AN INVESTIGATION INTO THE STRUCTURAL SUITABILITY OF STANDARD GRADE EXPANDED POLYSTYRENE (EPS) AS AN INNOVATIVE BUILDING MATERIAL

By

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DECLARATION

I, Bonke Mncwango, hereby declare that this dissertation is my own work. Where I have used other people's work, I have referenced it accordingly. This dissertation has not been published in any other University, apart from prior publication in the form of journal articles and conference papers which are listed in Annexure F.

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DEDICATION

This dissertation is dedicated to my late mother, Biziwe Rosemary Mncwango, thank you for the gift of the gospel as well as that of education.

ACKNOWLEDGEMENTS

My biggest thanks go to the almighty God who always trains my hands for war and my fingers for battle. Even at the conclusion of this work I still find myself asking what shall I render unto the Lord for all his benefits towards me.

I would also like to acknowledge all of my siblings and my wife for their continued support and encouragement.

Lastly, I would like to extend my sincere thanks to Prof. Dhiren Allopi who has been an excellent mentor on this journey.

ABSTRACT

Rapid urbanization has brought numerous economic, cultural and political development in South Africa; however, it has also led to some parts of the country turning into slums. The spread of slums is mainly driven by the lack of adequate housing provision by the Government. Although it has been twenty-five years since South Africa had its first democratic elections, millions of citizens still continue to live under squalid conditions as a result of lack of housing. The South African government cites numerous reasons for not being able to eradicate the housing backlog, including insufficient housing budget allocation as well as the worsening global economic climate. It is evident from the current housing backlogs that more building solutions that can reduce cost and construction time are needed. Further, new building materials should be explored in order to alleviate the environmental pressures that conventional building materials cause on the environment.

This research investigates the properties of standard grade Expanded Polystyrene (EPS) as a potential contributor in low-cost housing provision. Currently the construction of EPS dome houses using modified EPS is only occurring outside of South Africa and it requires the possession of intricate moulding equipment. Existing suppliers require a minimum order, for instance, Japan Dome House Company supplies dome houses at a minimum order of three-hundred units. This research examines the potential of carving standard grade EPS into a form of dwelling using a hot-wire tool to re-create a model similar to a commercially produced EPS dome house. EPS components were assembled and left exposed to the elements since the main method of analyses of the live model was through exposure, particularly against rain and wind experienced within the jurisdiction of Pietermaritzburg, South Africa. Analyses of the live model was supplemented by testing of compression, flexural and thermal qualities of EPS under laboratory conditions. With wind speeds of thirty-nine km/hr and a rainfall intensity of twenty-eight mm, the model was found to still be in its original state of composure after six-months even without having been permanently anchored to the ground. Existing industry models such as Moladi, Khaya ReadyKit and Fischer Housing were examined to provide a standard of

comparison for this investigation. This was done in order to distinguish how EPS dome houses differ to current existing alternative building technologies within the sector of low-cost housing.

Observation of the model revealed that it is possible to successfully re-create an EPS dome house without complex moulding equipment. Some of the main findings from the laboratory analysis were that, contrary to expectations, thermo-gravimetric analyses of three different densities (fifteen kg/m^3, twenty kg/m^3 and thirty kg/m^3) revealed that as the density of EPS increases, the maximum degradation value decreases. A study of the interaction of the polystyrene beads through microscopic analysis revealed that in higher EPS densities beads can rupture, leading to a compromise in both structural integrity and form. A water absorption test on EPS revealed that the percentage of water absorbed by EPS is similar to that absorbed by clay bricks over a 24-hour period, which makes the materials comparable in this regard.

In terms of the outcomes of the study, the researcher has already published articles in three journals and two conference proceedings.

This research will be of value to design professionals in alleviating the environmental impacts of commonly used conventional materials through the inclusion of EPS where low compressive loads are permissible.

Key words: Low-cost housing, Expanded Polystyrene, compressive strength, flexural strength

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LIST OF ABBREVIATIONS

ABT	Alternative Building Technologies
ASTM	American Society for Testing and Materials
BNG	Breaking New Ground
CAD–CAM	Computer-Aided Design and Manufacturing
EUMEPS	European Manufacturers of Expanded Polystyrene
EPP	Expanded Polypropylene
EPS	Expanded Polystyrene
EPSASA	Expanded Polystyrene Association of Southern Africa
HDA	Housing Development Agency
SHF	Social Housing Foundation
SHRA	Social Housing Regulatory Authority
TGA	Thermogravimetric Analyser

CHAPTER 1: INTRODUCTION

1.1 Background

Access to reliable and economically viable housing in the midst of rapid urbanisation is one of the goals of sustainable development as prescribed by the United Nations Development Programme (United Nations 2015).

The process of urbanisation has resulted in high rates of migration (Tacoli, McGranahan and Satterthwaite 2015), with large volumes of people migrating from rural to urban settings in search of new opportunities and better standards of living. Urbanization therefore translates to an increased demand for housing.

According to the Department of Human Settlements (2010), in response to the demand for housing and in line with the constitutional imperative of providing housing to the poor, the Government has, in terms of the Housing Act, 1997 (Act No 107 of 1997), initiated several programmes which provide poverty-stricken households with access to adequate housing.

Although South Africa has made significant progress following its history of apartheid, it still faces many challenges. According to Pallotti and Engel (2016) these include:

- There are many South Africans that are not employed;
- The quality of free education for black people is sub-standard;
- Public services are poorly located;
- The poor are continually marginalized by various existing spatial challenges;
- The disease burden of South Africa is increasing as a result of the deteriorating public health system;
- Public service performance is inefficient;
- There are extremely high levels of corruption; and
- South Africa continues to be a divided society.

The apartheid era left South Africa with a terrible legacy of inequality. This prevailing inequality often results in multiple service delivery riots and protests throughout the country (Alexander 2010). This is similar to what was experienced in the early 1940’s where the employed urban class was advancing rapidly, and small-scale riots and strikes arose due to mounting frustration over inadequate housing, wages and transport among Africans (Gerhart 1979).

South Africa is one of the many countries in the world where poverty amongst its citizens is prevalent. As Meyer (2016) puts it, “Poverty is a global phenomenon and has proven difficult to resolve. Strategies to address it need to be focused on factors associated with poverty through local research as problems differ from region to region.”

The majority of residential structures that impoverished communities build are hyper-permeable (Meth 2016). Meth (2016) further defines hyper-permeability as “an extreme form of indefensible housing since it encapsulates housing that presents multiple forms of permeability”. These structures generally have numerous surface voids as a result of the use of unreliable and inappropriate materials being used by communities to erect these structures. These materials include amongst others; road traffic signs, shade-cloth and cardboard (Hill and Stamey 1990) (Figure 1.1).

Figure 1.1: Informal housing
Source: All Africa (2012)

1.2 Problem statement

There is a significant backlog of housing in South Africa. This is mainly due to five primary issues: funding, affordability of housing, standard of houses built, location of settlements and land acquisition (Burgoyne 2008). These challenges relate to turbulence within the financial, social and political sphere of the built environment. An array of research studies exist that have explored the viability of increasing the efficiency with which houses are built within the realm of existing conventional materials; however, there are few research studies that explore what contributions unconventional building materials such as Expanded Polystyrene (EPS) can make in the face of South Africa's colossal housing challenges. The gap that exists in the arena of housing provision is: "what material alternatives can be incorporated in housing construction that may curb the growing number of informal dwellings?". In relation to EPS, this statement can be tested scientifically through the following procedures:

- Conducting laboratory tests to find the compressive strength, heat resistance and water absorption values of EPS.
- Comparing laboratory test values with existing results previously found on EPS.
- Observation and analyses of a miniature model to verify if the models' behaviour is consistent with what can be found through laboratory analysis.
- Assessment of existing housing policies to determine if the implementation of EPS constructed facilities would be in contravention of any legislation.

1.3 Research questions

The primary research question was therefore as follows:

How feasible is the use of standard grade Expanded Polystyrene (EPS) in the construction of dome house facilities?

The secondary research questions were as follows:

- How do the strength qualities of EPS compare to those of conventional materials?

- What are the benefits of a dome configuration dwelling as opposed to a conventional box-type configuration?
- Can a hot-wire machine satisfactorily carve EPS pieces to produce the desired curved moulds in the absence of complex machinery?
- How do EPS dwellings compare to other quick construction housing models using the parameters of cost, time and environmental considerations?

1.4 Aims and objectives of the research

This research aimed to explore the competence of EPS as a potential contributor in lowering the current housing backlog in South Africa.

The objectives of this research study were to:

- Review the main challenges and existing strategies of housing delivery in South Africa.
- Investigate through existing literature and through creating a miniature live model, whether standard grade EPS can be used as a form of low-cost housing.
- Conduct cost, time and environmental analysis of EPS against other quick-construction building solutions; and
- Draw a comparative matrix on the use of standard grade EPS versus other innovative housing models in the low cost housing arena.

This study was premised on the importance of poverty eradication and material efficiency as emphasised by the following factors;

1) The exhaustion of raw materials has dire economic effects.
2) Extraction of raw materials leads to adverse changes in land use and this has negative environmental consequences.
3) Non-renewable energy is being depleted by energy intensive manufacturing processes.
4) Harmful emissions resulting from manufacturing processes lead to serious environmental impacts.
5) Higher energy needs as well as scarce availability of resources lead to increased material cost impacts (Ruuska and Häkkinen 2014).

1.5 Dissertation outline

Chapter 1: Introduction

Chapter 1 details the context of the research and presents the problem statement along with the research aim and objectives as well as the research questions.

Chapter 2: Literature review on the use of EPS and as a material alternative in the building industry

Chapter 2 provides details of the current housing backlogs and the current housing initiatives in South Africa. It also provides an overview of the existing literature on EPS. Additionally, it highlights the structural components of EPS and its safety for use in forming the superstructure of a residential dwelling.

Chapter 3: Research design and methodology

Chapter 3 highlights the various laboratory tests conducted on EPS as well as the methodology of each performed test. The study setting for the placement of the live model is defined along with the relative climatic conditions.

Chapter 4: Expanded polystyrene live model design

Chapter 4 describes the construction method for a full-scale EPS dwelling by considering each standard step in the construction of a house from the foundation to the roof.

Chapter 5: Uses of expanded polystyrene as well as its associated cost implications

Chapter 5 shows a comparison of the construction time and cost of EPS dome houses with other available housing models by mean of a comparative matrix as well as a pie chart.

Chapter 6: Summary of findings, conclusions and recommendations

Chapter 6 considers all the findings from the various laboratory test results and provides a discussion on each finding. A final conclusion regarding the feasibility and suitability of standard grade EPS as a potential contributor to low-cost housing is presented.

CHAPTER 2: LITERATURE REVIEW ON THE USE OF EPS AND AS A MATERIAL ALTERNATIVE IN THE BUILDING INDUSTRY

2.1 Introduction

The current criticism of social housing in South Africa, in addition to the existence of an extensive backlog, is that the majority of housing units are built in disadvantaged urban edge localities where land is cheap and uncontested (Meth 2016). Furthermore, the type of units built are aesthetically unpleasing. They are built in such a way as to encourage the progressive accumulation of unhygienic living conditions. This progression ultimately leads to sub-standard living conditions due to over-population, rat infestation and foul smells signalling a polluted environment. It is therefore critical to consider the design and location of quality low-cost houses to ensure that adequate living conditions are maintained.

The time period that is covered by the literature review is from 1981 to 2018. The focus of this literature review is to provide an in-depth review of the background of the housing backlog in South Africa and the technical characteristics of alternative building materials, specifically EPS.

