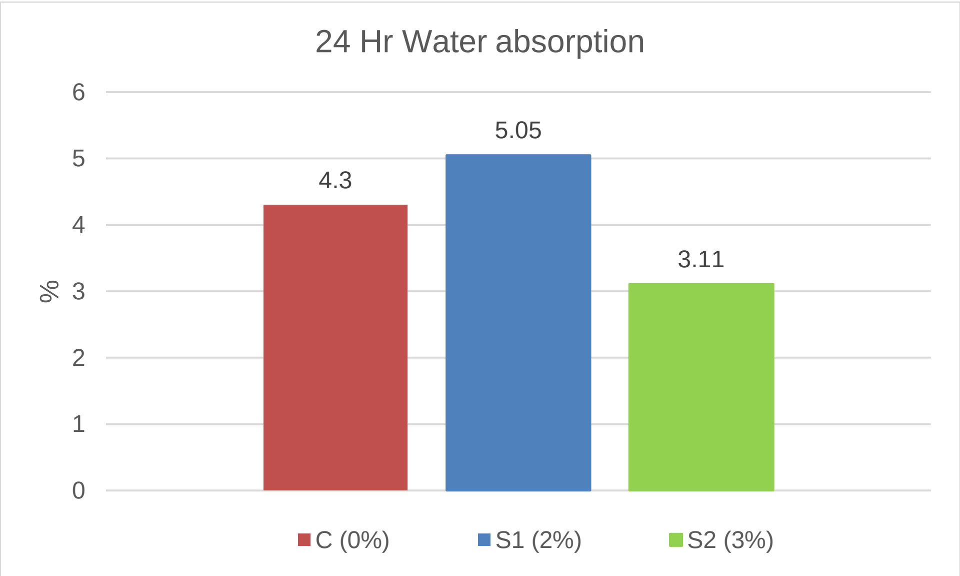
4.1.2.4 WATER ABSORPTION

The samples were collected from the brick factory (after cooling) and returned to the laboratory for more tests after they were subjected to real-world firing temperatures (950 °C), environments and firing atmospheres. 36 samples of each (C, S1 and S2) were selected at random to be subjected to water absorption tests according to SANS 227:2007. Samples were placed in water for 24 hours, removed and weighed to determine the total water absorbed by the samples in the time period.

The water absorption was calculated using the following formula:

$$\text{24h cold water absorption, \% (m/m)} = \frac{m2-m1}{m1} \times 100$$

Figure 0-4: 24 Hr Water absorption test results

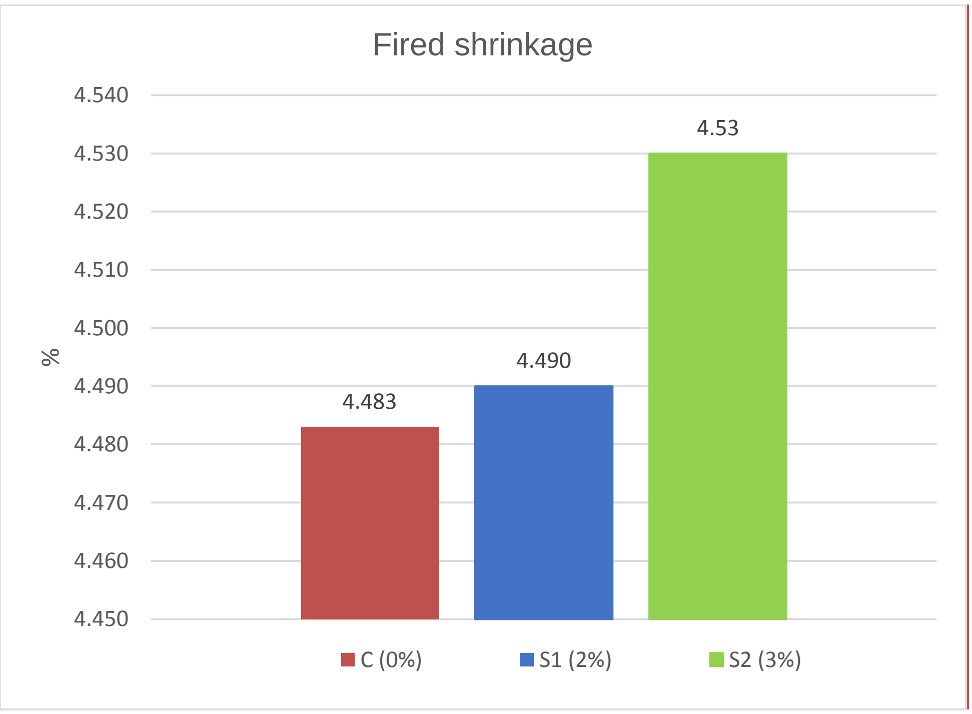


Water absorption tests on bricks are measured to determine the durability of the bricks such as the degree of burning, quality and behaviour of bricks in weathering. Bricks with water absorption of less than 7% provide better resistance to damage by freezing. The degree of compactness can also be obtained by water absorption tests, as water is absorbed by pores in the bricks. For fired clay bricks, waste glass particles fuse with the clay bodies and contribute to the densification of the clay brick (Abdeen & Shihada, 2017). The water absorption is higher with an increase in pores, therefore bricks with water absorption that is less than 3% can be referred to as being vitrified. Interestingly, the average water absorption of S1, containing 2% glass showed the highest water absorption. It was expected that the water absorption in the samples containing glass would be lower as the glass would have melted and fused into the clay body, becoming denser on the inside. This result was, however, still positive as the average between the samples containing glass (S1 and S2) was measured to be 4,08%, on par with the control sample. A decrease in water absorption was expected due to the zero water absorption capacity of glass material (Hameed *et al.*, 2018).

4.1.2.5 FIRED SHRINKAGE

The fired shrinkage of the samples was measured on the sample collected from the brick factory after firing. Nine samples from each batch were randomly selected for the purpose of this test. As glass melts at a lower temperature (between 700-800 °C) than the firing temperatures inside a tunnel kiln (between 800-1250 °C), depending on the factory and the products they produce, the glass was expected to melt into the pores of the clay body. This will generally result in an increase in fired shrinkage in the samples containing glass particles. The samples corresponded with this expectation as S2 showed the highest fired shrinkage as opposed to the other sample batches.

Figure 0-5: Average fired shrinkage of samples

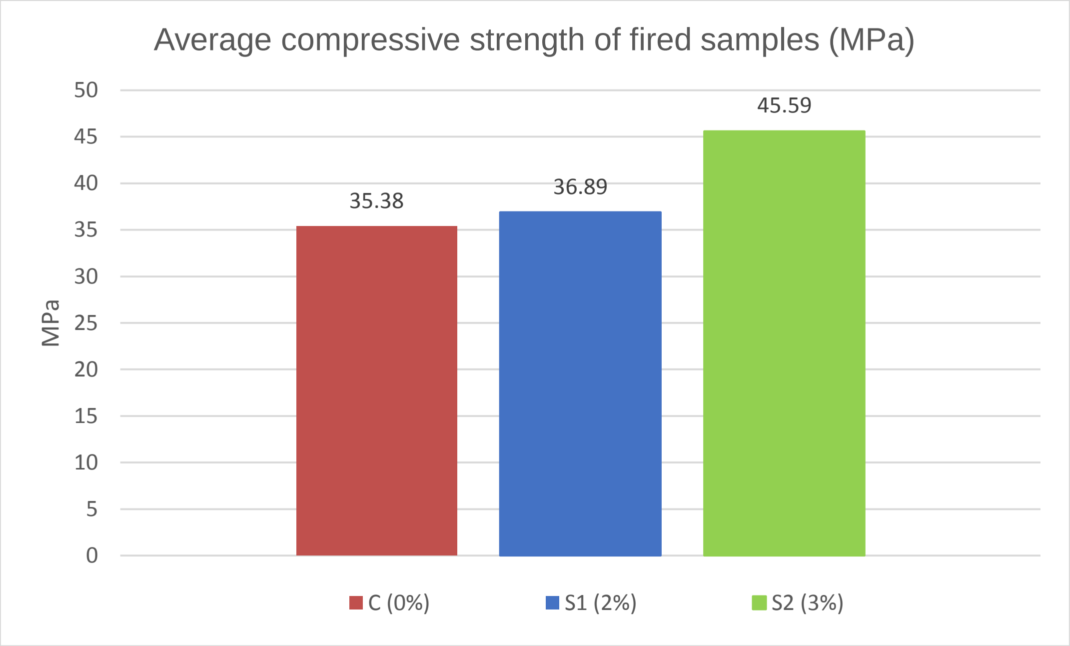


4.1.2.6 COMPRESSIVE STRENGTH

As stated in Chapter 3, 36 samples from each batch were sampled for compressive strength tests. The instrument used for the tests was a King Test crushing machine, which is capable of producing a crushing force of up to 2000 kN (King, 2019). The samples were put under a load of 15 MPa/min until the point of failure and the figures were calculated using the formula below to convert the kN of force to MPa:

$$\text{Compressive strength (MPa)} = \frac{\text{Failure load (N)}}{\text{Area of bed face (mm}^2\text{)}}$$

Figure 0-6: Graph indicating an increase of compressive strength of fired samples

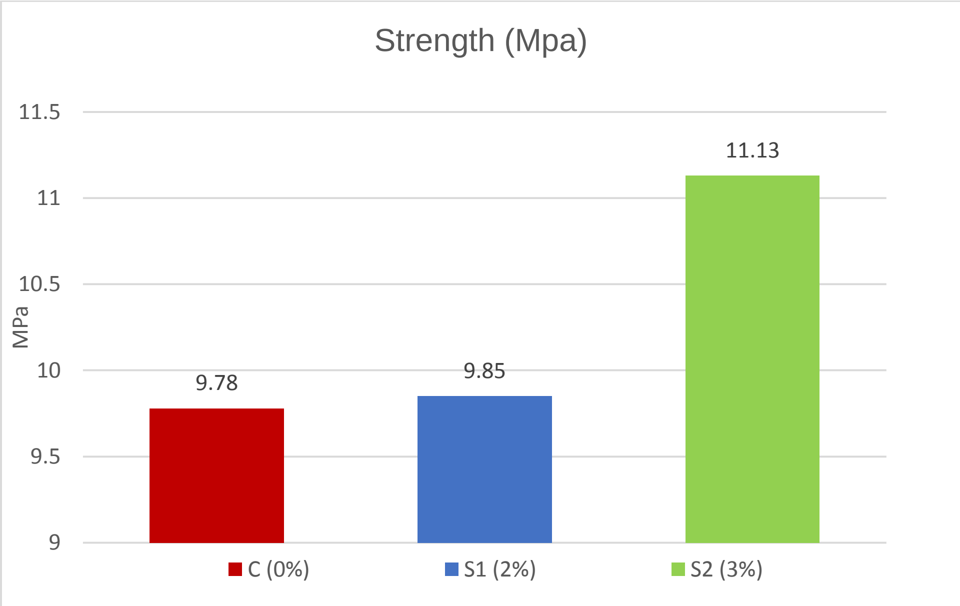


The results of the compressive strength tests were impressive as all samples from all three batches showed very high crushing strengths. A 4% increase was calculated between samples C and S1, however, the average compressive strength between S1 and S2 was substantial as the strength increased by 22% in compressive strength between S1 and S2. "The increase in strength with increase in temperature may be due to interaction of the oxides producing mullite and free silica in the form of cristobalite" (Abuh *et al.*, 2019). This result is critical in illustrating that glass does have a considerable impact on strength if introduced into clay bricks, especially into a clay type that was very strong from the start. The addition of waste glass considerably contribute to vitrification of the clay material, it also enhances the strength development by closing the internal pores with glassy phase (Abdeen & Shihada, 2017).

4.1.2.7 BREAKING STRENGTH

Lastly, 36 test units from the different batches were sampled for breaking strength testing, using an Instron, tensile testing instrument, using 3-point breaking to determine the tensile strength or modulus of rupture (MoR) of the samples.

Figure 0-7: Average breaking strength



Again, it is quite apparent that samples with 0% glass and those containing glass produced remarkable results, especially the samples containing 3% of glass. S2 showed an average breaking strength of 11.13 MPa, a 13% increase from the results of the control sample (C). This results further prove that glass introduced into clay bricks will create stronger, more durable products.