The first section of the literature review presents the history of housing in South Africa as this is crucial for understanding the reasons for the housing backlog. Housing policies are highlighted in order to show that it is not the absence of policies that is the main source of inefficient housing provision. This section also benchmarks South Africa's housing delivery performance against other countries with similar historical housing challenges. Six possible root causes are listed in conclusion as to why the current housing backlog exists.

The second section of the literature review describes various quick-construction alternatives within the sphere of poverty alleviation strategies. Thereafter, information on EPS and its uses in various industries, its competencies and its viability for house construction, is presented. The structural competencies of EPS are sourced from English language journal articles.

2.2 The history of housing in South Africa

2.2.1 Overview of low-cost housing delivery rate in South Africa

The current housing situation in South Africa is grim. The number of informal settlements across the country is increasing exponentially. According to the South African Institute of Race Relations (2015), the number increased from 300 in 1993 to 2225 in 2015. According to the National Department of Human Settlements (2015), a total of 2,835,275 houses have been built between 1994 and 2014. Additionally, 95,210 were built in 2014/15 and 100,339 in 2015/16 amounting to a total of 3,030,824 houses built since 1994. An analysis of these figures shows that approximately 377 houses have been built each day over 22 years. This contradicts the reported housing delivery rate of 1200 houses per day as mentioned in the 2017 Budget Speech (The South African 2017).

2.2.2 Housing in South Africa's past

The lack of adequate housing within South Africa dates back to the spatial structuring of cities during the 1850's (Davies 1981). Christopher (1983) states that one of the factors which led to structural segregation in South Africa was the concern by English and European settlers that everybody who was non-European was 'unhygienic'. This prompted the colonisers of South Africa to formulate legislation to ensure that Africans were housed as far as possible from urban areas and towns. The result of this was the inception of several formal locations for Africans. In 1923, Parliament enacted a law to formalize this originally known as the *'Urban Areas Act of 1923'* (Mabin 1992). This law enforced segregation by requiring all towns to establish separate portions of land where Africans would reside. These portions of land lacked basic services; that is, they did not have electricity, water or sewer service connections. This remains core to the emergence of disease and infections within African communities residing in informal settlements. The connection between health and the built environment is highlighted by Perdue, Stone and Gostin (2003) who state that the zoning ordinances of the 1920s led to a significant proportion of people being exposed to various health threats. Unfortunately, the present situation of housing within South Africa largely reflects these historical overtones.

The United Nations (2014) estimates that by 2050 more than 66 % of the population worldwide will reside in urban areas. This highlights the need for urgent strategies to address housing needs for the large number of people migrating to the cities.

2.2.3 Housing guidelines

There are numerous legal housing institutions which have specific mandates in relation to housing in South Africa. According to the Socio-Economic Rights Institute of South Africa (Tissington, 2011), the four major institutions are "the Housing Development Agency (HDA), the National Home Builders Registration Council (NHBRC), the Social Housing Foundation (SHF) and the Social Housing Regulatory Authority (SHRA)."

The most important pieces of legislation and policy framework that continue to drive the fight for adequate housing for all in South Africa are as follows (Department of Human Settlements 2009):

- The Constitution of the Republic of South Africa no. 108 of 1996;
- Housing Act No. 107 of 1997;
- Prevention of illegal Eviction from and Unlawful Occupation of Land Act No 19 Of 1998;
- National Norms and Standards for the construction of stand-alone residential dwellings financed through the National Housing Programmes (Department of Human Settlements 2007); and
- Social Housing Act No. 16 of 2008

According to the Centre for Affordable Housing Finance in Africa (2018), there are many South African households that do not "have access to housing credit through the formal banking sector". This concerning reality places emphasis on the need for government to review its current housing policies in order to assess how they can further enhance housing accessibility for all. A plethora of policies, programmes, and institutions have been initiated to address the housing challenge; however, few have proved to be effective in addressing the problem. Some of the popular previous key policies and programmes include:

a) A New Housing Policy and Strategy for South Africa (1994) (Whitepaper)

This White Paper on housing provides details on government's intention to build "one million state-funded houses in the first five years of office" from 1994 (Tissington 2011).

b) The Reconstruction and Development Programme (1994)

The Reconstruction and Development Programme was a policy aimed at ensuring socio-economic progress through the process of integration. It also had the purpose of ensuring that the effects of apartheid were dealt with through mobilisation of all South Africans (Ministry of the Office of the President 1994).

c) The Growth, Employment and Redistribution Strategy (1996)

The Growth, Employment and Redistribution Strategy was introduced when government faced challenges which were not within the scope of the Reconstruction and Development Programme. These challenges were mainly related to the pace at which social investment needs were accelerating compared to the resources which were being provided by the government (Le Roux 1997).

d) Breaking New Ground (BNG): A Comprehensive Plan for the Development of Sustainable Human Settlements (2004)

Breaking New Ground was adopted in September 2004, and it was mainly aimed at outlining the overall housing endeavour of government with particular focus on sustainability (Huchzermeyer 2006).

e) National Housing Code (2009)

The National Housing Code was first published in 2000 and was aligned to the Housing Act. The Housing Code details all the norms and standards and guidelines applicable to the National Housing Programme (South Africa Department of Human Settlements 2009).

Based on a review of the literature on housing policies and standards one can establish that the most important and basic requirement for any dwelling constructed by the Government is that the minimum floor area ought to be 40 m^2. Within the stipulated 40 m^2 floor area, it was also noted that another mandatory requirement is that there ought to be a separate bathroom and toilet as well as a shower and hand basin. EPS dome houses can be constructed to a floor area of 40 m^2 with a separate bathroom and toilet as well as shower and hand basin. EPS dome houses therefore would not be in contravention of any legislation. From the reviewed literature, it was also noted that within all the housing policies, there is no policy which explicitly describes the South African government's role in protecting its citizens from uncontrollably high building material prices.

2.2.4 Housing backlog and targets by Government

South Africa is at risk of unintentionally reproducing 'apartheid-style' localities if the housing backlog continues to escalate; however, the basis of segregation would no longer be race but rather class (Bond and Tait 1997).

In 2001, the Department of Housing released figures which showed that the housing backlog stood at 2,784,193 as shown in Tables 2.1 and 2.2. From Table 2.1 it can be seen that the highest backlog is in Gauteng. This is consistent with the views of Tacoli, McGranahan and Satterthwaite (2015) that cities will have the highest housing backlog due to increased migration.

Table 2.1: Department of Housing Statistics (2001)

Housing Backlog	
Province	**Backlog**
Eastern Cape	361,271
Free State	123,200
Gauteng	518,897
KwaZulu-Natal	402,803
Mpumalanga	211,620
Northern Cape	48,576
Northern Province	426,605
North West	411,221
Western Cape	280,000
South Africa	**2,784,193**

Source: Statistics South Africa (2001)

Table 2.2: Housing figures achieved by government yearly from 1994 to 2001

Province	1994/1997	1997/1998	1998/1999	1999/2000	2000/2001	Total
Eastern Cape	6,551	42,223	29,659	10,459	7,997	96,849
Free State	16,942	21,001	20,391	8,177	21,561	87,172
Gauteng	65,660	83,416	28,726	144,575	21,825	344,202
KZN	17,553	78,468	53,103	28,997	24,770	202,893
Mpumalanga	19,884	10,873	16,838	4,808	14,071	66,474
Northern Cape	8,532	6,103	6,621	1,558	6,613	29,427
Northern Province	11,108	15,743	22,899	12,401	1,561	63,712
North West	21,287	20,977	18,367	12,944	11,149	84,724
Western Cape	25,321	43,834	34,575	26,916	23,513	154,159
Total	**191,898**	**322,638**	**231,181**	**250,835**	**133,060**	**1,129,612**

Source: Statistics South Africa (2001)

The South African government has not ever been able to reduce the housing backlog nationally to below 2 million. According to Aigbavboa and Thwala (2018), in 2016 the housing backlog was approximately 2.1 million.

Government has targeted reaching a total of 6 million (cumulative) houses delivered by 2019 (Vukuzenzele 2017). This target is modest relative to the budget allocated by the Department of Human Settlements which is R33.4 billion (Engineering News 2017). Given this available budget, the housing backlog should be decreasing at a much faster rate, but Table 2.1 shows that this is not the case. If allocation of budget is not the main reason, other possible reasons for the backlog remaining stagnant, are corruption, mismanagement of funds, inadequate monitoring and control procedures, poor coordination of appointed service providers, inappropriate construction methods as well as inadequate planning (Moroke 2009).

To further substantiate that the abovementioned factors may be the reason for the stagnant housing backlog in South Africa, it is instructive to compare housing delivery in Brazil and Venezuela which have scaled up similar housing aid projects. Not only do Brazil and Venezuela have similar social housing projects to South Africa, but these two countries share a lot of other similarities with South

Africa. One of the most distinctive similarities is that both Brazil and Venezuela also have long histories of colonization (Marx 1998). Insituto Lulo (2014) states that 170 million (83 %) of the total population in Brazil reside in urban areas. Brazilian cities face numerous difficulties as a result of the uncontrolled urbanization, including a housing shortage of 5.4 million homes. The majority of the 5.4 million homes (73.6 %) are families that are steeped in extreme poverty. In an effort to accelerate the provision of housing, the Brazilian government launched its housing program known as 'Minha Casa, Minha Vida - My House, My Life' (Somers and Baud 2013). The implementation of this programme has resulted in 10.5 million people from low-income families being placed in 2.6 million housing units that the government has built (Insituto Lulo 2014).

Venezuela's housing programme known as 'Gran Misión Vivienda - Great Housing Mission' was introduced in 2011 aimed at providing low-cost houses to families earning below the minimum wage of the country (Castillo and Heimary 2015). A total of 630,330 houses were built by 2014 (Africa Check 2014).

A comparison of the housing delivery in South Africa, Brazil and Venezuela shows how relatively slow is the progress in addressing the housing challenge in South Africa (Table 2.3).

Table 2.3: Housing delivery, South Africa, Brazil and Venezuela

Country	**South Africa (1994 to 2016) 22 years**	**Brazil (2009-2015) 6 years**	**Venezuela (2011-2015) 4 years**
Total houses constructed and delivered	3,030,824	2,600,000	630,330
Houses constructed per day	377	1187	432

2.3 Expanded polystyrene as an alternative building technology for low cost housing

The NHBRC in the generic specifications guide of the National Department of Housing (Engineering News 2012) defines "Alternative Building Technologies (ABT)" as any deviation from traditional construction methods as specified in the

SANS 10400 – this does not necessarily mean material which has never been used. Examples of ABT's in South Africa include:

a) The FutureHouse walling system- This walling system consists of a pre-fabricated panel with a high density EPS core encapsulated in high tensile steel galvanized wire mesh. Panels are supplied in standard sizes; 1.2 m by 2.5 m wide, and 2.75 m by 3 m high. Custom heights can be made to order up to a maximum of 6 m height / length. Panel core EPS thickness variants are 40 mm, 60 mm, 80 mm and 100 mm depending on insulation requirements. These sizes are to suit standard wall heights, different wall functions and cost requirements (FutureHouse 2015).

According to FutureHouse (2015), the system has the following benefits: it 1) is thermally insulating and energy saving, 2) meets regulated energy efficiency building codes, 3) is simple to build even with untrained labour, 4) is sound and water resistant, 5) appears, feels and sounds like concrete or plastered brick wall, 6) is easily transported and cost effective, 7) is ideal for all types of buildings – residential, renovations, industrial, multi storey commercial, perimeter/security walls and agricultural.

b) Intermodal freight container housing modules- The International Organization for Standardization containers (ISO), according to Oloto and Adebayo (2006), are about "12.1m or 6.058m by 2.438m wide and 2.438m high boxes made of steel". These structures have a minimum area of approximately 27.95 m^2 and 13.6 m^2 respectively depending on the manufacturer. Figure 2.1 shows a typical ISO container used for housing.

Figure 2.1: Shipping containers
Source: Oloto and Adebayo (2006)

The concept of converting shipping containers to houses was initially developed by Malcolm Mclean in the 1950s and later advanced by Nicholas Lacey (ISBU Association, 2016). Lacey advanced the concept of converting shipping containers to permanent residential accommodation. These ISO shipping containers are designed to standards which ensure they withstand extreme weather conditions at sea. The shipping containers can also withstand stacking of nine other fully loaded containers suggesting they are ideal modular units as a result of their strength, weatherproof nature and availability. However, Archdaily (2011) notes an important limitation of using containers as an alternative housing form:

> Reusing containers seems to be a low energy alternative, however, few people factor in the amount of energy required to make the box habitable. The entire structure needs to be sandblasted bare, floors need to be replaced, and openings need to be cut with a torch or fireman's saw. The average container eventually produces nearly a thousand kilograms of hazardous waste before it can be used as a structure.

2.3.1 The history of Expanded Polystyrene

Expanded Polystyrene is a polymer and belongs to the category of thermoplastics (Utracki and Wilkie 2002). It has huge vast attention due to its diverse applications in miscellaneous industries. Although Eduard Simon formally discovered polystyrene in 1839, it only began to commercially be used in the 1930s (Andrady and Neal 2009).

By adjusting the polymerization structure it is possible to obtain polystyrene with a different tacticity (Porter, Allen and Breyer 1992). Tacticity (isotactic, syndiotactic and atactic) is the grouping of phenyl rings in relation to the polymer chain back-bone (Porter et al. 1992). Atactic polystyrene was discovered first, where the phenyl rings are arbitrarily dispersed along the polymer chain (Chai, Reagen, Zhu and Forrest 2018). In the atactic form, the phenyl rings are ordered on the same side of the polymer chain, whereas in the syndiotactic form they are alternatively arranged (Pasztor, Landes and Karjala 1991). Expanded polystyrene is used in different industries such as the automotive, medical and electronics industry (Expanded Polystyrene Association of Southern Africa 2006a).

Expansion in EPS is achieved through small amounts of pentane gas that is dissolved into the polystyrene base material during its production. When the gas is subjected to heat, it expands to form perfectly closed cells of EPS. According to the Expanded Polystyrene Association of Southern Africa (2006a), such cells occupy around “40 times the volume of the original polystyrene bead”. The EPS beads are then moulded into various forms suited for their intended purpose (Expanded Polystyrene Association of Southern Africa 2006a).

EPS has been used in the construction industry in multiple forms, including being used as pre-reinforced sheets for walls and slabs. EPS can also be assembled where the bearing capacity of soil is low since it has a very low dead weight when compared to conventional reinforced concrete structures (Raj, Nayak, Akbari and Saha 2014).

Polymerized styrene’s contain foaming and flame retarding agents (Laoutid et al., 2009). According to Makai, Kiss and Mucsi (2004), foamed polystyrene contains 1.5 % to 2 % polymerized polystyrene and 98 % to 98.5 % air. Biologically, it is inert and not toxic. Among its most important properties EPS has an advanced heat insulating ability, does not absorb water easily, and has chemical resistance to acids and alkalines. The typical thermal conductivity value of expanded polystyrene is between 0.03 W/mK and 0.04 W/mK. Its thermal conductivity ability depends on the temperature, vapour content and mass density. Properties of the heat insulating panels made from expanded polystyrene foam do not change with time. Foam neither decays, nor rots (Makai et al., 2004).

2.3.2 Expanded polystyrene applications in South Africa

According to the Polystyrene Packaging Council (2017), EPS may be used for insulation in the construction industry, and most prominently for packaging in medical applications, garden products and children's toys.

Contrary to this, in countries outside Africa, such as Europe, EPS is mostly used in building and construction (see Figure 2.2). This is mainly due to its numerous structural advantages.

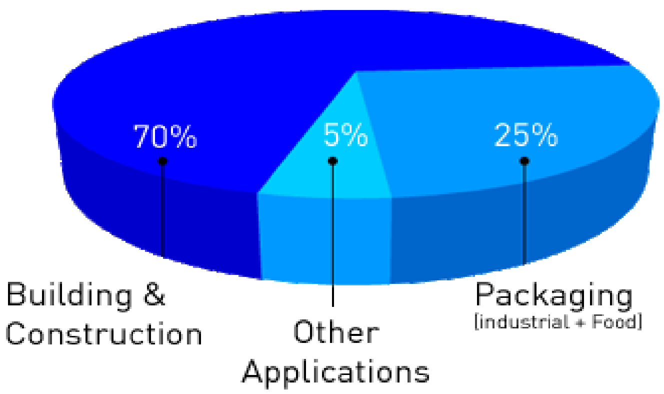

Figure 2.2: The use of EPS in Europe
Source: Association of Plastic Manufacturers (2017)

2.3.3 Viability of expanded polystyrene to form the bulk of superstructure in low cost housing

It is a requirement of the South African standard specifications for burnt clay masonry units that "the nominal compressive strength of face bricks be above 17.0 mPa, with individual strengths greater than 12.5 mPa" (South African National Standards 2007).

Most existing residential and commercial structures are constructed mainly of masonry and concrete, but research shows that EPS can compete with some of the strength qualities of masonry and concrete. Some of the capabilities of EPS are further highlighted below.

EPS has a bead structure and the more closely packed together the beads are, the denser the EPS becomes (Figure 2.3) (Gibson and Ashby 1999; Ossa and Romo 2009).

Figure 2.3 shows the following:

a) EPS specimen;
b) beads;
c) beads and closed cells;
d) closed cells.

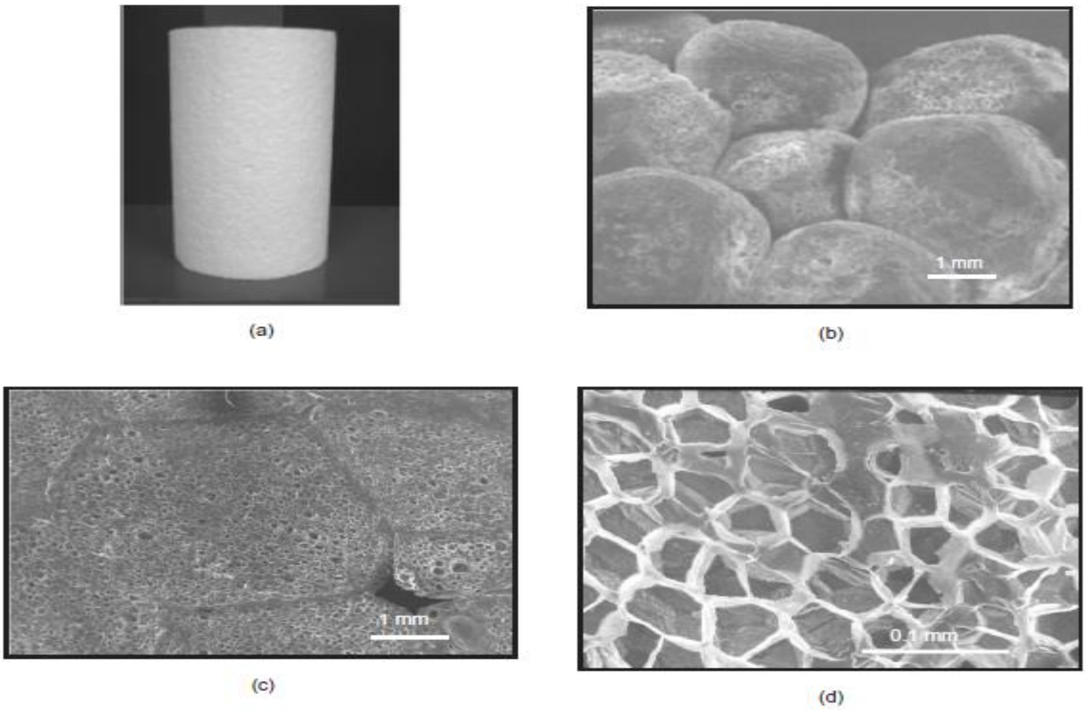

Figure 2.3: Microstructure of EPS
Source: Gibson and Ashby (1999)

Gibson and Ashby (1999) and Ossa and Romo (2009) highlight the importance of the voids that exist within EPS. A limitation, however, is that they do not go further to explore how the nature of voids in EPS differs with varying densities. Knowledge about the void structure of EPS is important for designers in understanding the permeability potential of varying densities.

Preber, Bang, Chung and Cho (1994) selected four parameters to establish a detailed stress and strain relationship of EPS. These parameters are defined and detailed in Figure 2.4.

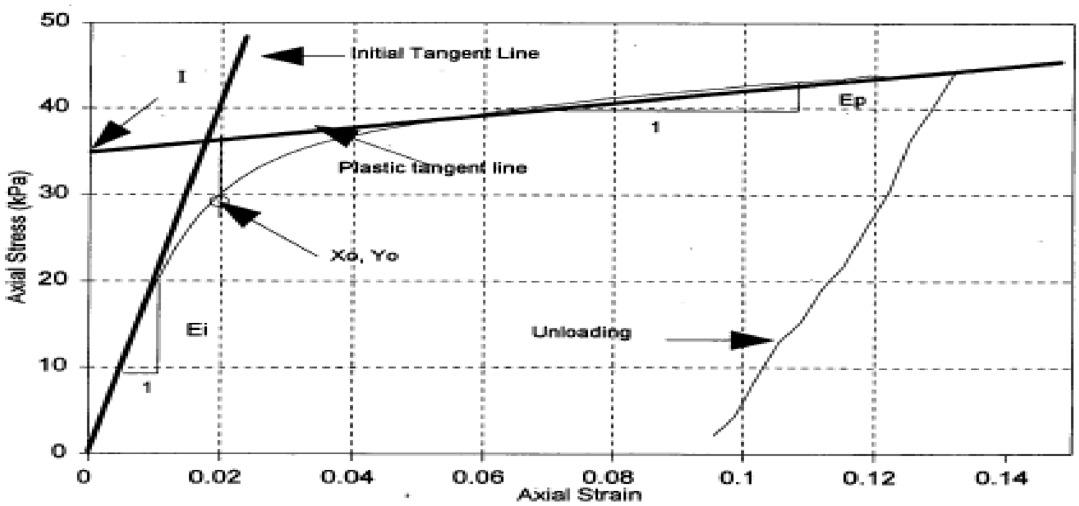

Figure 2.4: Stress and strain relationship of EPS in relation to its different parameters

Source: Preber, Bang, Chung and Cho (1994)

Figure 2.4 shows that the stress-strain relationship of EPS is of a linear nature and will continue up till an axial strain of 2 %. After 2 % there is no noteworthy change in deviator stress versus axial strain. For a housing structure constructed out of EPS, this is advantageous because it means that once the axial strain reaches 2 %, the material will no longer continue to deform due the deviator stress.

Yucel, Basyigit and Ozel (2003) noted that the strength of EPS under pressure and its resistance to deformation under heat exposure increase parallel to an increase in unit weight. as shown in Figure 2.5.