4.3 SUMMARY OF TEST RESULTS

Table 4-1: Summary of test results

	Parameter	Control (C) (0% glass)	Sample 1 (S1) (2% glass)	Sample 2 (S2) (3% glass)
950 °C	Water added for extrusion	21,20%	21%	21%
	Workability	Good	Good	Good
	Water absorption	5,05%	4,30%	3,11%
	Green Shrinkage	3,59%	3,46%	3,34%
	Moisture content	23,45%	22,82%	22,77%
	Fired Shrinkage	4,48%	4,49%	4,53%
	Breaking strength (MoR)	9,78 MPa	9,85 MPa	11,13 MPa
	Crushing strength	35,38 MPa	36,89 MPa	45,59 MPa

4.4 COMPARISON OF RESULTS FROM THIS STUDY AND DATA FROM OTHER RESEARCH

Further research was conducted to determine if similar tests were conducted by other researchers in other areas in South Africa and in other parts of the world. Fortunately, evidence was found that similar tests were conducted on clay samples from a clay brick factory in the Eastern Cape (EC) and from a different clay brick factory in Gauteng (Gau2) in South Africa, further studies were gathered from Turkey (Tur). Similar studies were conducted around the world (see Annexure A8 for data from Russia, Pakistan and Palestine), however, the parameters varied substantially from study to study, therefore the focus was put on the data from Turkey as the parameters of testing were similar to the parameters in this study. Similar tests were conducted on the test samples and the results, when compared, were compelling. For clarification purposes, the samples from this project (C, S1 and S2) and other research were named as followed:

Table 4-2: Compared tests sample names

Name: Sample origin	**Sample names**
JN: Results from this study	C (0% glass), S1 (2% glass), S2 (3% glass)
EC: Eastern Cape	LC0 (0% glass), LC1 (2% glass), LC2 (3% glass)
Gau2: Gauteng	P0 (0% glass), P2 (2% glass), P4 (4% glass), P6 (6% glass)
Tur: Turkey	T0 (0% glass), T2 (2,5% glass), T5 (5% glass), T10 (10% glass)

Comparing results from this study with other studies cannot be regarded as true comparisons as various factors may have an impact on the results obtained from other research, such as different firing temperatures in samples, firing methods, percentage of glass added to the samples and the types of clay used in the studies. The purpose of measuring the comparisons is to prove whether there is a measurable improvement between the samples containing 0% glass and the samples containing glass, regardless of the number of samples tested, the amount of glass added or temperatures in which the samples were fired as well as the conditions of firing. The data from other research compared to what was gathered from this project is found in Table 4-3 below:

Table 4-3: Results compared to other studies

Parameter	JN: C	JN: S1	JN: S2	EC: LC0	EC: LC1	EC: LC2	Gau2: P	Gau2: P2	Gau2: P4	Gau2: P6	Tur: T0	Tur: T2	Tur: T5	Tur: T10
% glass added	**0%**	2%	3%	**0%**	2%	3%	**0%**	2%	4%	6%	**0%**	2,5%	5%	10%
Water added for extrusion	**21,20%**	21,00%	21,00%	**20,90%**	20,90%	20,80%	**N/A**	N/A	N/A	N/A	**N/A**	N/A	N/A	N/A
Workability	**Good**	Good	Good	**Good**	Good	Good	**Good**	Good	Good	Good	**N/A**	N/A	N/A	N/A
24 Hr Water absorption	**5,05%**	4,30%	3,11%	**18,73%**	16,95	16,91	**13,44%**	13,20%	12,18%	10,61%	**19,45%**	19,06%	18,35%	17,73%
Green Shrinkage	**3,59%**	3,46%	3,34%	**3,25%**	2,54%	2,21%	**3,36%**	3,44%	3,31%	3,22%	**3,95%**	3,72%	3,64%	3,53%
Moisture content	**23,45%**	22,82%	22,77%	**N/A**	N/A	N/A	**21,10%**	22,72%	22,58%	21,54%	**N/A**	N/A	N/A	N/A
Firing Temperature	**950 °C**	950 °C	950 °C	**850 °C**	850 °C	850 °C	**1100 °C**	1100 °C	1100 °C	1100 °C	**850 °C**	850 °C	850 °C	850 °C
Fired Shrinkage	**4,48%**	4,49%	4,53%	**3.25%**	2.54%	2.21%	**4,55%**	5,36%	5,56%	6,11%	**5,35%**	5,15%	4,65%	4,35%
Breaking strength (MoR)	**9,78 MPa**	9,85 MPa	11,13 MPa	**6,80 MPa**	7,0 MPa	7,2 MPa	**6,56 MPa**	7,62 MPa	8,51 MPa	9,53 MPa	**N/A**	N/A	N/A	N/A
Crushing strength (MPa)	**35,38 MPa**	36,89 MPa	45,59 MPa	**13,8 MPa**	17,2 MPa	17,6 MPa	**20,55 MPa**	24,67 MPa	26,84 MPa	31,48 MPa	**16,45 MPa**	18,75 MPa	20,15 MPa	20,62 MPa

(MPa- Megapascal; N/A – Information not available)

Figure 0-8: Water absorption compared

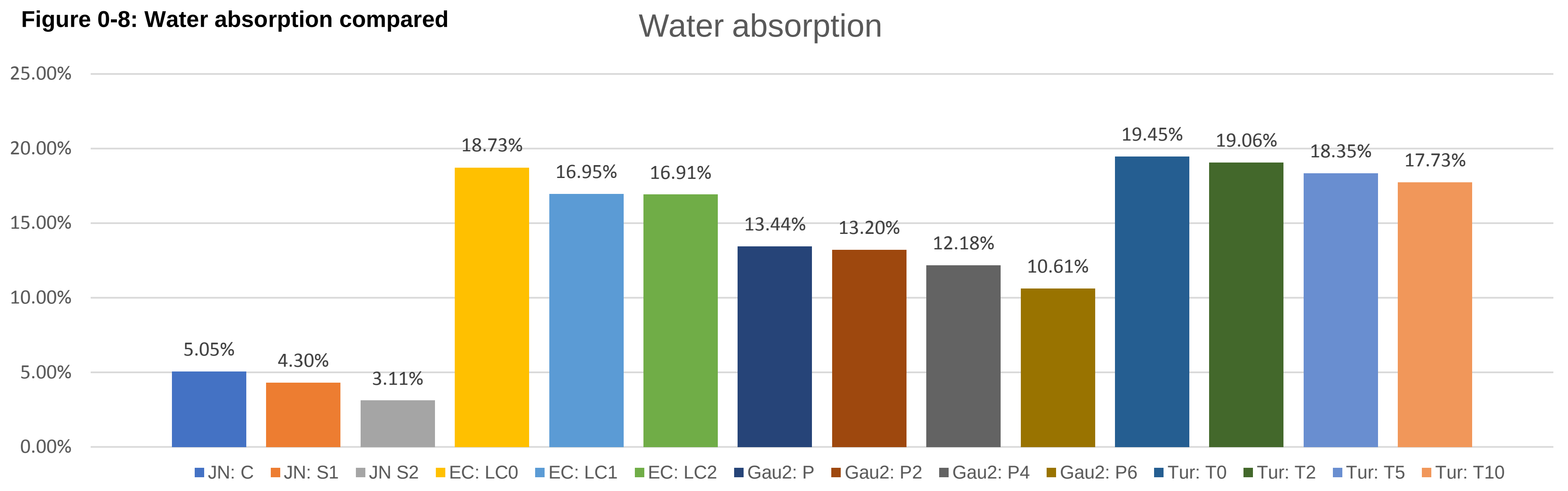


Figure 0-9: Green shrinkage compared

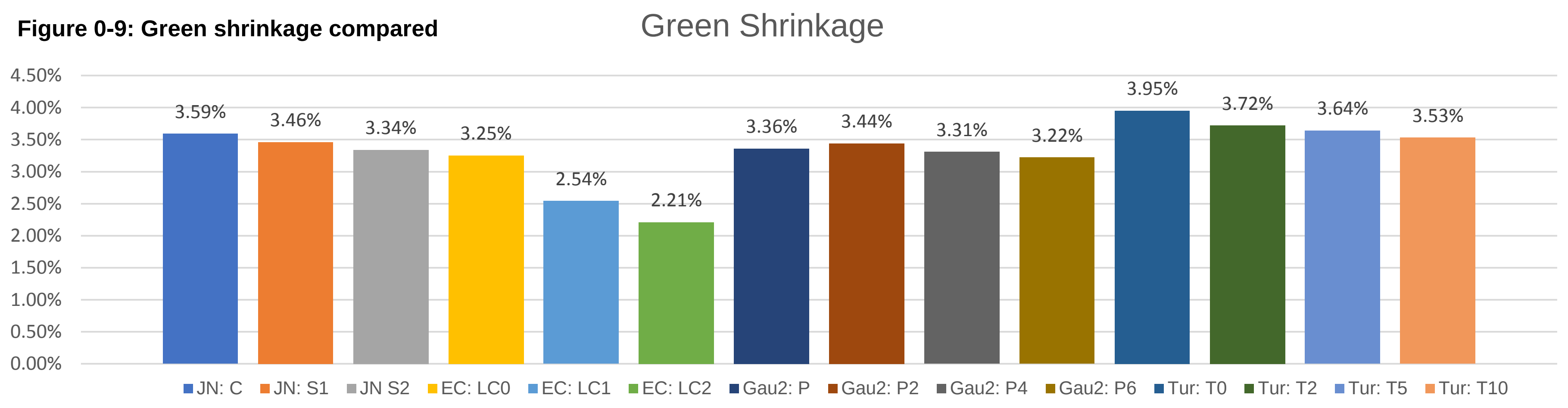
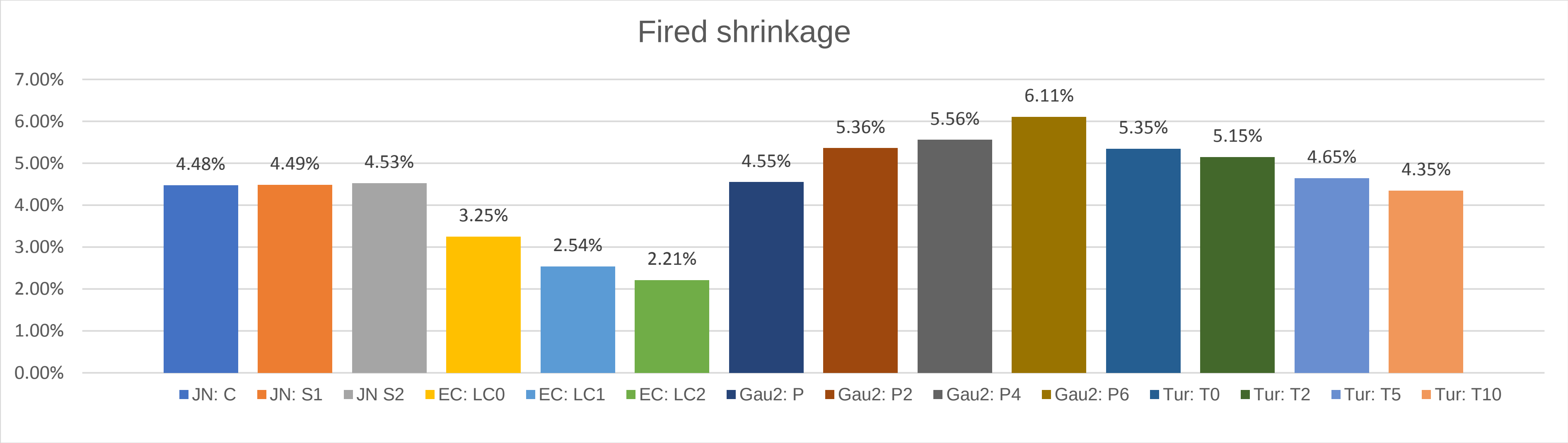


Figure 0-10: Fired shrinkage compared



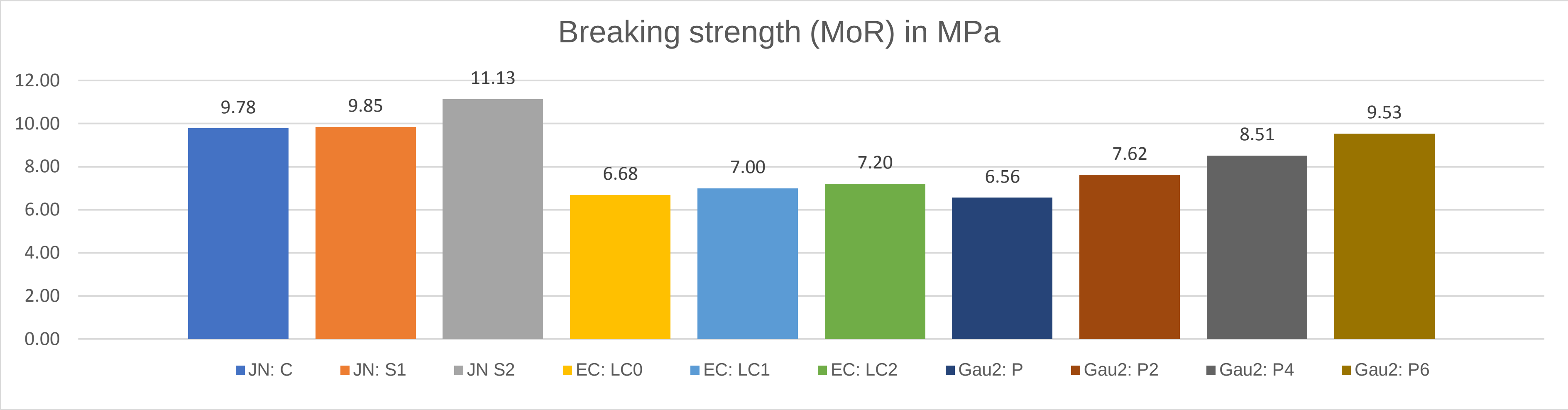
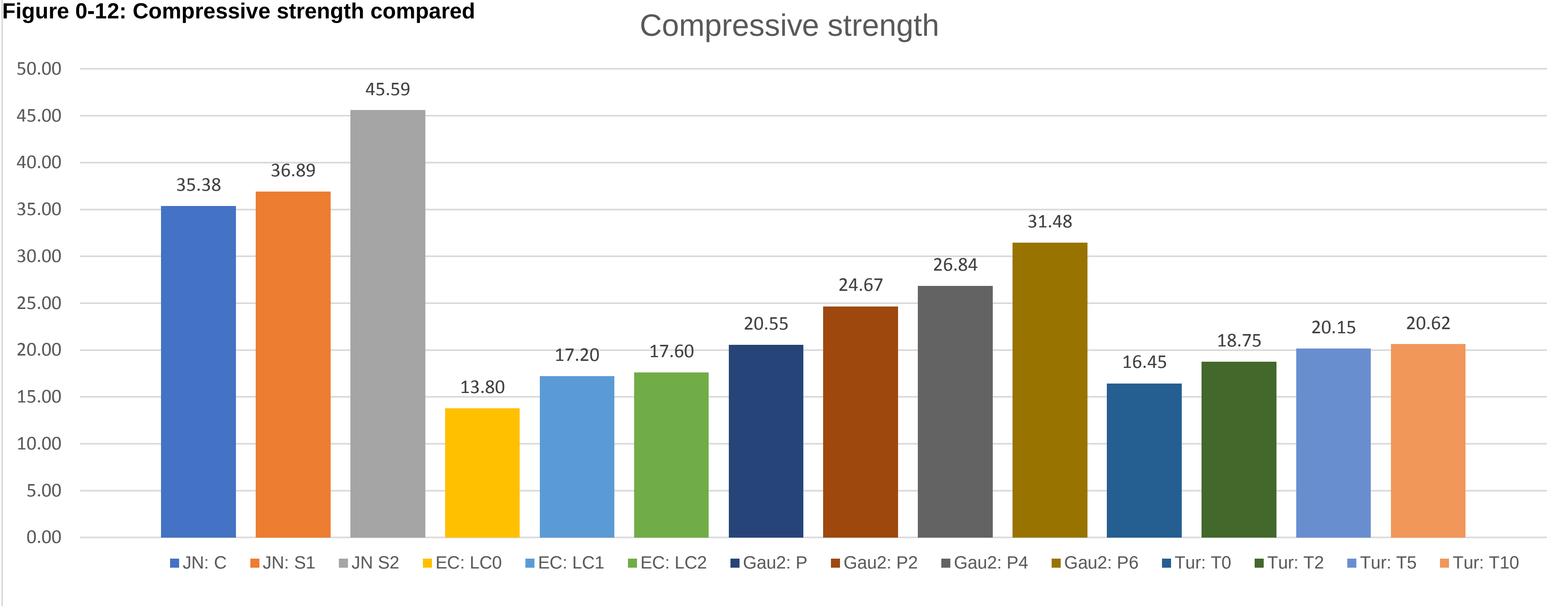


Figure 0-11: Breaking strength compared

Figure 0-12: Compressive strength compared



4.5 CONCLUSION UPON COMPARING TEST RESULTS

Remarkably, the data generated by other studies correlate with the data generated for this study, regardless of the percentage of glass added to the clay material, different firing temperatures and the methods of firing. This is beneficial as it proves the hypothesis that glass addition to clay brick generally has a positive impact on the final product. More details on the findings can be found in section 5.3 in Chapter 5.

4.6 GLASS PROCESSING RESULTS

The seven tests performed on crushing of glass materials to the desirable size yielded overwhelmingly positive results as we are now able to determine the required type of machinery, the optimal configuration of crushing machines, the settings for the machines, its power consumption, capital investment required and the operating costs for the processing plant to deliver the raw material to industry. Results from Tests 1, 3 and 7 were used to determine the following requirements for the processing plant.

Table 4-4: Crushing test results

Test no:	Test machine	% of product passing 1 mm	Remark
1	Impact crusher	43,6	Primary stage of dual-stage crushing
3	Hammermill	97,4	Single-stage hammer mill crushing
7	Hammermill	97,8	Secondary-stage of dual-stage crushing

Results from Test 1 indicated that almost 44% of the material passed through the 1 mm screen after one passing through the machine. This means that 56% of the glass materials were still larger than the required size (<1 mm) to be adequate for the introduction into clay brick manufacturing and requires secondary crushing. Results from Test 3 indicated that 97,4% of the material put through the hammer mill passed through the 1 mm screens if the hammer mill was installed as the primary crushing machine. At first glance, results from this test may indicate that the hammermill is sufficient to deliver the required product size on its own, however it is important to keep in mind that the hammer mill in the primary position would endure a tremendous amount of stress and wear due to the abrasiveness of the glass and its milling action. Similarly, Test 7 indicated that 97,8% of the material passed through the 1 mm screen with the impactor positioned in the primary position and the hammer mill in the secondary position. Even though Tests 3 and 7 yielded similar results, the impactor is capable of crushing close to 44% of the material in the primary stage, only 56% will pass through the hammer mill resulting in nearly 50% less wear, significantly reducing maintenance costs and potential downtime. Saying this, a dual-stage process is recommended.

Throughput of material through the process is critical, depending on the configuration, single-stage hammer mill crushing would require the hammer mill to process up to 3.75 tph, however with the dual-stage configuration, the impactor is capable of processing >10 tph and by processing 44% of the material, the hammer mill will only be required to process material exceeding 1 mm in size (the remaining 56%), equating to 2.1 tph, resulting in less stress and wear on the components. Test 7 proved to be the optimal configuration required to produce <1 mm glass material at the lowest operating cost.

If the processing equipment in the processing plant is used as production machines, the difference in power requirements is minimal between single- and dual-stage configurations. The hammer mill in the primary configuration would utilise 25,67 kW of power and a dual-stage configuration would require less power at 25,19 kW of power. The results of the tests can be seen below:

Table 4-5: Installed power required with Hammermill as primary crusher

Machine	Throughput (tph)	Specific power consumption (kWh/t)	Crushing power (kW)	No-load power (kW)	Hammermill power (kW)
Hammer mill (NOVO 490/190)	3,75	5,503	20,64	5,03	**25,67**

Table 4-6: Installed power required for dual-stage crushing

Machine	Throughput (tph)	Specific power consumption (kWh/t)	Crushing power (kW)	No-load power (kW)	Hammermill power (kW)
Impact crusher (AP-S 0403)	3,75	1,070	4,01	4,4	**8,41**
Hammer mill (NOVO 490/190)	2,1	5,919	12,43	4,35	**16,78**
				Total	**25,19**

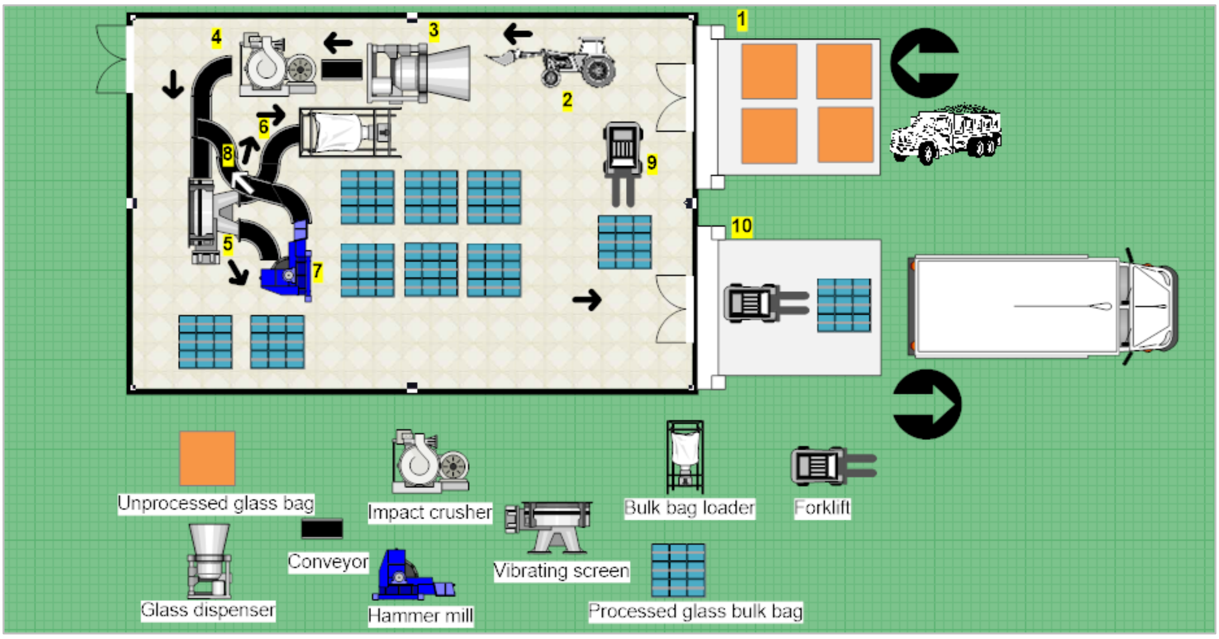
4.6.1 CONCLUSION GLASS PROCESSING

The results of all tests proved that the required size of <1 mm particle can be achieved with machines available on the market. A product of <1 mm can be generated with a maximum of 5% of the product required to be put through the process a second time. The dual-stage process is recommended with the impact crusher in the primary position and the hammer mill in the secondary position due to the reduced power required to complete the processing and the potential saving on wear and maintenance costs. With the dual-stage configuration, the hammer mill will only be required to process the oversized material after the screening, thereby reducing throughput and wear, which is especially advantageous as it is a high-wear machine due to its milling action. The wear rate on the impact crusher was calculated to be approximately 15 g/tonne, unfortunately, wear rate on the hammer mill was not established, however, an estimation by a subject matter expert concluded that the wear rate can be as much as five times higher on the hammer mill (75 g/tonne) due to its milling action and the abrasiveness of glass.

4.7 CAPITAL INVESTMENT REQUIRED FOR PROCESSING PLANT

In order to develop a processing plant according to the specifications dictated by the test results, an area of approximately 300 m² is required to allow sufficient areas for unloading, storage, stockpiles, dispatch (exterior of building); and crushing equipment, offices and processing (inside of building), with the adequate power supply to power the plant and machinery. The proposed facility will be able to process up to 660 tonnes of waste glass per month. See below for the proposed layout of the processing plant.

Figure 0-13: Proposed floorplan and layout of the processing plant



4.7.1 WASTE GLASS PLANT PROCESS FLOW:

1. Unloading of waste glass bulk bags.
2. Transfer of waste glass material to box feeder (glass dispenser).
3. Waste glass is discharged onto a conveyor belt.
4. Primary crushing of glass in impact crusher.
5. Material is screened (<1 mm is sent for loading; oversized material is routed to hammer mill.
6. <1 mm material is discharged into bulk bags.

7. Secondary crushing of glass material in the hammer mill.
8. Oversized material (approx. 5%) is re-routed back to hammer mill for further processing.
9. Bulk bags are transported via forklift to dispatch area.
10. Bulk bags are loaded and dispatched to clay brick manufacturers.

The cost of setting up a processing plant can be substantial due to the number of plant and equipment required to process in excess of 600 tonnes of waste glass per month. See below for an estimation on the capital investment required to establish a glass processing plant for processing glass to less than 1 mm.

Table 4-7: Estimated capital investment and operating costs required for a complete glass processing plant

Processing plant	Capital expenditure	Overheads per month
Fork lift x 1	R 200 000,00	
Front End Loader x 1	R 280 000,00	
Belt Conveyers 4 m x 6 (@ R 18 000.00 each)	R 108 000,00	
Belt Conveyers 6 m x 2 (@ R 25 000.00 each)	R 50 000,00	
Vibrating Screen x 1	R 125 000,00	
Hazemag Impactor AP-S 0403 x 1	R 550 000,00	
Hazemag Novorotor 490/190 x 1	R 625 000,00	
Box Feeder x 1	R 65 000,00	
Storage bins x 8 (@ R 12 000.00 each)	R 96 000,00	
Bulk bag loader x 1	R 40 000,00	
Fuel (estimated)		R 20 000,00
Salaries (2 x labourers and 1 supervisor)		R 33 120,00
Rent (300 m^2 @R 50 per m^2)		R 15 000,00
Maintenance on machinery		R 8 751,60
Misc. expenses		R 5 000,00
Electricity		R 2 275,62
Total	**R 2 139 000,00**	**R 84 147,22**

The total operating cost per month was calculated using the wear rates determined by the crushing tests to calculate the monthly maintenance costs, the power consumption required to optimally crush the glass material together with other variables such as fuel and labour were added to the monthly overhead expenditure per month.