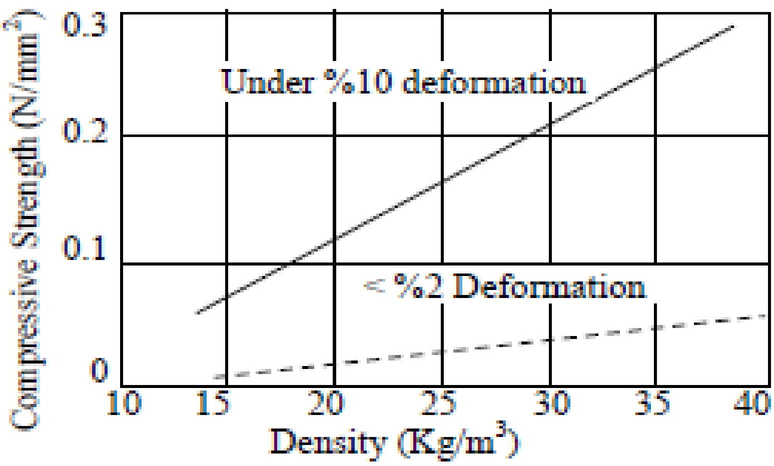

Figure 2.5: EPS's resistance to deformation

Source: Yucel, Basyigit and Ozel (2003)

Figure 2.5 implies that if a greater density is used for an EPS dome house, it would have a greater tolerance for load and a greater resistance against deformation. However, each increase in density would naturally be costlier than lower densities such as 15 kg/m^3. Therefore, an appropriate density that is fit for purpose whilst cost effective needs to be considered when selecting the density of EPS for any particular project.

Yucel *et al.* (2003) further stated that water suction capacity will change according to unit weight and production quality as demonstrated in Figure 2.6.

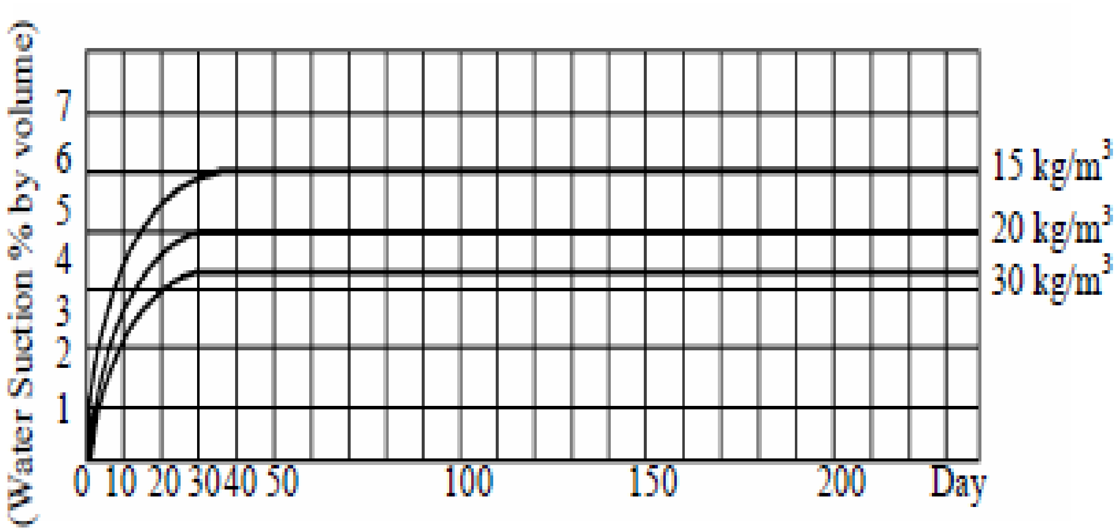

Figure 2.6: Water suction capacity of EPS
Source: Yucel et al. (2003)

Figure 2.6 by Yucel et al. (2003) shows that the water absorption potential of EPS is very low. The results show that the moisture resistance of EPS increases as the density increases. From Figure 2.6 it is evident that the straight line that is seen for all the different densities after 30 days implies that there is a limited percentage of water that can be absorbed by EPS. Once this percentage has been reached, no more absorption can take place. This percentage is dependent on the number of voids in the structure of the EPS according to its relative density. This quality of EPS would be highly advantageous during rainy seasons, as there would be minimal concern that EPS constructed houses would collapse due to water absorption.

Gnip, Keršulis, Vaitkus and Vėjelis (2004) tested the compression strength of expanded polystyrene and show the corresponding mechanical states of expanded polystyrene slabs under stress (Figure 2.7). The figure further shows how expanded polystyrene slabs resist compressive forces which are intended to disturb and deform them.

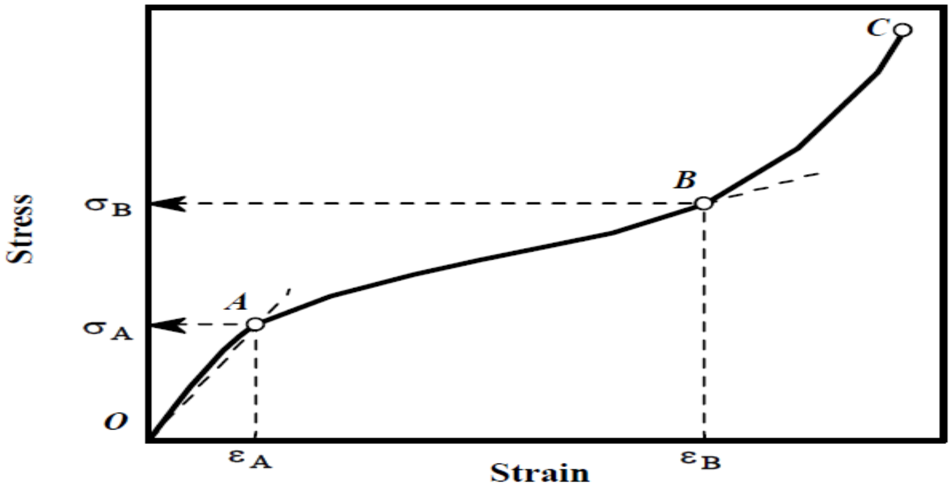

Figure 2.7: Stress and corresponding mechanical states of EPS slabs

Source: Gnip, Keršulis, Vaitkus and Vėjelis (2004)

The studies reviewed on the stress, strain and compressive characteristics of EPS show that the initial modulus of EPS is a function of the density. Although the studies successfully show that the stress will increase at any given strain level as the density increases, they do not provide the context of how EPS differs in this regard with conventional materials such as masonry.

A Korean company, Dome House Korea, has what it calls 'EGF panel technology' (Dome House Korea 2015). EGF panel technology are multipurpose expanded polystyrene sheets which can either be used for insulation in a housing structure or to form the actual housing structure. In 2012, Dome House Korea assessed test specimens of 50 mm x 50 mm x 50 mm in terms of their flexural strength, compressive strength and thermal expansion of EPS (Table 2.4). Although they sufficiently present the strength qualities of EPS, their investigation was based on modified EPS samples instead of virgin material such as standard grade EPS.

Table 2.4: Compressive strength, flexural strength and thermal conductivity for 20 kg/m³ to 25 kg/m³

Density (kg/m³)	Compressive strength (N/m²)	Flexural strength (N/m²)	Thermal conductivity (Avg. temp 23 °C ±2 °C) (W/m.K)
Above 20 but below 25	Above 8 but below 12	Above 22 but below 30	0.040<

Source: Dome House Korea (2015)

Japan Dome House Co. Ltd has developed intricate moulding equipment, capable of moulding large EPS pieces to efficiently form dome houses (Japan Dome House Co. Ltd 2018). These dome shaped EPS houses have the following benefits: 1) ultra-thermal insulating properties, 2) gale resistant, 3) semi-permanent durability, 4) high earthquake resistance (Figures 2.8 to 2.11).

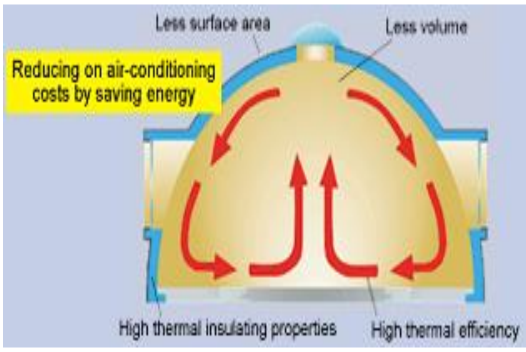

Figure 2.8: Ultra-thermal insulating properties

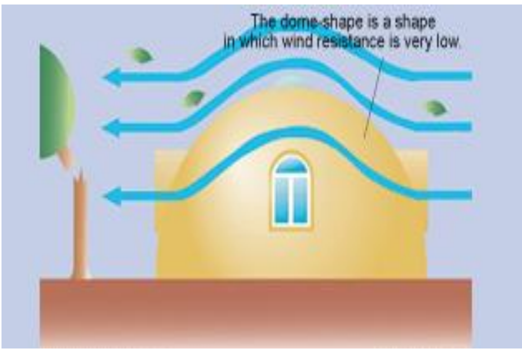

Figure 2.9 Gale resistant

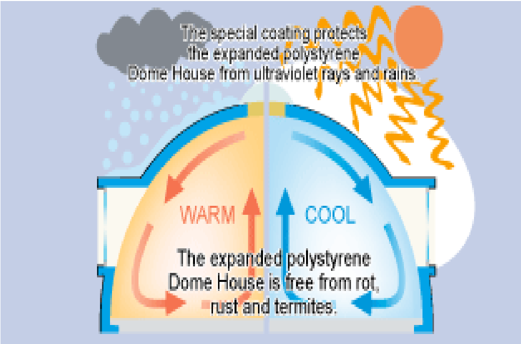

Figure 2.10: Semi-permanent durability

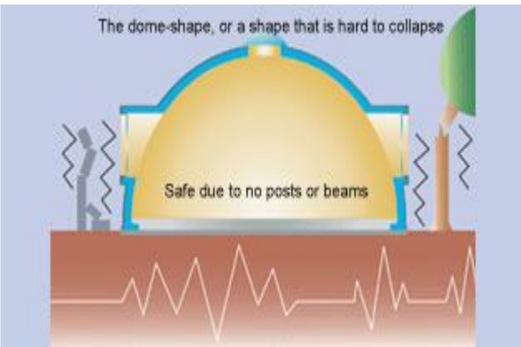

Figure 2.11: High earthquake resistance

There are very few materials such as EPS that are capable of being recycled for up to 9 cycles without their original properties being distorted (Maharana and Negi 2007). Building houses out of such a material would positively contribute to the built environment and to green building initiatives. Green building has been shown to reduce health and environmental strains in the long term as well as to generate noticeable market advantage (Edwards 2003). The effectiveness of green building initiatives can be further enhanced by strategies such as the use of prefabricated units. As stated by Jaillon and Poon (2008), there are immense economic, social and environmental benefits related to using prefabrication in construction.

2.4 Case studies

2.4.1 Aso Farm Village

Aso Farm Village in Kaga Province, Japan, is home to the world's first known EPS dome house community as constructed by Japan Dome House Co. Ltd (Dirt Cheap Builder, 2017). The village consists of 480 dome houses (Figure 2.12). EPS dome houses in Japan only started gaining popularity in 2005 when the ministry of land, infrastructure, transport and tourism endorsed their continued construction by certifying them as safe and habitable structures (Lyster and Verchick 2018).

Figure 2.12: Aso Farm Village, Japan, EPS Dome houses

Source: Dirt Cheap Builder (2017)

The CO_2 emissions for these EPS dome houses are far lower than the CO_2 emissions for a concrete structure of a relatively similar square meterage and therefore supports environmental protection initiatives (Figure 2.13).

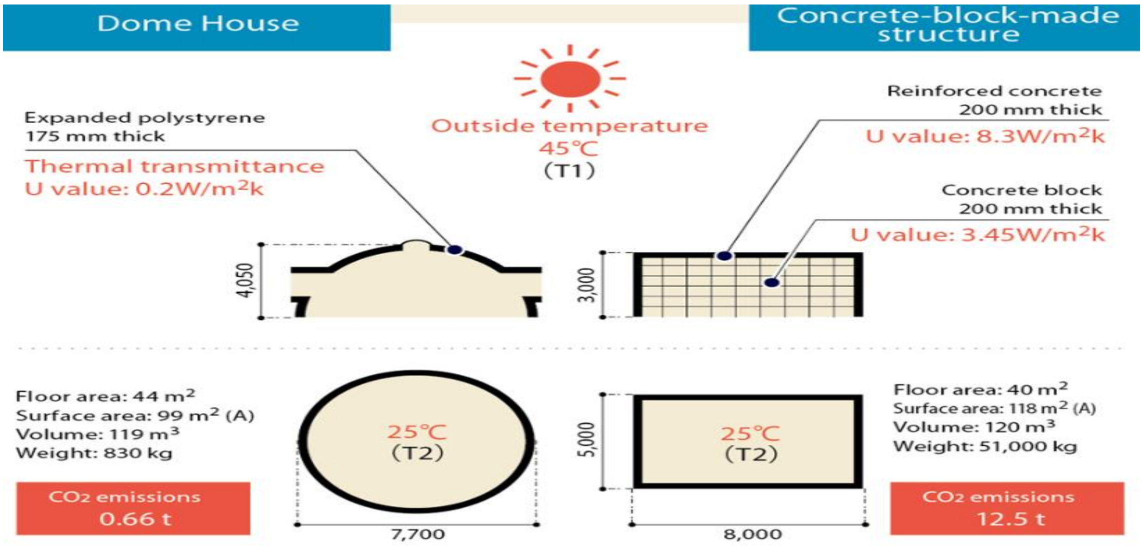

Figure 2.13: Thermal demonstration by Japan Dome House Co. Ltd

Source: Japan Dome House Co. Ltd (2018)

2.4.2 AIDS Village South Africa

The first Acquired Immune Deficiency Syndrome (AIDS) Village in Johannesburg, South Africa was built using dome structures. Approximately 450 people reside in this village. The foundation is set on conventional bricks fused with concrete. The bricks continue to the level of the windows before an air form shutter is secured inside the walls. The shutter is inflated to the required pressure and then bricks are laid to follow the set mould shape (Dome Space 2010). Although the AIDS Village exhibits some of the benefits of an EPS dome structure, the construction process could have been simplified with the use of prefabricated pieces such as EPS. With a simpler construction process, it would have been possible to use less person power in the erection of the structure.

Figure 2.14: AIDS village South Africa

2.5 Conclusion

This chapter outlined the broad background of both the history of housing in South Africa as well as the nature of EPS. In terms of the history of housing in South Africa, the researcher described the early stages of the housing crisis. From statistics, it was then shown that the housing backlog has not changed since 2001. It was then shown that the stagnancy of the housing backlog may be as a result of obstacles such as corruption and mismanagement of funds. In terms of EPS, the researcher outlined the history and applications of EPS. A discussion followed regarding the viability of EPS as well a case study of where the use of EPS has been maximized to beyond norms of general packaging or insulation.

It is evident from the reviewed literature that developed countries such as Europe, Korea and Japan have maximized the use of EPS in construction more than South Africa. Optimal use of materials such as EPS in developing countries (i.e. South Africa) tends to be hindered by the absence of complex moulding equipment and limited knowledge with regard to various innovations linked to EPS.

The majority of studies reviewed solely assessed the structural soundness of EPS. The aspect of how EPS compares with conventional materials such as concrete and masonry has not been adequately addressed. In addition to assessing the structural soundness of EPS, this research aimed to assess its practicality by exploring how it differs from conventional materials. This research investigated whether the use of a hot-wire system to carve large EPS pieces in the absence of commercial equipment is feasible for the manufacture of prefabricated EPS dome house moulds.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

Any new building materials need to first be subjected to adequate laboratory analysis. Comprehensive technical assessments are necessary to ensure that deformations in any material are within permissible limits. Successful laboratory analysis opens up a window of opportunity to make a meaningful contribution to the construction industry.

Kibert (2016) states that 'green building' is a design philosophy which focuses on increasing the efficiency of resource use. These resources include energy, water or materials. The purpose of green buildings is to reduce the overall impact of the built environment on the health of humans and the environment. Although the use of concrete and masonry dates far back in history, their impact on the environment and the losses they impose on the earth outweigh their benefits (Blankendaal, Schuur and Voordijk 2014).

3.1.1 Research aim

This research aimed to investigate whether standard grade EPS is structurally competent to be used to form the superstructure of a residential dome house.

3.1.2 Research objectives

The objectives of the research were to:

- Assess whether standard grade EPS is competent in terms of compressive properties;
- Measure whether standard grade EPS is competent in terms of water resistance;
- Test whether standard grade EPS is thermally stable;
- Assess the flexural resistance of standard grade EPS; and

- Determine whether it may be used as a replacement of hyper-permeable materials in the face of increasing housing backlogs.

3.2 Research approach and design

Quantitative research methods were employed to assess the competency of standard grade EPS, including:

- Live model observation- A miniature EPS dome house was constructed and observed in the outdoor environment for a period of 6 months.
- Laboratory testing- This was undertaken using the measures of compressive strength, water absorption and thermal resistance. Findings emanating from these tests were used to determine whether EPS has the ability to protect inhabitants against extreme weather conditions as well as from physical harm.

In addition to the structural viability of EPS, it was critical to establish whether the use of EPS would be economically plausible. To determine the economic plausibility of EPS, a bill of quantities for all items required to build a 40 m^2 EPS dome house was compared to a Bill of Quantities (BOQ) for a standard 40 m^2 conventionally built house.

Additional data was sourced from manufacturers and suppliers such as Iso Moulders, Moladi, Khaya ReadyKit and Fischer Industries in order to compare the constructed EPS dome house to existing low cost housing models.

3.2.1 Live model design

Live working scientific models are built to endorse or to disprove theory. They make certain features of the world easier to simulate, quantify, visualize or define (Bailer-Jones 2009). Though often at a smaller scale compared to reality, they allow for the analysis of live features that can be used to enhance the performance of a future full-scale model. Thus, the construction of a miniature EPS dome house model was necessary to further analyse how standard grade EPS dome houses would respond in a natural environment.

Polymers are soft materials which are often considered to be weak. Contrary to this, the Expanded Polystyrene Association of Southern Africa (2018) reports that "a 200mm-thick layer of EPS with a density of 20kg/m^3 represents the same amount of energy as a 17mm-thick layer of pine wood".

It is commonly believed that a residential dwelling is considered to be 'normal' if it conforms to the conventional 'box' shape. Similarly, materials such as masonry and concrete are considered as 'conventional' building materials due to their extensive historic use. The first three items in the assessment criteria of the National Home Builders Registration Council (National Home Builders Registration Council 2013) in terms of ABT's are structural performance, fire resistance and water penetration.

The miniature live model needed to sufficiently demonstrate effectiveness in the abovementioned criterion in order to be comparable to the performance of dome houses that are constructed by Japan Dome House Co. Ltd.

The live model used for this research was constructed using the Tolino/Risi model tool in an EPS moulding factory (Hot Wire Systems 2018). The technical specifications for the hot-wire cutter used to create the live model are detailed in Table 3.1. EPS components were measured at a radius of 600 mm and carved to form a dome.

Table 3.1: Technical specifications of hot-wire cutting machine

Technical Specification- Tolino/Risi 3013	
Cutting length	1340 mm
Cutting Depth	330 mm
Transformer	Pri: 230 50Hz/ Sec: 37V/160VA
Weight	17,5 kg
Support Plate	Sheet steel, with steel amplification.
Bow	Painted, fully welded, with industrial ball bearing guides
Art	HWS-ST-86700
Extra Wire	HWS-ST-88000
Stand Base	HWS-ST-88000

Source: Hot Wire Systems (2018)

Figure 3.1:Tolino/Risi 3013 Hot-wire machine
Source: Hot Wire Systems (2018)

3.2.2 Limitations

- According to the knowledge of the researcher, there is no EPS mould supplier in South Africa that has procured a moulder from the international market that is large enough to mould EPS pieces that would comply with the minimum standard of $40m^2$ as stipulated by the Department of Human Settlements (2010).
- The aesthetic appeal of the structure was not considered in this study since it would involve an investigation into the social acceptance of dome shaped dwellings versus conventional box-shaped dwellings and hence numerous ethical considerations.

3.2.3 Study setting

The live model was placed in an outside environment in Pietermaritzburg, KwaZulu-Natal, South Africa. Pietermaritzburg is the capital city of KwaZulu-Natal province, one of the nine provinces in South Africa. A graph of the low and high points of temperature in Pietermaritzburg are depicted in Figure 3.2 (Meteoblue 2018).

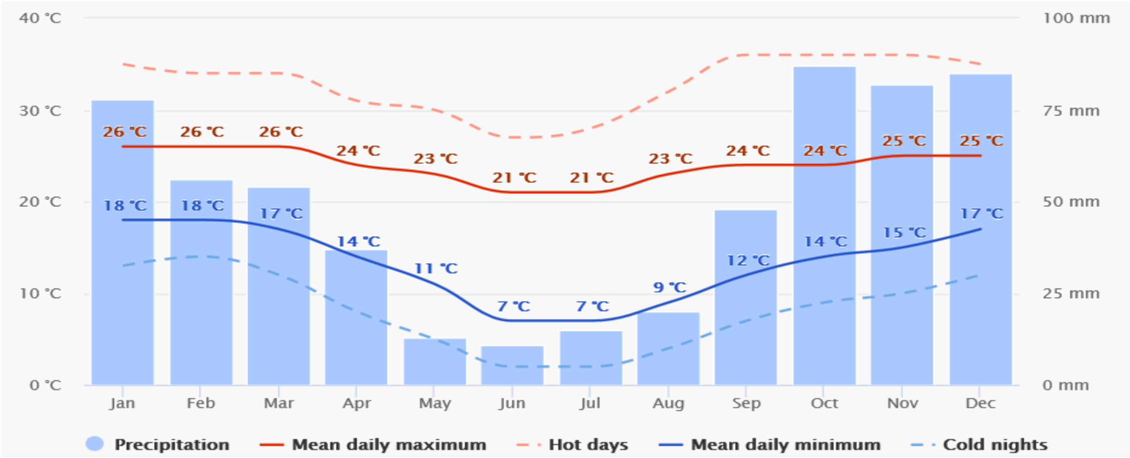

Figure 3.2: General climate of Pietermaritzburg, KwaZulu-Natal

3.2.4 Description of live model

The dimensions of the model are 1200 mm diameter X 600 mm carved dome of 15 kg/m^3 density.

3.2.5 Observation method

The EPS live dome model was exposed to the climatic elements from 1 February to 31 July 2018 (i.e. 6 months). The weather conditions for each month is given from figure 3.3 to 3.8. A visible aspect of material degradation such as discoloration was used to extrapolate the six-month period (February to July) to twelve months.