Table 4-8: Calculation of processing cost at full capacity

100% Production	
Tonnes processed per month	**660**
Hours worked per month @ 3.75 tonnes per hour	176
Price of a kWh (Industrial)	R 1,85
% Tons through Impactor	100%
kWh Impactor as tested	1,07
Impactor kWh per month	188,32
% Tons through Hammer Mill	56,0%
kWh Hammer Mill as tested	5,919
Hammermill kWh per month	1041,74
Maintenance and electricity on equipment	
Total kWh per month	R 1230,06
Total kWh cost per month (Electricity)	**R 2 275,62**
Wear cost Impactor per ton	R 2,21
Wear cost Hammer Mill per ton	R 11,05
Total wear cost per ton	R 13,26
Total wear cost Impactor	R 1 458,60
Total wear cost Hamer Mill	R 7 293,00
Total maintenance cost on equipment	**R 8 751,60**
Transport	
Cost/km @34 tons per truck for plant	R 23,00
Delivery price per km	R 30,00
Profit per km	R 7,00
Salaries	
Labourer 1 salary per month	R 8 000,00
Labourer 1 overtime per month	R 1 200,00
Labourer 1 salary with overtime per month	R 9 200,00
Labourer 2 salary per month	R 8 000,00
Labourer 2 overtime	R 1 200,00
Labourer 2 salary with overtime per month	R 9 200,00
Supervisor salary per month	R 12 800,00
Supervisor overtime @ pay x 1.5 per hour	R 1 920,00
Supervisor salary with overtime per month	R 14 720,00
Total labour expense per month (Salaries)	**R 33 120,00**
Rent per month	**R 15 000,00**
Fuel	**R 20 000,00**
Misc.	**R 5 000,00**
Total glass processing cost per ton (tot labour + total maintenance / 660 tonnes)	R 63,44
Total glass processing cost per month	**R 41 871,60**
Profit	
Asking price per ton	R 400,00
Glass processing cost per ton (R/t)	R 63,44
Nett profit per ton (Rand)	**R 336,56**
Nett profit per month (x 660 tons)	**R 222 128,40**

4.7.2 RETURN ON INVESTMENT

The return on investment for the processing plant was calculated by dividing the capital investment required for the plant by the nett profit projected based on processing 660 tonnes of glass per month at the price of R 400.00 per tonne of the processed material. See below for detailed calculations on profit and return on investment.

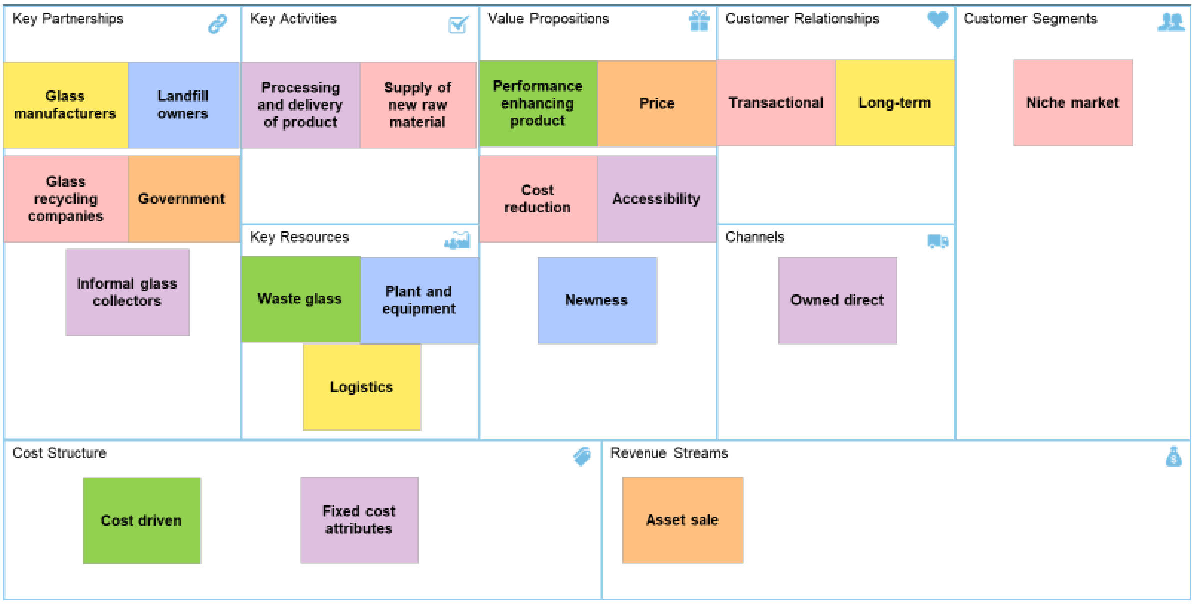
Table 4-9: Return on investment of processing plant

Return on investment (ROI)	
Total sales per month	**R 222 128,40**
Total expenditure per month	**R 84 147,22**
Total nett profit per month	**R 137 981,18**
R 2 139 000,00 / R 137 981,18	=15,50
ROI in months	**16**
ROI in years	**1 year and 4 months**

4.8 APPLYING THE OSTERWALDER BUSINESS MODEL CANVAS

The Osterwalder business model canvas will be used to develop a business plan for an aspiring entrepreneur to take this business plan and create a profitable business from beneficiating waste glass in clay brick manufacturing processes. The nine components of the Osterwalder business canvas (BMC) will be explained in its application based on the glass processing plant business.

Figure 0-14: Osterwalder business model canvas for the processing plant



4.8.1 KEY PARTNERSHIPS

4.8.1.1 GLASS MANUFACTURERS

Key partnerships with manufacturing companies is vital to enable the business (processing plant) to establish the possibility of receiving waste glass (which is unusable for the manufacturer) on a regular basis as the end-user will require a set quantity of the processed material for their manufacturing process (i.e. customer 1 may require 270 tonnes of processed material per month for brick production). All-types of glass manufacturers (bottles, flat glass, etc.) can be potential partners as the waste collected from them will likely comprise of the majority of waste glass received as it will be coming straight from the source. Key partnerships with the companies producing the most waste remain essential in obtaining exclusivity in obtaining the waste material directly from the source.

4.8.1.2 GLASS RECYCLING COMPANIES

Glass recycling companies can also be potential partners even though they are in a similar line of business, the sheer amount of waste produced in South Africa needs to be the focal point in which competing companies should work together to minimise the waste for the greater good of the environment. It might be challenging to partner with other recycling companies, however as stated above, the focus needs are on minimising the waste headed to already overflowing landfills.

4.8.1.3 LANDFILL OWNERS

Landfill owners can be vitally important partners as the mission of the business will be to minimise waste by creating a new raw product to be used for manufacturing. Partnering with landfill owners can be mutually beneficial as the processing plant will require large amounts of waste glass to be removed from landfills, creating more space for the landfill owner and also to obtain waste material ready for processing.

4.8.1.4 GOVERNMENT

The government of South Africa might be a potential partner as the processing plant is in the position to make a valuable contribution to the country's environment and the economy, therefore by processing waste material, possible incentives may become available for the processing plant to benefit from, such as carbon credits on the law passed recently on carbon tax. Secondly, by establishing a partnership that is mutually beneficial between the government and the processing plant, both parties can benefit from this relationship. The South African government's Department of Trade and Industries (DTI) have been offering incentives to businesses investing in the manufacturing sector and therefore has the capability to administer an incentive programme of this nature (Harris, 2013).

4.8.1.5 INFORMAL GLASS COLLECTORS

Even though the quantities receivable from informal bottle, glass collectors are substantially less than the sheer volume of waste glass currently in landfills, these partnerships can stimulate job creation and become a sustainable source of income for unskilled or unemployed citizens of South Africa, by collecting waste material to be sold to the processing plant for processing. The owner of the processing plant can stimulate job creation in South Africa by employing informal glass collectors to gather waste glass that would otherwise be dumped at landfills. A further feasibility study would need to be conducted to determine the feasibility of employing informal glass collectors and the potential challenges that involve employing unskilled labour.

4.8.2 KEY ACTIVITIES

4.8.2.1 PROCESSING AND DELIVERY OF THE PRODUCT

The key activities of the processing plant will be to add value to a waste product by crushing the waste material to be used by clay brick manufacturing factories to improve the quality of the products they produce. The plant will use industrial equipment to do the processing (crushing, milling) of the waste products.

4.8.2.2 SUPPLY OF RAW MATERIAL

The processing plant will also batch and package the process material in bulk bags for its customers to enable the end-user to receive the product in bulk. Secondly, the option for delivery of the products can be an attractive revenue stream for the plant to diversify its operations.

4.8.3 KEY RESOURCES

4.8.3.1 GLASS AND WASTE GLASS

Key resources for the processing plant are waste glass, unusable glass products and glass headed for landfills. This is the main resource that the processing plant will be dependent on to conduct its operations. Fortunately, with the landfills in South Africa receiving in excess of 1 million tonnes of waste glass per year, the outlook for the plant looks promising. The viability of this study can be confirmed as: “the utilisation of glass waste substantially reduces dumping-site space, which has a great significance in environmental protection” (Leshina & Pivnev, 2002).

4.8.3.2 PLANT AND EQUIPMENT

The processing plant will make use of industrial equipment to process the material to the desired sizes. In processing the quantities required for the market, maintenance and replacement of worn parts will become a regular occurrence therefore detailed maintenance schedules and inspections need to be developed and managed to minimise down-time and breakdowns. A surplus of materials is recommended to be able to supply the market in times when maintenance is scheduled and/or break downs occur.

4.8.3.3 LOGISTICS

The business plan is focused on producing the material required for clay brick manufacturers and also to deliver the product to its customers. Logistics will become an essential component of the business combined with the processing of material, therefore all vehicles and parts used in the plant are regarded as key resources.

4.8.4 COST STRUCTURE

4.8.4.1 COST-DRIVEN

The business plan for the glass processing plant will rely on a cost-driven cost structure as the profitability of the business will be reliant on the quantity of product sold and the cost at which it is sold. The cost-driven cost structure is based on the low-cost industry, therefore selling of large quantities of material is essential for the survival of the business.

4.8.4.2 FIXED COST ATTRIBUTES:

The cost of the product in the market directly correlates with the processing cost of the material, therefore any variation in processing cost will have an impact on the final selling price, however, the profit margin will vary depending on the quantities sold per customer in order to keep the selling price of the product per tonne consistent and to minimise price variations which could have a negative impact on customer relationships.

4.8.5 VALUE PROPOSITIONS

4.8.5.1 PERFORMANCE-ENHANCING PRODUCT

The biggest benefit the processed material has is the ability to improve the quality of the final clay brick products. It has been proven by the research conducted for this project and with the compared results from other studies. It is a performance-enhancing product that can be produced at a relatively low cost. Potential benefits for clay brick manufacturers to use glass in the manufacturing of clay bricks include, better-performing products due to increased strength and durability, cost-saving in manufacturing as glass acting as a flux will reduce firing temperatures resulting in secondary savings. This is confirmed by researchers stating that glass could be entirely used to replace traditional feldspar in order to reduce firing temperatures in ceramic tile or clay brick production (Loryuenyong *et al.*, 2009).

4.8.5.2 PRICE (VS ALTERNATIVES)

One major benefit of the product is its price compared to alternatives in the market, one mineral currently used in the industry as a fluxing material is feldspar, which costs between R 1200 - R 2600 per tonne (Zibo, 2020), depending on the particle size required, with the finer material generally being more expensive. It is possible to utilise waste glass as a flux to replace fluxes such as feldspar or other mineral fluxes to save energy in ceramic manufacturing processes (Tiffo *et al.*, 2015). Fortunately, by calculating the processing cost (electricity, maintenance and wear) the plant will be able to sell the processed material at R 400 per tonne.

4.5.2.3 COST REDUCTION

By adding the processed glass to the manufacturing process of any clay firing process will have a substantial cost reduction for the manufacturer opposed to using feldspar as the price of processed glass can potentially save the manufacturer up to three times more as opposed to the cost of feldspar. Furthermore, by using glass as a substitute for feldspar, the brick manufacturer will have a further cost reduction in productions as the utilisation of waste glass can also be used to reduce energy consumption with a view to achieve economic purpose, as stated by Tiffo *et al* (2015), “waste glass replaces feldspar completely since the latter is expensive and not available everywhere for effective economic consumption while the former is easily found near urban zones”.

4.5.2.4 ACCESSIBILITY

Accessibility of the product may become an important value proposition for the customers if the processing plant could produce a surplus of material to be made available for customers in the industry.

4.5.2.5 NEWNESS

The results of tests were overwhelmingly positive and no other products on the market can produce similar results at the price calculated for processing. The newness of the product will likely be a value proposition as this product will be the first of its kind on the market.

4.8.6 CUSTOMER RELATIONSHIPS

4.8.6.1 TRANSACTIONAL

Customer relationships are crucial to the success of the processing plant as the satisfaction of the customer is directly proportionate to the success of the business. The type of customer relationships in this model will be transactional initially as it is expected for the customer to work with the new products for a period of time and to adjust their manufacturing processes accordingly, this can take time but with the knowledge and experience learned from doing the processing, the entrepreneur in charge of the plant should consult and assist the customers as much as possible to turn the transactional relationships into long-term relationships.

4.8.6.2 LONG-TERM

Long-term relationships with customers should be built by supplying customers with the product they need on a regular basis. This is possible if the processing plant can manage its production and ensure that there will be material available for their customers at all times.