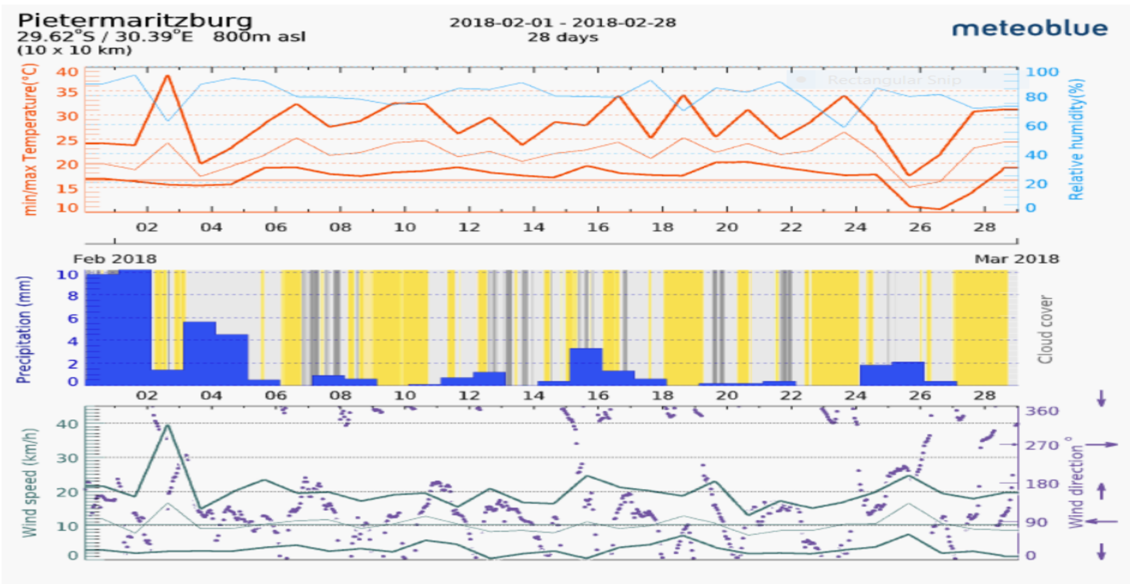

Figure 3.3: Temperature, precipitation and wind schedule for February 2018
Source: Meteoblue (2018)

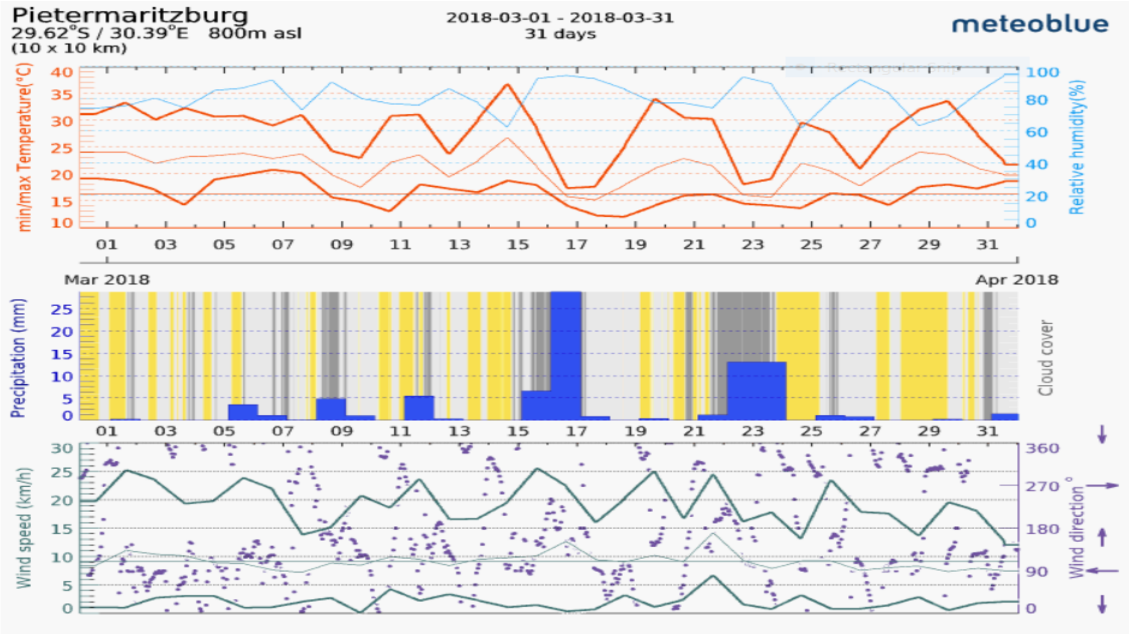

Figure 3.4: Temperature, precipitation and wind schedule for March 2018
Source: Meteoblue (2018)

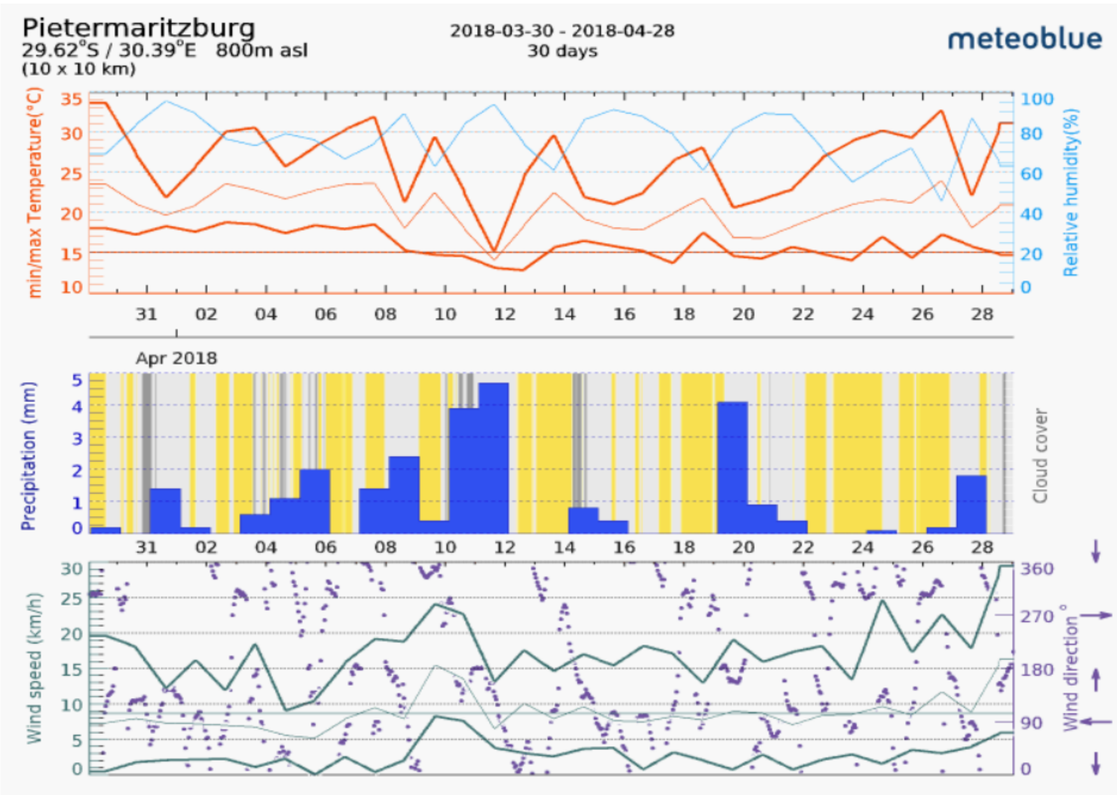

Figure 3.5: Temperature, precipitation and wind schedule for April 2018
Source: Meteoblue (2018)

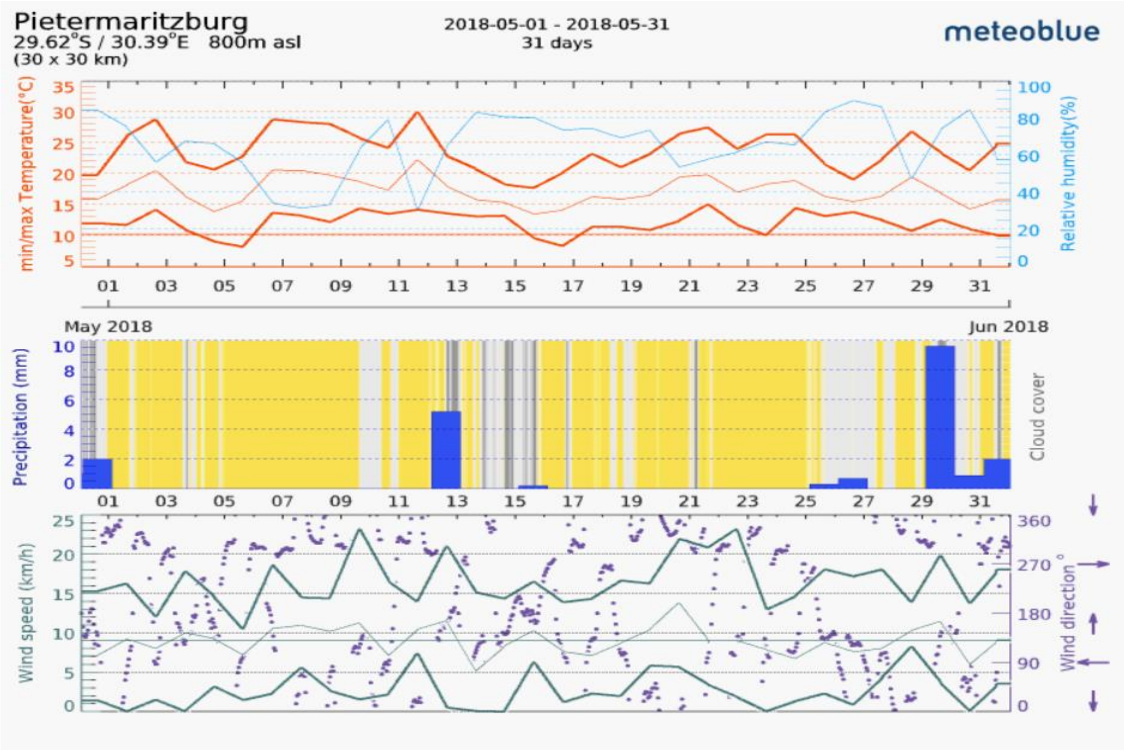

Figure 3.6: Temperature, precipitation and wind schedule for May 2018
Source: Meteoblue (2018)