4.8.7 CUSTOMER SEGMENTS

4.8.7.1 NICHE MARKET

The end-product produced by the processing plant is developed for a specific market, however, it can be used in other construction materials as an aggregate, the main benefits will only be realised in firing the brick or tile to see the increase in durability and strength, therefore it is focused on a niche market. The customers of the plant will all be segmented into one category to enable the manager of the plant to learn and better understand the needs of its customers in a particular segment.

4.8.8 CHANNELS

4.8.8.1 OWNED DIRECT

The channels in which the plant will conduct its business are owned-direct channels, meaning that the marketing, sales - and delivery channels of the product will be managed and maintained by the business itself. It is the best way to ensure that the business can understand its customer's needs and to have a hands-on approach.

4.8.9 REVENUE STREAMS

4.8.9.1 ASSET SALE

The main revenue stream accessible for the plant is based on the sales of the product processed in the facility. This business model and financial projections are based on the sale of more than 600 tonnes of processed glass per month at R 450 per tonne. Fortunately, the cost for delivery of the product is also factored in, therefore leasing of trucks for delivery is a contributor to the revenue of the company.

4.8.9.2 RENTING/LEASING

A small percentage of the plant's revenue originates from delivery of the processed material as the price for delivery of the product, less than or equal to 100 km distance, further distances will also increase the price. Saying this, a small fraction of the business's revenue is receivable with the delivery of the processed products.

4.9 CHAPTER 4 SUMMARY

- The results from the extruded samples were analysed and it was found that the moisture content of the samples containing glass decreased, which could be attributed to the inert nature of the glass filling the pores of the clay body.
- Green shrinkage of the samples containing admixtures of glass also decreased as the drying temperature (110 °C) of the samples were too low to melt the glass particles and instead, glass particles acted as an aggregate or filler in the dried clay material.
- No visible defects or warpage in the dried samples were observed, indicating that the samples were adequately mixed and dried overnight.
- After firing, water absorption levels increased with the samples containing glass 2% admixtures, however, water absorption decreased significantly with samples containing 3%. This phenomenon can be attributed to the samples becoming vitrified during firing, indicating that the glass did act as a flux and could be fired at lower temperatures to achieve the required water absorption levels to allow bonding of the clay brick with mortar when building.

- The fired shrinkage of the samples containing glass increased, possibly due to the glass particles melting into the pores of the clay material during firing.
- Samples containing 2% and 3% showed an impressive increase in compressive strength, with a 4% increase between the control and S1 and a 22% increase between S1 and S2.
- The breaking strength of the samples also increased by 13% between the control samples and S2.
- The results from this study were compared to results from other literature (from South Africa and Turkey) and the majority of the data correlated with the figures from this study.
- The optimal processing equipment, with the appropriate settings, were determined to enable an entrepreneur to have a benchmark for purchasing the necessary equipment for a waste glass processing plant.
- A possible layout of a waste glass processing plant was developed, with a framework consisting of establishment cost, operating cost, return on investment and the potential profit from the plant was calculated.
- The Osterwalder business model canvas as explained in Chapter 3 was applied to the processing plant and all of the segments attributed to the business model were identified.
- Uniquely, the processed waste glass as a raw material for clay brick manufacturers delivers enormous value to the brickmakers as the product is both performance-enhancing, as well as cost-reducing as the processed material, can be processed and sold for much less than its closest comparable substitute product, feldspar.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, conclusions of all tests will be explained, and recommendations will be made accordingly. In short, the laboratory and full-scale tests were successful along with the crushing trials.

5.2 LIMITATIONS

The limitations of this research project were attributed to the type of clay used for the project. All clays used in the manufacturing of clay bricks differ from each other based on its chemical - and mineralogical compositions around the world. Some clays are stronger than others, some have better workability, therefore the clay procured from the factory is not representative of all clays used for brick manufacturing. However, the constant factor researched was determining whether the glass admixtures improved the quality and durability of the fired products. That is why it was necessary to compare results from this study with research from other parts of the country and from other countries around the world to measure if the results found in this study correlated with evidence gathered by other researchers.

5.3 CONCLUSION ON FINDINGS FROM LABORATORY TESTS

- Laboratory scale tests were successful as extrusion and workability of the clay containing glass were positive.
- No warpage or cracks developed during drying or firing of the samples in laboratory driers and kilns.
- Crushing trials on a small-scale were successful as the desired particle size (<1 mm) was achieved using a 2-kW hammer mill with manual milling. This required further trials to be proven on an industrial scale.
- The proof of concept (POC) was proved and real-world simulations of the laboratory scale tests were required to evaluate the technical properties of the samples.

5.4 CONCLUSION ON REAL-WORLD SIMULATIONS

A total of 108 samples were extruded for the purpose of testing the samples fired in an industrial scale, along with normal clay bricks in a tunnel kiln. The samples were placed among other clay bricks on a kiln car in different positions to re-create firing of bricks in different firing zones. The kiln was fired using coal with burners from top-to-bottom, no side-firing was possible in this kiln.

After collecting the samples from the factories, tests were conducted according to SANS 227:2007 specifications. The tests consisted of measuring green shrinkage, moisture content, warpage, fired shrinkage, water absorption, breaking strength and compressive strength.

5.4.1 GREEN SHRINKAGE

Green shrinkage in the samples decreased as more glass was added to the mixture. The control samples containing 0% measured an average green shrinkage of 3,59%, while the samples containing glass S1 measured an average of 3,56% and S2 measuring an average of 3,34% out of 36 samples from each batch. This is consistent with literature where it stated that clay containing waste glass (cullet) had a lowered drying shrinkage (Abdeen & Shihada, 2017). Secondly, Frederico, *et al* (2005) confirmed that finer glass material (between 132 µm and 150 µm) at 4% admixture caused shrinkage to decrease.

5.4.2 MOISTURE CONTENT

The average moisture content measured from each batch (36 samples) also decreased as the percentage of glass increased with the control samples called C measured 23,45%, S1 measured 22,82% and the moisture content of S2 measured 22,77%. Hameed (2018) confirms this phenomenon as this can be “due to the reduction in moisture content and increase in the glassy phase of brick at higher burning temperature”.

5.4.3 WARPAGE

After drying the samples, the warpage test was carried out on 36 samples from each batch. No signs of warpage were identified, nor was dog-earring or visible cracks identified on the samples tested. This concluded that drying of the samples was successful and prompted that the samples were ready to be fired in an industrial tunnel kiln.

5.4.4 FIRED SHRINKAGE

Fired shrinkage increased as the percentage of glass added to the samples increased. This was expected as the glass inside the clay bodies melted inside the samples, filling the pores where the organic matter or combustible material would have burned off during firing. The average fired shrinkage of the control samples was measured at 4,48%, with S1 measuring 4,48% and S2 measuring 4,59%. Even though the increase in shrinkage was minimal, the clay brick manufacturer can compensate for the increased shrinkage by adding more clay material to counteract the difference lost during firing. In ceramic materials, linear shrinkage is directly proportionate to the degree of sintering (Peña *et al.*, 2016).

5.4.5 WATER ABSORPTION

The water absorption of the fired samples also showed a decrease in the samples containing glass versus the control. The average water absorption of the 36 control samples measured 5,05% water absorption after 24-hour soaking, S1 samples containing 2% glass were measured at 3,30% and samples containing 3% glass's water absorption were measured to be 3,11%. This is a positive result as bricks with less water absorption is less prone to water penetration and damage, therefore becoming a more durable product. The general rule is that water absorption in clay bricks should be between 8% and 20% (du Toit & van Vuuren, 2016), to allow the bricks to absorb moisture in the mortar and create a stronger bond in the building process. As stated by Abdeen & Shihada (2017): "to increase density and decrease water absorption of clay bricks, the firing temperature must be raised". The result in this test, being less than 5% indicates that the samples became vitrified during firing. The recommendation required for the bricks in question to fall in the 8-20% range for water absorption, will be to lower the firing temperature, this will also result in a significant energy saving for the manufacturer.

5.4.5 BREAKING STRENGTH (MOR)

The results of the average breaking strength tests showed impressive results as an increase in strength was measured to increase with more glass in the clay. The average breaking strength measured in the control samples were recorded at 9,78 MPa, while S1, containing 2% measured a slight increase in measuring 9,85 MPa, however, samples with 3% glass were measured to be 11,13 MPa. This information is crucial for brickmakers who struggle with maintaining strength in their bricks.

5.4.5 COMPRESSIVE STRENGTH

Compressive strength is a mechanical property measured to qualify brick performance (Peña *et al.*, 2016). Compressive strength tests carried out on 36 samples from each batch showed extraordinary results as the average MPa in the control batch were measured to be 35,38 MPa, the strength increased in samples containing 2% as the MPa was measured to be 36,89 MPa, however, the samples containing 3% showed impressive gains in strength as the average strength for samples containing 3% glass measured 45,59 MPa. According to Abuh *et al.* (2019), the higher the cold crushing strength (compressive strength), the higher the resistance to abrasion and vice versa.

5.4.6 DO THE SAMPLES CONFORM TO SANS 227 REQUIREMENTS?

The samples were tested as FBS bricks as they were made from the clay, the manufacturer uses to make FBS bricks, thus test results were measures against FBS requirements. Based on the tests conducted, the samples passed the visual inspection according to the shape, appearance, texture and colour requirements of the SANS 227 standard as no visual cracks or deviations were observed, the sample showed minimal signs of warpage (less than 5 mm). The nominal compressive strength for FBS bricks should be minimal 12 MPa, the control samples measured 35,48 MPa, which would pass the minimum requirements, however, samples containing waste glass showed a significant increase in compressive strength, measuring 36,89 MPa for samples S1 and S2 measuring nominal strength of 45,59 MPa. These results confirm that the samples tested do pass the requirements set out by the SANS 227 standard for burnt clay masonry units.

5.5 CONCLUSION ON COMPARING TEST RESULTS TO OTHER RESEARCH

5.5.1 WORKABILITY

The addition of glass powder does not influence the workability of the raw clay material, all of the studies that were compared proved that even up to 6% of glass addition to the clay material, keeps the workability of the clay constant and workable, it will not make the clay material easier to work with but it is safe to assume that it does not create problems in workability. Increasing the percentage of glass may increase abrasiveness of the raw material on the extruding equipment and dies but no remarkable difference has been measured with lower quantities (up to 3%).

5.5.2 GREEN SHRINKAGE

The graphs from all of the studies show that there is a reduction in green shrinkage as more glass is added to the mixture, this can be justified by the fact that glass is an inert material and will not shrink within the unfired clay body, thus reducing the total percentage of green shrinkage in the unfired ("green") bricks.

5.5.3 WATER ABSORPTION

After the firing process was completed on all of the studies, a persistent decrease in water absorption was observed across all samples compared. This can be proved by understanding that glass particles have a lower melting point than clay, meaning that the glass particles melt into the pores of the clay material and seals the material on the inside, minimising the number of pores in the fired brick and stopping the water from penetrating the brick. In all reported test results, water absorption was found to decrease as glass content is increased, more so with increased firing temperatures (Abdeen & Shihada, 2017). This reduction in water absorption results in bricks becoming more durable and more water-resistant in harsh weather conditions.

5.5.4 FIRED SHRINKAGE

Interestingly, the samples analysed for this study and the information retrieved on the Gau2 test results show a low-moderate increase in fired shrinkage. Contrastingly, all other results indicate that there is a decrease in fired shrinkage depending on the quantity of glass added to the mixture. This can be attributed to the type of clay found in the region as both the batches indicating an increase in the fired shrinkage were collected in the same region of South Africa, therefore a similar chemical or mineralogical composition may have an element or organic material present which burns away during the firing process. The clays from other parts of the country and in a different part of the world show that there is a decrease in the fired shrinkage of the fired bricks.

5.5.5 BREAKING STRENGTH (MOR) AND COMPRESSIVE STRENGTH (CCS)

Fascinatingly, all of the data indicate that there was a substantial increase in the breaking strengths and compressive strengths of all samples containing glass. This result proves that glass additions improve the durability and strength of clay bricks significantly. This again proves that products of better quality can be made by adding waste glass to the raw clay material.

5.6 EVALUATION OF IMPACTS

The following impacts were evaluated to determine the effects glass admixtures in the manufacturing of clay bricks had on the environment, the economy, financial effects and the effects glass admixtures had on the final products which were manufactured for the purpose of this project.

5.6.1 ENVIRONMENTAL

The proposed output of material per month at optimal capacity is 660 tonnes of material per month. This number is calculated on the basis of a single, 8-hour shift per day at 3.75 tonnes per hour in a 22-workday cycle per month. This number can be increased if double-shifts and more workers are employed in the process. Increasing the output per month will have an alarming impact on the processing cost of the material per month. Customers must, however, justify the higher output before it should be considered. Glass is not a biodegradable material; therefore, it creates a problem for solid waste disposal. Disposal into landfills does not provide an environmentally friendly solution (Abdeen & Shihada, 2017). Even though the estimated waste in landfills exceed 1 million tonnes per year, improving the footprint of a processing plant by acquiring more customers will increase the processed material over time and reduce the amount of waste glass in South Africa.