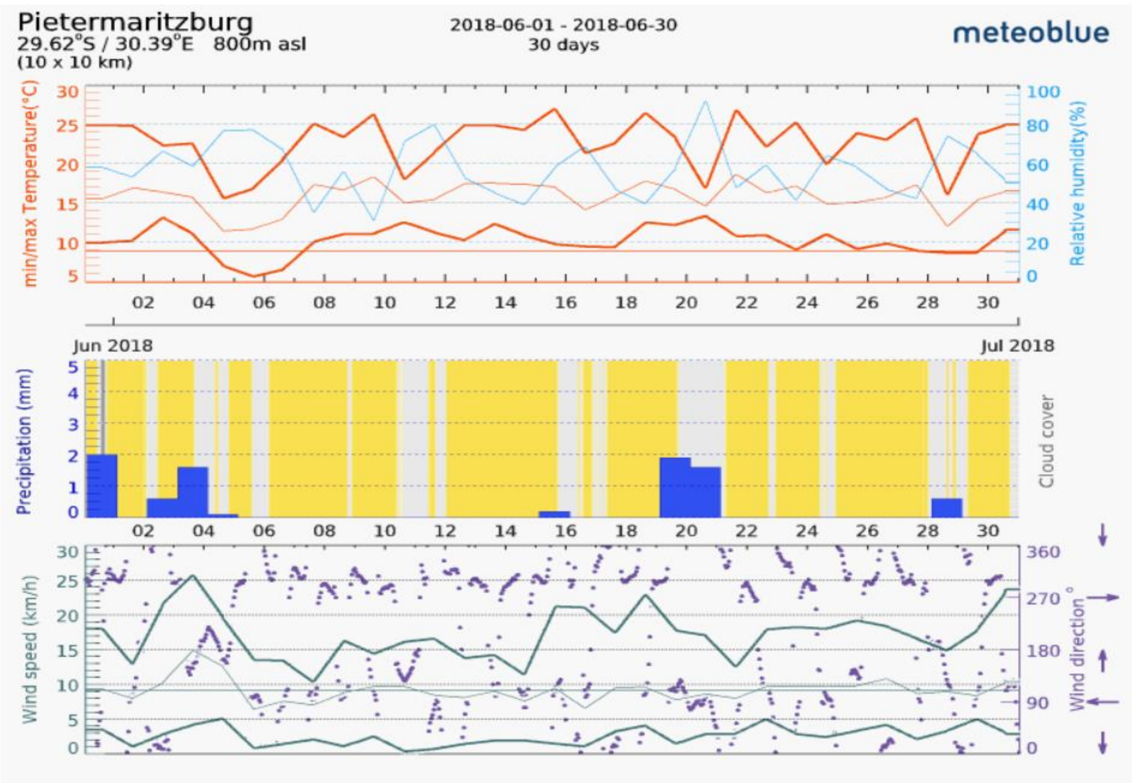

Figure 3.7: Temperature, precipitation and wind schedule for June 2018
Source: Meteoblue (2018)

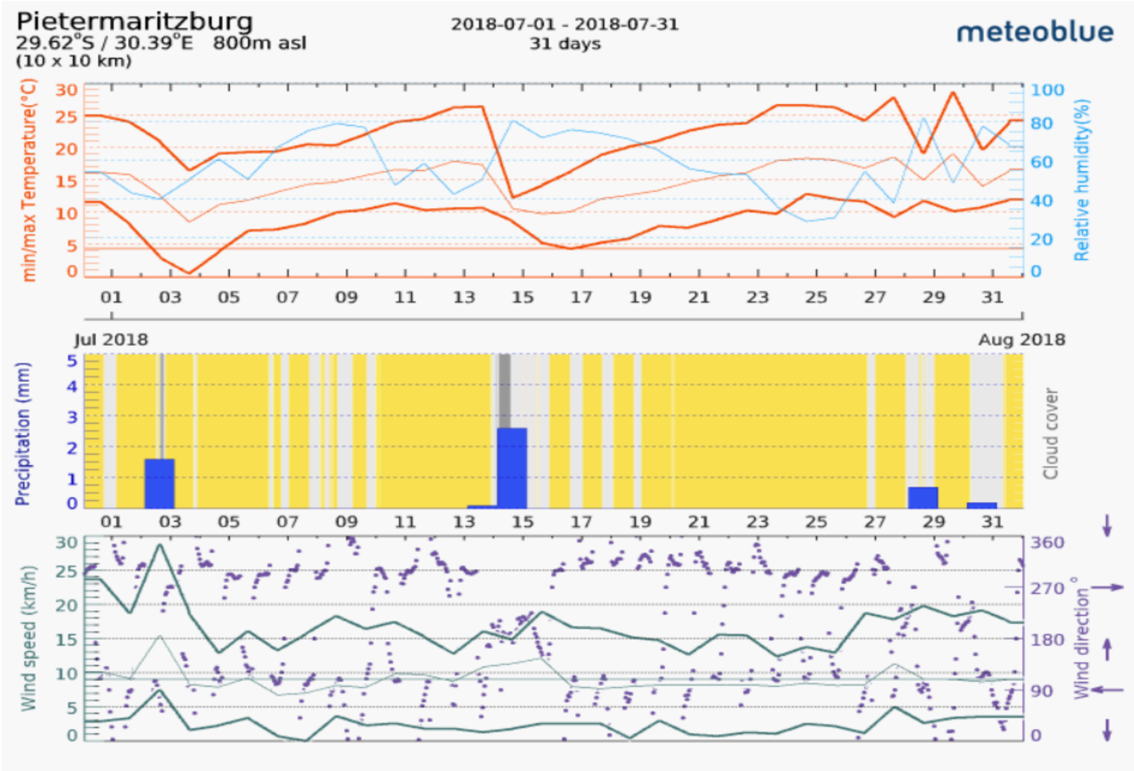

Figure 3.8: Temperature, precipitation and wind schedule for July 2018
Source: Meteoblue (2018)

Figure 3.9: Expanded polystyrene model placed for the first time in February 2018

Figure 3.10: Expanded polystyrene model at close range in March 2018

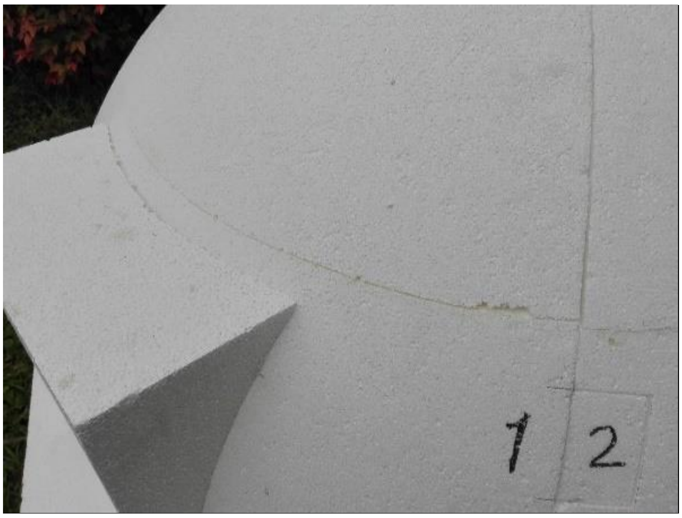

Figure 3.11: Expanded polystyrene model at close range in April 2018

Figure 3.12: Expanded polystyrene model at close range in May 2018

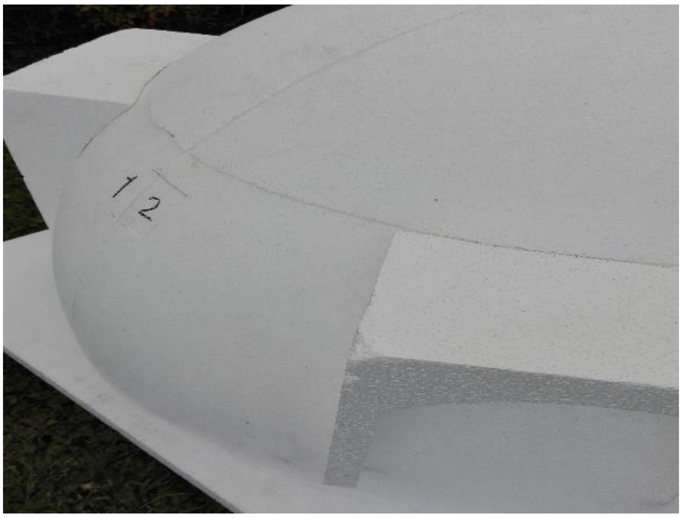

Figure 3.13: Expanded polystyrene model side view of pieces 1 and 2 in May 2018

Figure 3.14: Expanded polystyrene model side view of pieces 3 and 4 in May 2018

3.3 Laboratory Tests

3.3.1 Microscopic analyses to understand the morphology of EPS

Density is a measure of mass per volume. An increase of density within the context of EPS implies that the many repeating units begin to be packed closer and closer together as the numerical value of density increases. The EPS beads are demonstrated in Figure 3.15. The input and output process of forming EPS is demonstrated in Figure 3.16. Polymerization is the process of forming EPS, and styrene and pentane are the two major components that are required.

Figure 3.15: Expanded Polystyrene beads
Source: Xu, Jiang, Xu and Li (2012)

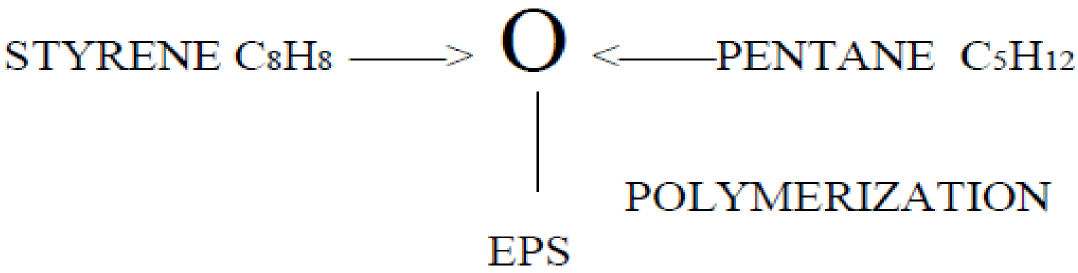

Figure 3.16: Input and output of forming EPS

Michaeli, Schrickte and Berdel (2009) used a 3D computer graphic generator to generate an X-ray micro-computed tomography scan of an EPS sample. From Figure 3.17 it is interesting to note the inter-dependency of each spherical contributor in the sample. This image explains how the lightweight structure of EPS has the ability to yield so much strength when it is subjected to load.

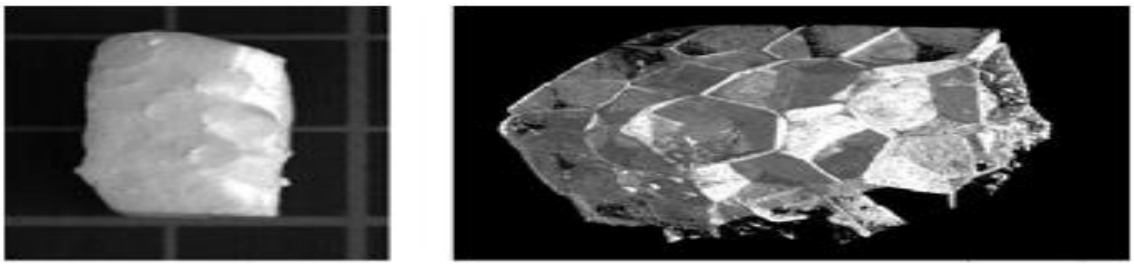

Figure 3.17: Tomography scan of an EPS sample
Source: Michaeli et al. (2009)

3.3.1.1 Equipment used for analysis

A Carl Zeiss Augiga Cobra fib-fesem was used to analyse how each spherical bead interacts with the next in EPS (Figures 3.18 and 3.19). According to the Research Equipment Database (2018), this instrument has a scanning electron microscope that has an exceptional resolution. The high resolution enables successful precision milling and nanofabrication.