5.6.2 ECONOMICAL

On the proposed business plan, working on a single-shift workday by working 22 days per month, the estimated nett profit of the processing plant can amount to R 1 655 774. 16 per year. If the plant can sell all of its processed material (660 tonnes) in a month at R 400.00 per tonne, the taxable profit according to the company tax legislation in South Africa is 28%, which calculates to R 463 616,76 which can be contributed to the economy of South Africa per year. Peña *et al.* (2016) suggest that the introduction of waste glass into the batch is promising for decreasing energy consumption and fuel saving.

5.6.3 FINANCIAL

The financial impact can be measured by the initial capital investment required to set up the processing plant, either by constructing the processing plant or by renting the facility to house the plant and equipment. The financial impact will be for the entrepreneur who wishes to use the business plan in this study to generate the capital required to purchase and install the equipment in the plant. It was estimated that the initial cost of the plant amounts to approximately R 2,2 million with monthly expenditures estimated to be R 84 147,22. The return on investment in optimal production is calculated to be less than 2 years. This ROI justifies the establishment of the plant if the entrepreneur can secure a client base which will utilise all of the processed material per month.

5.6.4 FINAL PRODUCT

Testing of the final products fired in an industrial kiln showed promising results as all impacts from adding waste glass to clay bodies showed positive results. The samples showed an increase in breaking and compressive strengths in all samples measured, the samples tested for this study as well as the results from the other studies conducted on samples containing glass in various percentages. Furthermore, cullet (waste glass) could act as a flux inducing the vitrification of bricks delivering higher mechanical resistance, higher density and less water absorption to the final material (Peña *et al.*, 2016).

5.7 RECOMMENDATIONS

- It is recommended that glass additions of up to 5% should be considered by clay brick manufacturers as on average fluxing materials range between 1-5% is added to bricks to reduce the firing temperatures and improve final products. Other research suggests adding up to 30% of glass, however then the addition will not be compared to other fluxing materials, then it will be considered as an additive. Abdeen & Shihada (2017) recommends that the compressive strength of the fired clay bricks increased with increasing amount of waste glass content, up to 30% by weight and firing temperature up to 1100 °C. It is recommended that similar mechanical properties obtained at very high temperatures (> 1200 °C) can be obtained at 1100 °C with the addition of waste glass at varying proportions (Abuh *et al.*, 2019).
- It is recommended that glass particles smaller than 1 mm be used in the manufacturing of clay bricks as smaller particles melt easier and can fill pores that are smaller than 1 mm, however, the rule of thumb is that glass particles should be as small as possible, to limit potential bubbling and to mix better with the clay material. Finer glass particles are recommended, this concurs with a study in which the fineness of the glass particles was evaluated, it was concluded that the finer the particle sizes, the higher was the compressive strength measured (Abdeen & Shihada, 2017).
- Glass can be used as an aggregate in other construction materials such as cement and concrete, yet it will only act as an aggregate and will not provide additional strength. Glass powder does, however, improve pore structure and enhance its mechanical properties at a later age due to pozzolanic activity (Sičáková & Špak, 2019).
- Glass powder can also be supplied to other industries to thicken paints and enamels, as blasting media and in glazes for other ceramic applications such as sanitaryware manufacturing.
- It is advised that extensive tests be conducted with the raw materials from specific clay brick manufacturers who are interested in the material to determine

the optimal firing temperatures as glass acts as a flux, determining the optimal particle size to work in synergy with the clay and to determine the perfect percentage of addition to be used in the manufacturing process.

- Transportation of the processed material should be outsourced for the first period of production to place more focus on the management of the plant and to improve operational functions within the plant.

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ANNEXURE A 1: RAW DATA FROM TESTING

Table A 1: Raw data from test (Control sample)

C - Control											
	Wet Weight	Dry Weight	Moisture Content (%)	Wet Length	Dry Length	Green Shrinkage	Fired Length	Fired Shrinkage	Total Shrinkage	24 Hr Soak Weight	24 Hr Water Absorption (%)
TL 1	332,1	267,9	23,96	100	96,46	3,54	92,3	4,31	7,70	281	4,89
TL 2	331,4	267,3	23,98	100	96,34	3,66	91,98	4,53	8,02	279,9	4,71
TL 3	329,5	265,8	23,97	100	96,4	3,60	92,33	4,22	7,67	277,20	4,29
TL 4	333,7	269	24,05	100	96,88	3,12	92,91	4,10	7,09	281,6	4,68
AVG			23,99			3,48	92,38	4,29	7,62	279,93	4,64
TM 1	328,6	266,7	23,21	100	96,24	3,76	92,06	4,34	7,94	282,2	5,81
TM 2	336,3	273	23,19	100	96,69	3,31	93,16	3,65	6,84	288,4	5,64
TM 3	333,1	271,1	22,87	100	96,33	3,67	92,57	3,90	7,43	284,7	5,02
TM 4	329	267,5	22,99	100	96,5	3,50	92,08	4,58	7,92	283,10	5,83
AVG			23,06			3,56	92,47	4,12	7,53	284,60	5,58
TR 1	333	270,8	22,97	100	96	4,00	91,56	4,63	8,44	277,40	2,44
TR 2	328,6	267,3	22,93	100	96,1	3,90	91,58	4,70	8,42	273,90	2,47
TR 3	336,3	272,9	23,23	100	96,17	3,83	91,12	5,25	8,88	279,1	2,27
TR 4	326,2	265,4	22,91	100	95,97	4,03	91,83	4,31	8,17	273,6	3,09
AVG			23,01			3,94	91,52	4,72	8,48	276,00	2,57
ML 1	330,2	266,2	24,04	100	96,43	3,57	92,36	4,22	7,64	274,9	3,27
ML 2	334,7	270	23,96	100	96,455	3,55	90,67	6,00	9,33	278,30	3,07
ML 3	329,2	265,6	23,95	100	96,24	3,76	92,06	4,34	7,94	274,5	3,35
ML 4	328,2	265,1	23,80	100	96,18	3,82	91,88	4,47	8,12	274,5	3,55
AVG			23,94			3,67	91,74	4,76	8,26	275,55	3,31
MM 1	331,8	268,2	23,71	100	96,36	3,64	92,14	4,38	7,86	283,7	5,78
MM 2	324,3	263,7	22,98	100	96,58	3,42	92,52	4,20	7,48	276,4	4,82
MM 3	333	270,3	23,20	100	96,93	3,07	92,61	4,46	7,39	283,6	4,92
MM 4	333,7	270,9	23,18	100	96,75	3,25	92,43	4,47	7,57	283,5	4,65
AVG			23,27			3,35	92,43	4,38	7,58	281,80	5,04
MR 1	327,1	265,9	23,02	100	96,2	3,80	91,63	4,75	8,37	272,20	2,37
MR 2	330,1	268,2	23,08	100	96,31	3,69	91,11	5,40	8,89	275,4	2,68
MR 3	329,5	269,6	22,22	100	96,07	3,93	91,3	4,97	8,70	275,4	2,15
MR 4	329,9	268,8	22,73	100	96,36	3,64	91,72	4,82	8,28	275,4	2,46
AVG			22,76			3,77	91,44	4,98	8,56	274,60	2,42
BL 1	326,7	263,9	23,80	100	96,54	3,46	91,36	5,37	8,64	270,1	2,35
BL 2	330,2	266,3	24,00	100	96,55	3,45	91,14	5,60	8,86	272,3	2,25
BL 3	330,2	266,3	24,00	100	96,46	3,54	91,67	4,97	8,33	273,9	2,85
BL 4	332,4	268,2	23,94	100	96,36	3,64	91,69	4,85	8,31	276,4	3,06
AVG			23,93			3,52	91,47	5,20	8,54	273,18	2,63
BM 1	331,4	267,4	23,93	100	96,96	3,04	92,34	4,76	7,66	278,9	4,30
BM 2	329,5	265,7	24,01	100	97,04	2,96	92,41	4,77	7,59	277,3	4,37
BM 3	332,7	268,3	24,00	100	96,92	3,08	92,77	4,28	7,23	281,8	5,03
BM 4	333,6	269,1	23,97	100	96,91	3,09	92,17	4,89	7,83	281,8	4,72
AVG			23,98			3,04	92,42	4,68	7,58	279,95	4,60
BR 1	332,2	269,9	23,08	100	96,41	3,59	91,9	4,68	8,10	278,4	3,15
BR 2	325,2	264,1	23,14	100	95,85	4,15	91	5,06	9,00	269,9	2,20
BR 3	331	268,8	23,14	100	95,9	4,10	91,7	4,38	8,30	274,90	2,27
BR 4	331	268,9	23,09	100	96,02	3,98	90,92	5,31	9,08	276	2,64
AVG			23,11			3,96	91,38	4,86	8,62	274,80	2,56

ANNEXURE A 2: RAW DATA FROM SAMPLE S1

Table A 2: Raw data from test (Sample S1)

Sample: S1											
	Wet Weight	Dry Weight	Moisture Content (%)	Wet Length	Dry Length	Green Shrinkage	Fired Length	Fired Shrinkage	Total Shrinkage	24 Hr Soak Weight	24 Hr Water Absorption (%)
TL 1	337,9	275,6	22,61	100	96,38	3,62	92,22	4,32	7,78	293,1	6,35
TL 2	325,6	264,4	23,15	100	96,13	3,87	93,13	3,12	6,87	282,5	6,85
TL 3	332,5	269,8	23,24	100	96,48	3,52	92,56	4,06	7,44	288,10	6,78
TL 4	332,2	269,6	23,22	100	96,49	3,51	93,03	3,59	6,97	287,3	6,57
AVG			23,05			3,63	92,74	3,77	7,27	287,75	6,64
TM 1	329,8	267,8	23,15	100	96,12	3,88	92,55	3,71	7,45	283,2	5,75
TM 2	331,5	269,2	23,14	100	96,34	3,66	92,4	4,09	7,60	284,3	5,61
TM 3	326,1	264,8	23,15	100	96,5	3,5	93,01	3,62	6,99	278,8	5,29
TM 4	329,5	268,6	22,67	100	96,67	3,33	92,33	4,49	7,67	279,20	3,95
AVG			23,03			3,59	92,57	3,98	7,43	281,38	5,15
TR 1	327,3	266,5	22,81	100	96,55	3,45	93,15	3,52	6,85	283,90	6,53
TR 2	331,2	269,7	22,80	100	96,52	3,48	92,46	4,21	7,54	287,10	6,45
TR 3	331,9	270,9	22,52	100	96,03	3,97	92,48	3,70	7,52	284	4,84
TR 4	331,4	270,1	22,70	100	96,51	3,49	92,26	4,40	7,74	284,1	5,18
AVG			22,71			3,60	92,59	3,96	7,41	284,78	5,75
ML 1	333,2	272,2	22,41	100	96,06	3,94	92,45	3,76	7,55	288,4	5,95
ML 2	336,3	274,1	22,69	100	96,41	3,59	92,55	4,00	7,45	290,00	5,80
ML 3	331,7	270,5	22,62	100	96,3	3,7	92,34	4,11	7,66	284,8	5,29
ML 4	331,8	270,4	22,71	100	96,67	3,33	92,25	4,57	7,75	284,3	5,14
AVG			22,61			3,64	92,40	4,11	7,60	286,88	5,54
MM 1	331,3	269,5	22,93	100	96,82	3,18	92,17	4,80	7,83	282,3	4,75
MM 2	331,4	268,7	23,33	100	96,63	3,37	91,98	4,81	8,02	281,9	4,91
MM 3	327,2	265,3	23,33	100	96,83	3,17	92,66	4,31	7,34	279	5,16
MM 4	334,6	272,2	22,92	100	96,53	3,47	92,32	4,36	7,68	285,1	4,74
AVG			23,13			3,30	92,28	4,57	7,72	282,08	4,89
MR 1	330,4	268,4	23,10	100	96,29	3,71	93,08	3,33	6,92	289,40	7,82
MR 2	332,1	270,9	22,59	100	96,52	3,48	93,58	3,05	6,42	291,3	7,53
MR 3	331,7	271,6	22,13	100	96,13	3,87	94,05	2,16	5,95	291,1	7,18
MR 4	331,8	270,58	22,63	100	96,32	3,68	93,58	2,84	6,42	290,60	7,40
AVG			22,61			3,69	93,57	2,85	6,43	290,60	7,51
BL 1	331,9	271,7	22,16	100	96,83	3,17	92,82	4,14	7,18	282,7	4,05
BL 2	334,9	273,8	22,32	100	96,58	3,42	93,93	2,74	6,07	288,6	5,41
BL 3	332,3	271,3	22,48	100	96,5	3,5	92,31	4,34	7,69	284,8	4,98
BL 4	340,2	277,6	22,55	100	96,6	3,4	92,52	4,22	7,48	292,1	5,22
AVG			22,38			3,37	92,90	3,86	7,11	287,05	4,91
BM 1	332,8	270,9	22,85	100	97,23	2,77	91,81	5,57	8,19	280,8	3,65
BM 2	336,1	273,1	23,07	100	97,11	2,89	92,21	5,05	7,79	284,1	4,03
BM 3	332,5	270,1	23,10	100	97,13	2,87	91,97	5,31	8,03	281,4	4,18
BM 4	331	268,5	23,28	100	96,88	3,12	92	5,04	8,00	280	4,28
AVG			23,07			2,91	92,00	5,24	8,00	281,58	4,04
BR 1	331,5	269,5	23,01	100	96,83	3,17	94,66	2,24	5,34	294,4	9,24
BR 2	333	270,7	23,01	100	96,89	3,11	93,47	3,53	6,53	290,7	7,39
BR 3	328,6	267,2	22,98	100	96,3	3,70	92,12	4,34	7,88	286,80	7,34
BR 4	324,4	265,7	22,09	100	96,37	3,63	93,38	3,10	6,62	286,3	7,75
AVG			22,77			3,40	93,41	3,30	6,59	289,55	7,93

ANNEXURE A 3: RAW DATA FROM SAMPLE S2

Table A 3: Raw data from test (Sample S2)

Sample S2											
	Wet Weight	Dry Weight	Moisture Content (%)	Wet Length	Dry Length	Green Shrinkage	Fired Length	Fired Shrinkage	Total Shrinkage	24 Hr Soak Weight	24 Hr Water Absorption (%)
TL 1	335,4	274,4	22,23	100	96,89	3,11	92,15	4,89	7,85	281,4	2,55
TL 2	332,9	272,7	22,08	100	96,93	3,07	91,91	5,18	8,09	278,8	2,24
TL 3	332,8	272,1	22,31	100	97,07	2,93	92,08	5,14	7,92	279,20	2,61
TL 4	329,2	267,7	22,97	100	96,59	3,41	92,37	4,37	7,63	277,8	3,77
			22,40			3,13	92,13	4,90	7,87	279,30	2,79
TM 1	333,2	269,9	23,45	100	96,76	3,24	92,86	4,03	7,14	282,2	4,56
TM 2	325,1	263,2	23,52	100	96,7	3,3	92,82	4,01	7,18	272,6	3,57
TM 3	332,8	269,3	23,58	100	96,47	3,53	92,92	3,68	7,08	281	4,34
TM 4	336,6	271,8	23,84	100	97,27	2,73	92,2	5,21	7,80	279,60	2,87
			23,60			3,20	92,70	4,23	7,30	278,85	3,84
TR 1	327,2	265,6	23,19	100	96,47	3,53	92,13	4,50	7,87	274,40	3,31
TR 2	329,4	267,1	23,32	100	96,47	3,53	92,58	4,03	7,42	276,20	3,41
TR 3	330,5	267,8	23,41	100	96,68	3,32	92,33	4,50	7,67	279,9	4,52
TR 4	329	266,6	23,41	100	96,58	3,42	92,25	4,48	7,75	277,4	4,05
			23,33			3,45	92,32	4,38	7,68	276,98	3,82
ML 1	331,1	269,1	23,04	100	96,81	3,19	92,27	4,69	7,73	276,1	2,60
ML 2	330	268,3	23,00	100	96,67	3,33	91,87	4,97	8,13	275,10	2,53
ML 3	332,9	271,6	22,57	100	96,63	3,37	92,01	4,78	7,99	280,2	3,17
ML 4	334,4	272,8	22,58	100	96,33	3,67	91,69	4,82	8,31	281,4	3,15
			22,80			3,39	91,96	4,81	8,04	278,20	2,86
MM 1	336	273	23,08	100	96,98	3,02	92,96	4,15	7,04	284,1	4,07
MM 2	328,1	266,7	23,02	100	96,35	3,65	92,85	3,63	7,15	277	3,86
MM 3	327,9	265,7	23,41	100	96,37	3,63	92,81	3,69	7,19	275,3	3,61
MM 4	328	265,8	23,40	100	96,85	3,15	92,6	4,39	7,40	275,1	3,50
			23,23			3,36	92,81	3,97	7,20	277,88	3,76
MR 1	331,2	276,6	19,74	100	96,13	3,87	91,98	4,32	8,02	279,10	0,90
MR 2	339,6	267,5	26,95	100	96,72	3,28	91,8	5,09	8,20	285,6	6,77
MR 3	328,5	271,9	20,82	100	96,66	3,34	91,89	4,93	8,11	276,7	1,77
MR 4	334,3	264,2	26,53	100	96,66	3,34	92,27	4,54	7,73	281,4	6,51
			23,51			3,46	91,99	4,72	8,02	280,70	3,99
BL 1	333,8	271,7	22,86	100	96,93	3,07	92,28	4,80	7,72	279,7	2,94
BL 2	328,2	267	22,92	100	96,71	3,29	92,02	4,85	7,98	274,3	2,73
BL 3	336,3	273,3	23,05	100	96,92	3,08	91,85	5,23	8,15	280,1	2,49
BL 4	335,2	272,5	23,01	100	96,52	3,48	91,88	4,81	8,12	278,2	2,09
			22,96			3,23	92,01	4,92	7,99	278,08	2,56
BM 1	338	275,4	22,73	100	96,37	3,63	91,52	5,03	8,48	279,9	1,63
BM 2	331	270,9	22,19	100	96,42	3,58	91,53	5,07	8,47	274,8	1,44
BM 3	333,7	273,1	22,19	100	96,53	3,47	91,69	5,01	8,31	280,4	2,67
BM 4	333,1	271,2	22,82	100	97,2	2,8	92,13	5,22	7,87	279,3	2,99
			22,48			3,37	91,72	5,08	8,28	278,60	2,18
BR 1	329,1	269,9	21,93	100	96,76	3,24	91,81	5,12	8,19	272,3	0,89
BR 2	333,2	290,6	14,66	100	96,47	3,53	91,83	4,81	8,17	274,3	-5,61
BR 3	332,3	269,9	23,12	100	96,4	3,60	91,88	4,69	8,12	275,40	2,04
BR 4	329,7	268,2	22,93	100	96,39	3,61	91,4	5,18	8,60	277,8	3,58
			22,66			3,48	91,73	4,95	8,27	275,17	2,17

ANNEXURE A 4: COMPRESSIVE STRENGTH TEST RESULTS: C

Table A 4: Compressive strength test results (sample C)

Sample Name: C

3*LOAD*SPAN/(2*BREADTH*HEIGHT*HEIGHT)

	Breadth	Depth	Area	Load	CCS
TL	mm	mm	mm^2	N	Mpa
1	37,38	25,36	947,96	42272	44,59
2	37,71	25,05	944,64	34490	36,51
3	37,71	25,36	956,33	24899	26,04
4	37,82	25,26	955,33	25760	26,96
AVE	37,66	25,26	951,06	28383	29,84
STDP	0,16	0,13	4,92	7088,58	7,59
Co o V	0,43819	0,5011	0,5174902	24,9747514	25,4438

	Breadth	Depth	Area	Load	CCS
TM	mm	mm	mm^2	N	Mpa
1	38,10	26,14	995,93	30628	30,75
2	38,14	26,09	995,07	27969	28,11
3	37,88	25,60	969,73	50204	51,77
4	38,08	25,55	972,94	26808	27,55
AVE	38,05	25,85	983,42	28468	28,80
STDP	0,10	0,27	12,14	9513,14	10,02
Co o V	0,26412	1,049158	1,23455	33,416581	34,779

	Breadth	Depth	Area	Load	CCS
TR	mm	mm	mm^2	N	Mpa
1	37,45	25,59	958,35	43714	45,61
2	37,65	25,47	958,95	59552	62,10
3	37,55	25,75	966,91	34765	35,95
4	37,57	25,10	943,01	46790	49,62
AVE	37,56	25,48	956,80	41756	43,73
STDP	0,07	0,24	8,65	8882,05	9,38
Co o V	0,18969	0,94011	0,9043717	21,2711467	21,4474

	Breadth	Depth	Area	Load	CCS
ML	mm	mm	mm^2	N	Mpa
1	37,66	25,01	941,88	44637	47,39
2	36,58	25,05	916,33	36313	39,63
3	38,01	24,77	941,51	43963	46,69
4	37,50	24,97	936,38	41667	44,50
AVE	37,44	24,95	934,02	40648	43,61
STDP	0,53	0,11	10,44	3269,40	3,04
Co o V	1,4112	0,431677	1,11818	8,0432652	6,9645

	Breadth	Depth	Area	Load	CCS
MM	mm	mm	mm^2	N	Mpa
1	37,90	25,52	967,21	27021	27,94
2	37,75	25,51	963,00	33873	35,17
3	37,90	25,78	977,06	23489	24,04
4	37,77	25,40	959,36	29423	30,67
AVE	37,83	25,55	966,66	26644	27,55
STDP	0,07	0,14	6,62	3775,22	4,06
Co o V	0,18598	0,54605	0,6846402	14,1689498	14,7232

	Breadth	Depth	Area	Load	CCS
MR	mm	mm	mm^2	N	Mpa
1	37,44	24,55	919,15	43726	47,57
2	37,48	25,09	940,37	35420	37,67
3	37,19	25,11	933,84	59489	63,70
4	37,40	25,40	949,96	19950	21,00
AVE	37,38	25,04	935,83	33032	35,41
STDP	0,11	0,31	11,21	14284,45	15,50
Co o V	0,29934	1,226289	1,19757	43,244291	43,767

	Breadth	Depth	Area	Load	CCS
BL	mm	mm	mm^2	N	Mpa
1	37,40	24,90	931,26	29850	32,05
2	37,35	25,10	937,49	41324	44,08
3	37,30	25,05	934,37	59976	64,19
4	37,40	25,01	935,37	48182	51,51
AVE	37,36	25,02	934,62	39785	42,55
STDP	0,04	0,07	2,24	10923,94	11,66
Co o V	0,11096	0,29444	0,2400331	27,4571967	27,4106

	Breadth	Depth	Area	Load	CCS
BM	mm	mm	mm^2	N	Mpa
1	37,68	25,11	946,14	27526	29,09
2	37,62	25,21	948,40	35938	37,89
3	37,87	25,23	955,46	46210	48,36
4	37,85	25,20	953,82	24319	25,50
AVE	37,76	25,19	950,96	29261	30,83
STDP	0,11	0,05	3,81	8477,43	8,83
Co o V	0,28435	0,182749	0,40101	28,971776	28,649

	Breadth	Depth	Area	Load	CCS
BR	mm	mm	mm^2	N	Mpa
1	37,72	25,02	943,75	40306	42,71
2	37,39	24,77	926,15	31913	34,46
3	37,38	25,16	940,48	29186	31,03
4	37,46	25,02	937,25	50141	53,50
AVE	37,49	24,99	936,91	33802	36,07
STDP	0,14	0,14	6,62	8176,31	8,66
Co o V	0,36739	0,56257	0,7069518	24,1890723	24,0094

ANNEXURE A 5: COMPRESSIVE STRENGTH TEST RESULTS: S1

Table A 5: Compressive strength test results (sample S1)

Sample Name: S1

3*LOAD*SPAN/(2*BREADTH*HEIGHT*HEIGHT)

	Breadth	Depth	Area	Load	CCS
TL	mm	mm	mm^2	N	Mpa
1	38,34	25,67	984,19	33105	33,64
2	38,25	25,76	985,32	22565	22,90
3	38,33	26,03	997,73	20256	20,30
4	38,12	26,12	995,69	49068	49,28
AVE	38,26	25,90	990,73	34913	31,53
STDP	0,09	0,19	6,04	11371,23	11,40
Co o V	0,23009	0,71651	0,60920224	32,570497	36,1626

	Breadth	Depth	Area	Load	CCS
TM	mm	mm	mm^2	N	Mpa
1	38,05	25,74	979,41	40581	41,43
2	37,79	25,79	974,60	34029	34,92
3	37,95	25,60	971,52	39445	40,60
4	38,17	25,51	973,72	40244	41,33
AVE	37,99	25,66	974,81	40090	41,12
STDP	0,14	0,11	2,88	2656,72	2,71
Co o V	0,36663	0,433089	0,2955155	6,62689	6,58159

	Breadth	Depth	Area	Load	CCS
TR	mm	mm	mm^2	N	Mpa
1	38,75	26,02	1008,28	29236	29,00
2	38,34	26,23	1005,66	22453	22,33
3	38,28	25,62	980,73	29330	29,91
4	37,93	25,04	949,77	28712	30,23
AVE	38,33	25,73	986,11	27433	27,86
STDP	0,29	0,45	23,58	2884,69	3,23
Co o V	0,75949	1,7623	2,39071143	10,515483	11,5893

	Breadth	Depth	Area	Load	CCS
ML	mm	mm	mm^2	N	Mpa
1	38,37	26,09	1001,07	37380	37,34
2	38,39	25,76	988,93	26590	26,89
3	38,10	25,62	976,12	50297	51,53
4	37,98	26,49	1006,09	40026	39,78
AVE	38,21	25,99	993,05	38573	38,88
STDP	0,18	0,34	11,60	8434,73	8,76
Co o V	0,45893	1,290249	1,1678343	21,8668	22,5285

	Breadth	Depth	Area	Load	CCS
MM	mm	mm	mm^2	N	Mpa
1	38,00	25,84	981,92	24556	25,01
2	38,10	25,40	967,74	37105	38,34
3	38,28	25,55	978,05	32650	33,38
4	37,74	25,54	963,88	31177	32,35
AVE	38,03	25,58	972,90	33644	34,69
STDP	0,20	0,16	7,35	4499,90	4,77
Co o V	0,51326	0,62566	0,75517266	13,375049	13,7379

	Breadth	Depth	Area	Load	CCS
MR	mm	mm	mm^2	N	Mpa
1	38,72	26,30	1018,34	21735	21,34
2	38,46	25,65	986,50	17960	18,21
3	38,81	26,26	1019,15	30060	29,50
4			0,00		
AVE	38,66	26,07	756,00	23252	23,01
STDP	0,15	0,30	436,67	5054,88	4,76
Co o V	0,38382	1,140903	57,761291	21,7399	20,6734

	Breadth	Depth	Area	Load	CCS
BL	mm	mm	mm^2	N	Mpa
1	38,07	25,86	984,49	45929	46,65
2	38,84	25,99	1009,45	16818	16,66
3	37,82	25,77	974,62	39757	40,79
4	38,23	26,06	996,27	40088	40,24
AVE	38,24	25,92	991,21	41925	42,56
STDP	0,38	0,11	13,03	11145,24	11,49
Co o V	0,98317	0,43392	1,31418017	26,583964	27,0045

	Breadth	Depth	Area	Load	CCS
BM	mm	mm	mm^2	N	Mpa
1	37,93	25,59	970,63	33604	34,62
2	37,87	25,20	954,32	41236	43,21
3	37,82	25,49	964,03	37486	38,88
4	38,21	25,36	969,01	42391	43,75
AVE	37,96	25,41	964,50	38679	40,12
STDP	0,15	0,15	6,36	3445,87	3,69
Co o V	0,39753	0,575035	0,6590706	8,90883	9,19866

	Breadth	Depth	Area	Load	CCS
BR	mm	mm	mm^2	N	Mpa
1	38,65	26,19	1012,24	14565	14,39
2	38,38	25,86	992,51	25161	25,35
3	38,05	25,75	979,79	34403	35,11
4	38,44	25,60	984,06	27089	27,53
AVE	38,38	25,85	992,15	28884	29,33
STDP	0,22	0,22	12,47	7094,44	7,42
Co o V	0,56094	0,83911	1,25695398	24,561567	25,2827

ANNEXURE A 6: COMPRESSIVE STRENGTH TEST RESULTS: S2

Table A 6: Compressive strength test results (sample S2)

Sample Name: S2

	Breadth	Depth	Area	Load	CCS
TL	mm	mm	mm²	N	Mpa
1	37,44	25,81	966,33	28936	29,94
2	37,39	25,67	959,80	39963	41,64
3	37,61	25,29	951,16	44518	46,80
4	37,83	25,59	968,07	37536	38,77
AVE	37,57	25,59	961,34	40672	42,40
STDP	0,17	0,19	6,64	5666,46	6,12
Co o V	0,45811	0,74351	0,69042499	13,9319744	14,42063

	Breadth	Depth	Area	Load	CCS
TM	mm	mm	mm²	N	Mpa
1	37,83	25,29	956,72	36862	38,53
2	37,75	25,22	952,06	50422	52,96
3	37,80	25,24	954,07	39133	41,02
4	37,61	25,15	945,89	34103	36,05
AVE	37,75	25,23	952,18	40130	42,14
STDP	0,08	0,05	3,99	6203,30	6,49
Co o V	0,2235	0,1992	0,4193	15,4580166	15,3989585

	Breadth	Depth	Area	Load	CCS
TR	mm	mm	mm²	N	Mpa
1	37,78	24,95	942,61	65143	69,11
2	37,89	25,05	949,14	36001	37,93
4	37,80	25,32	957,10	35077	36,65
3	37,95	25,36	962,41	22927	23,82
AVE	37,86	25,17	952,82	45407	47,90
STDP	0,07	0,17	7,55	15521,79	16,66
Co o V	0,18158	0,69214	0,79241169	34,1837008	34,78733

	Breadth	Depth	Area	Load	CCS
ML	mm	mm	mm²	N	Mpa
1	37,74	25,45	960,48	55676	57,97
2	37,61	25,65	964,70	38497	39,91
3	37,58	25,48	957,54	28749	30,02
4	37,69	25,35	955,44	35782	37,45
AVE	37,66	25,48	959,54	39676	41,34
STDP	0,06	0,11	3,47	9898,90	10,27
Co o V	0,1685	0,4239	0,3621	24,9493308	24,8385998

	Breadth	Depth	Area	Load	CCS
MM	mm	mm	mm²	N	Mpa
1	37,73	25,43	959,47	25585	26,67
2	37,76	25,49	962,50	37660	39,13
3	37,78	25,46	961,88	49436	51,40
4	37,75	25,51	963,00	63277	65,71
AVE	37,76	25,47	961,71	50124	52,08
STDP	0,02	0,03	1,35	13968,36	14,48
Co o V	0,04775	0,11899	0,14073022	27,8674209	27,79814

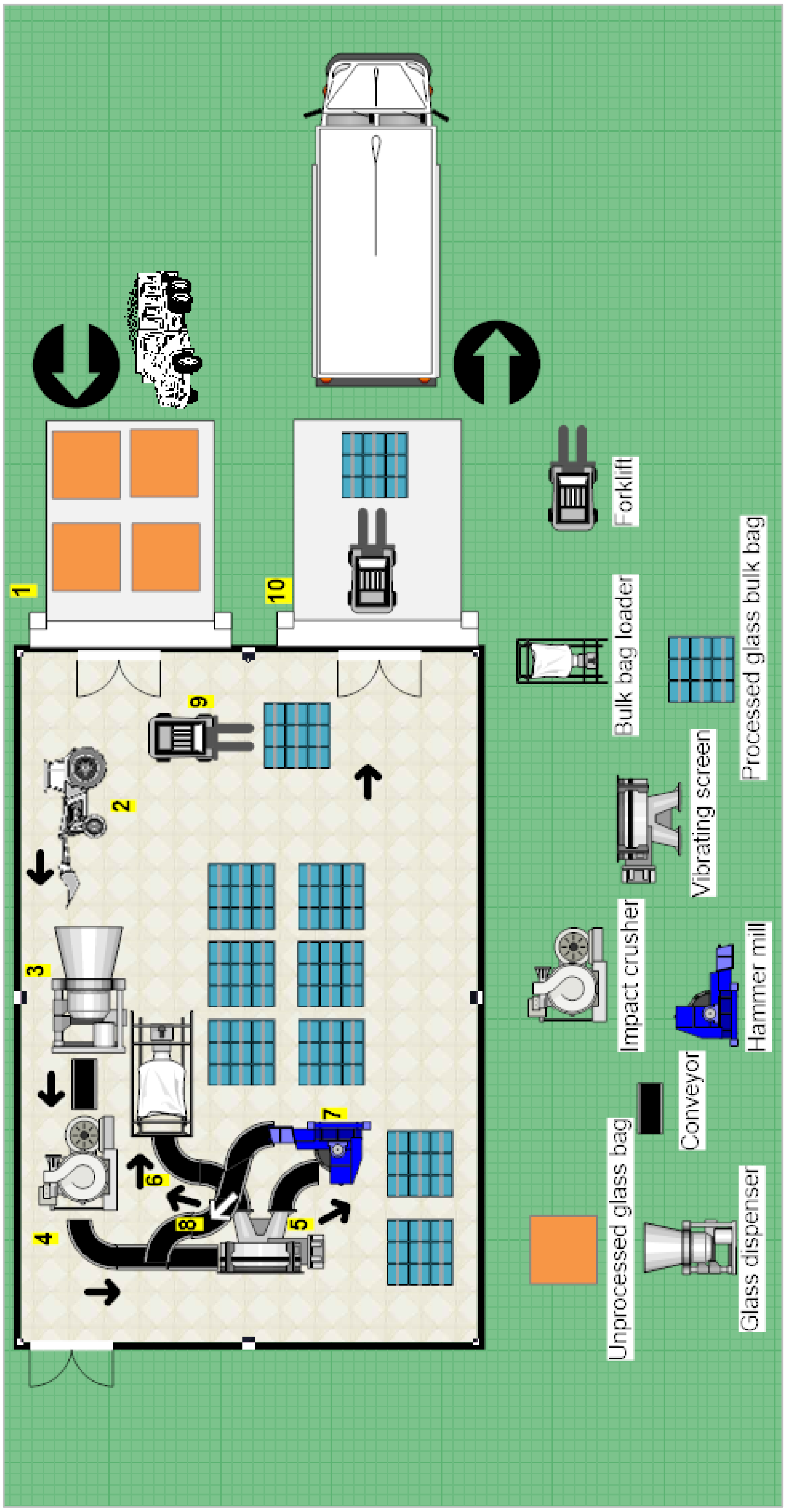
	Breadth	Depth	Area	Load	CCS
MR	mm	mm	mm²	N	Mpa
1	37,80	25,54	965,41	28986	30,02
2	37,76	25,60	966,66	42210	43,67
3	37,78	25,52	964,15	57274	59,40
4	37,82	25,63	969,33	22453	23,16
AVE	37,79	25,57	966,39	42823	44,36
STDP	0,02	0,04	1,92	13340,56	13,87
Co o V	0,0592	0,1735	0,1983	31,1525587	31,2619155

	Breadth	Depth	Area	Load	CCS
BL	mm	mm	mm²	N	Mpa
1	37,61	25,51	959,43	34734	36,20
2	37,85	25,50	965,18	48088	49,82
3	37,68	25,44	958,58	40275	42,02
4	37,68	25,41	957,45	49985	52,21
AVE	37,71	25,47	960,16	46116	48,01
STDP	0,09	0,04	2,98	6126,53	6,35
Co o V	0,23461	0,1631	0,31040668	13,2850505	13,23286

	Breadth	Depth	Area	Load	CCS
BM	mm	mm	mm²	N	Mpa
1	37,31	25,65	957,00	23083	24,12
2	37,41	25,39	949,84	41904	44,12
3	37,57	25,78	968,55	30191	31,17
4	37,63	25,31	952,42	23021	24,17
AVE	37,48	25,53	956,95	31726	33,14
STDP	0,13	0,19	7,17	7705,23	8,15
Co o V	0,3385	0,7454	0,7495	24,2867918	24,6100696

	Breadth	Depth	Area	Load	CCS
BR	mm	mm	mm²	N	Mpa
1	37,37	25,01	934,62	59914	64,10
2	37,75	24,90	939,98	46977	49,98
3	37,75	25,36	957,34	59583	62,24
4	37,69	25,30	953,56	56781	59,55
AVE	37,64	25,14	946,37	55814	58,97
STDP	0,16	0,19	9,37	5245,07	5,44
Co o V	0,41923	0,76628	0,98964061	9,39745056	9,22098

ANNEXURE A 7: PROPOSED LAYOUT OF PROCESSING PLANT



ANNEXURE A 8: STUDIES FROM AROUND THE WORLD

Table A 7: Results from studies conducted around the world

Parameter	Tur: T0	Tur: T2	Tur: T5	Tur: T10	Rus: R5	Rus: R10	Rus: R15	Rus: R20	Pak: 0WG	Pak: 5WG	Pak: 10WG	Pak: 15WG	Pak: 20WG	Pal: A2	Pal: B2	Pal: C2	Pal: D2	Pal: E2
% glass added	**0%**	2,50%	5%	10%	5%	10%	15%	20%	0%	5%	10%	15%	20%	0%	10%	20%	30%	40%
Water added for extrusion	**N/A**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	28,57%	28,57%	27,77%	28,57%	29,17%	8% (Moulded bricks)	8% (Moulded bricks)	8% (Moulded bricks)	8% (Moulded bricks)	8% (Moulded bricks)
Workability	**N/A**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24 Hr Water absorption	**19,45%**	19,06%	18,35%	17,73%	12,23%	11,75%	10,80%	±9,4%*	±17,5%*	±16,5%*	±16,25%*	±16%*	±15,5%*	15,63	13,53%	12,75%	11,44%	10,86%
Green Shrinkage	**3,95%**	3,72%	3,64%	3,53%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Moisture content	**N/A**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Firing Temperature	**850 °C**	850 °C	850 °C	850 °C	980 °C	980 °C	980 °C	980 °C	950 °C	950 °C	950 °C	950 °C	950 °C	1000 °C	1000 °C	1000 °C	1000 °C	1000 °C
Fired Shrinkage	**5,35%**	5,15%	4,65%	4,35%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0,64%	0,84%	1,01%	1,32%	1,67%
Breaking strength (MoR)	**N/A**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	± 4 MPa*	± 4,5 MPa*	± 5,7 MPa*	± 6,7 MPa*	± 7,1 MPa*	N/A	N/A	N/A	N/A	N/A
Crushing strength (MPa)	**16,45 MPa**	18,75 MPa	20,15 MPa	20,62 MPa	±13 MPa*	±17 MPa*	±20 MPa*	±34 MPa*	± 14 MPa*	± 13 MPa*	± 15 MPa*	± 16 MPa*	± 24 MPa*	21,33 MPa	30,67 MPa	32,34 MPa	42,75 MPa	43,17 MPa

(Tur: Turkey (Demir, 2016); Rus: Russia (Leshina & Pivnev, 2002); Pak: Pakistan (Hameed *et al.*, 2018); Pal: Palestine (Abdeen & Shihada, 2017); MPA: Mega-Pascal; N/A: Information not available; *Information is estimated from graph)