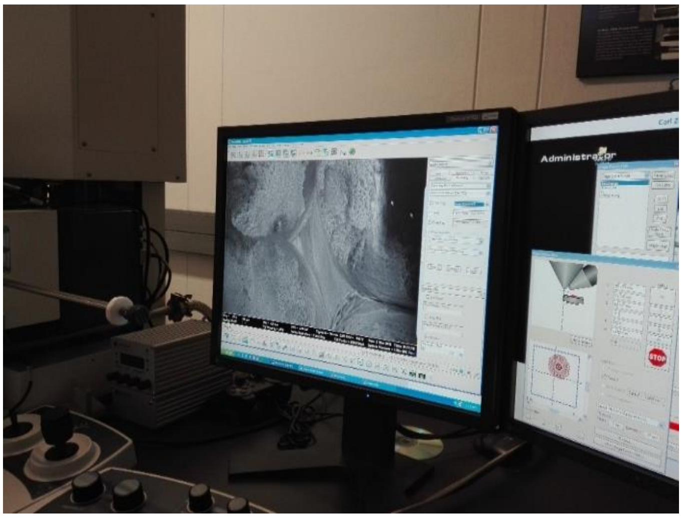

Figure 3.18: Carl Zeiss Agugiga Cobra fib-fesem control station

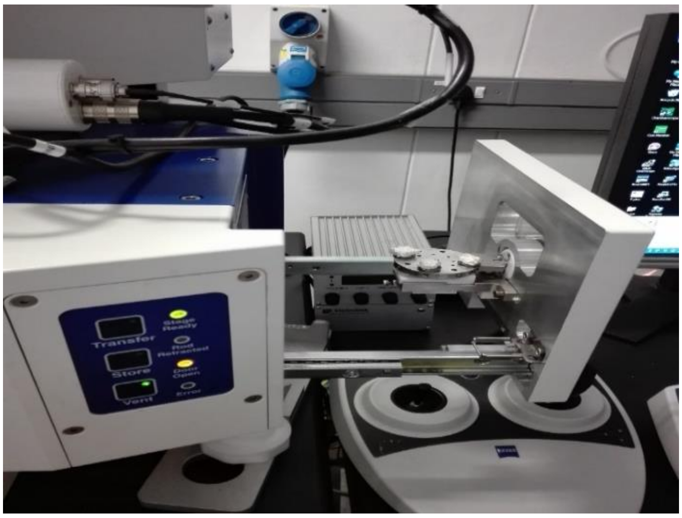

Figure 3.19: Carl Zeiss Agugiga Cobra fib-fesem control station sample feed

3.3.2 Compressive strength test

Lateral and vertical impact is always a concern for any structure. Lateral and vertical impact can be as a result of any air-borne object, either self-propelled or assisted, impacting the structure. The first line of defence for the contents contained in any dwelling are its walls. It is therefore a prerequisite of a sound structure that the walls comprise sufficient compressive strength. In order to test whether EPS has sufficient compressive strength, a laboratory test was conducted in terms of the American Society for Testing and Materials (ASTM) D 1621-00 standard (Figure 3.20).

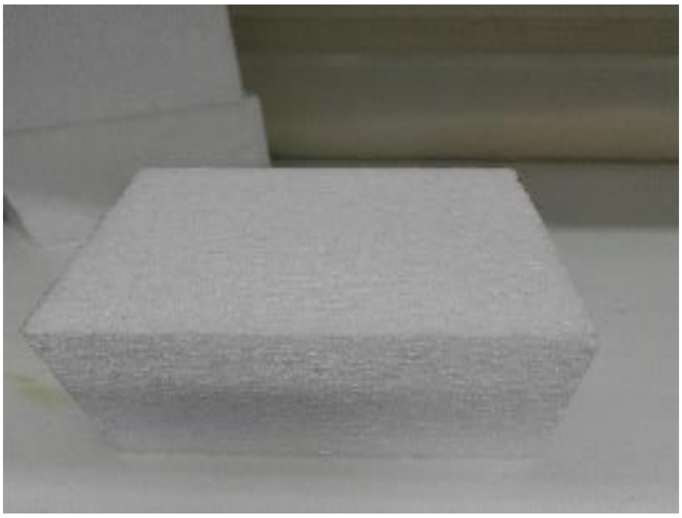

Figure 3.20: EPS specimen prepared for compression test

3.3.2.1 Apparatus

- Instron 5966, k8883
- Load indicator
- Deformation indicator

3.3.2.2 Procedure

- Eight specimens were considered for each density category (15 kg/m^3, 20 kg/m^3 and 30 kg/m^3)
- The dimensions of the specimens were measured
- A uniformly distributed load was applied to the test specimens at a rate of 2.5 mm/min ± 0.25 mm/min for each specimen.
- Load was applied until yield point or until approximately 13 % of the original thickness was achieved
- Modulus of elasticity in compression, was calculated by:

$$E_c = WH/AD$$ (Equation 3.1 Modulus of Elasticity)

- The estimated standard deviation was calculated by:

  $s = \sqrt{(\varepsilon x^2 - nX^2)/(n-1)}$ (Equation 3.2 Standard deviation)

3.3.3 Flexural strength test

Airborne objects pose a serious threat to the wall of any building structure, regardless of the type of material. It is therefore important that the flexural properties of any material used to form the walls of a structure ensure the safety of the inhabitants.

Flexural strength is also frequently referred to as the modulus of rupture. Flexure reveals the stress in a material before it yields during a flexural test. During the flexural test, a rectangular cross section is placed as a simple beam under centre loading in order to determine its breaking load and therefore it's flexural strength (Figure 3.21).

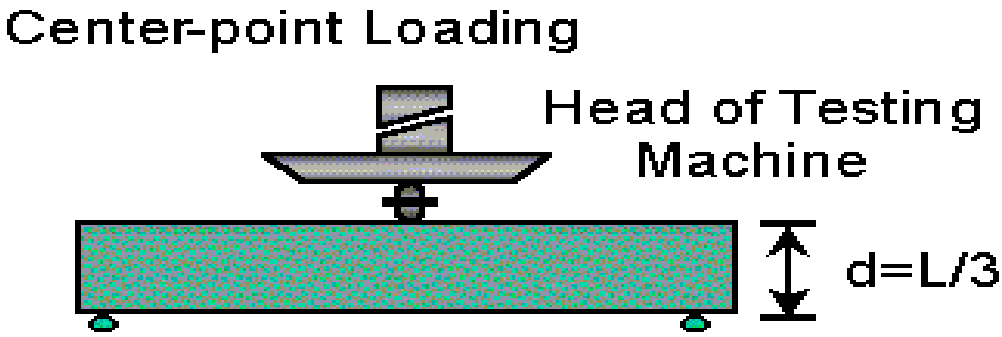

Figure 3.21: Flexural strength test of EPS

3.3.3.1 Summary of test method

The specimen is deflected until rupture occurs. The equations used are based on the assumption that the material is uniform and presumes that the stress-strain characteristics below the elastic limit are linearly elastic.

3.3.3.2 Apparatus

The testing machine used was an Instron 5966-k8883. The number of test specimens to be tested is prescribed to be at least four specimens. Ten specimens were prepared for this test. Table 3.2 lists the recommended guidelines that were used as minimum requirements for the test specimen geometry.

Table 3.2: Minimum requirements for test specimen geometry

Recommended:
L/d = 10 Require 20 ≥ L/d ≥ 2
That the support span be ten times the thickness
L/b = 2.5 Require L/b ≥ 0.8
That the support span be two and a half times the width
b/d = 4 Require b/d ≥ 1
That the width be four times the thickness

Where:
L = Support span (mm)
D = Thickness of specimen (mm)
B = Width of specimen (mm)

Dimensions of test specimen were therefore decided to be:

- Support span = 100 mm
- Thickness = 10 mm
- Width = 40 mm

3.3.3.3 Procedure

Each specimen's width and depth was measured to the nearest 0.3 mm at the centre of the support span (Figure 3.22).

The crosshead rate was calculated by the equation:

$$R = ZL^2/6d \qquad \text{(Equation 3.3 Crosshead rate)}$$

Flexural strength was calculated by the equation:

$$S = 3PL/2bd^2 \qquad \text{(Equation 3.4 Flexural strength)}$$

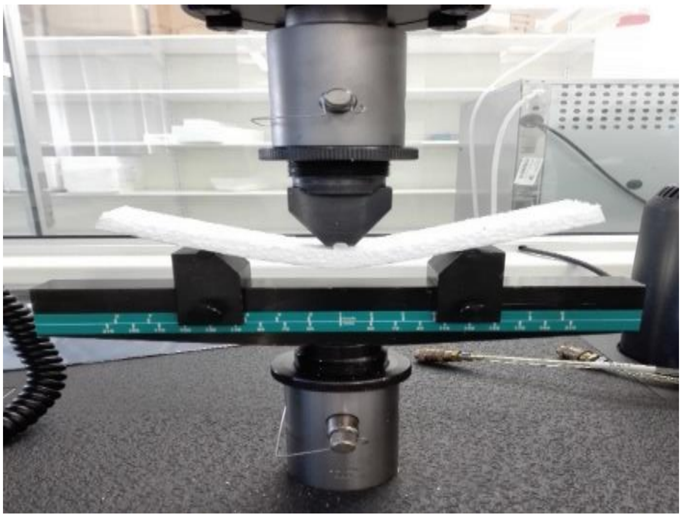

Figure 3.22: EPS sample being subjected to flexure

3.3.4 Thermal resistance test

Spontaneous combustion is also one of the main concerns regarding any structure. It is therefore expected that any building, whether commercial or residential, be able to withstand spontaneous fire. Hendry (2001) stated that the periods of time stipulated in building regulations for masonry regarding adequate protection against fire can therefore be used for other materials as a standard for being regarded as an incombustible material. However, Home Energy Saver (1977), as early as the 1970's, pointed out that no building material is truly fireproof. This statement has proven to be true over the years as buildings which have been deemed to be 'fire-proof' have, in fact, been consumed by fire.

Even the top 50 performing countries in the world in terms of Gross Domestic Product still have challenges in relation to building infrastructure that is highly susceptible to fire consumption (World Development Indicators Database, 2016). For example, United Arab Emirates, ranked in 30th place for its Gross Domestic Product, is described as harbouring numerous buildings which are infernos waiting to happen due to numerous electrical failures (Alqassim and Daeid 2014).

The Clay Brick Association of South Africa (2018) suggests that clay bricks can resist deformation for a total time of 240 minutes at maximum temperatures of between 1000 ^{o}C and 1200 ^{o}C. These are remarkable feats in the building industry as the figures demonstrate resilience and reliability.

The Thermal Stability test for EPS was conducted in line with ASTM E 2550-07. The equipment used for the thermogravimetric analysis was the TGA Q500.

3.3.4.1 Summary of test method according to ASTM E 2550-07 guidelines

An inert container is used to hold a sample that is heated at a continuous rate of 1 ºC min-1 to 10 ºC min-1. Once the heating starts, the sample is recorded as a function of time versus temperature. When any thermal decomposition occurs, the change is marked by a deviation from the initial baseline mass.

3.3.4.2 Apparatus

The essential instrumentation that a Thermogravimetric Analyser (TGA) will have is:

- A thermobalance composed of a furnace to provide uniform heating at a constant temperature.
- A temperature sensor.
- A continuously recording balance to measure the specimen mass with a minimum capacity of 10 mg and a sensitivity of 610 µg.

Figure 3.23: TGA Q500

Figure 3.24: Samples being loaded into heat furnace

3.3.4.3 Procedure of thermogravimetric analysis according to the ASTM E 2550-07 guidelines

Each specimen is weighed and placed into the TGA at ambient temperature. The application of heat continues until a continuous mass is reached or up until the temperature is above the useful range of the material being tested.

3.3.5 Water absorption test

The water absorption test was conducted according to the ASTM D 570-98 standard test method. Each specimen was cut to dimensions of 50 mm length, 50 mm width and 50 mm thickness. The specimens were distinguished according to their densities of 15 kg/m^3, 20 kg/m^3 and 30 kg/m^3, with a total of 3 specimens for each density. A sensitive balance was used to obtain the dry mass of the specimens to an accuracy of 0.0001 g. The test was conducted through immersion of test specimens horizontally under 200 mm height of water for a 24-hour period at a temperature of 23 ºC (Figures 3.25 and 3.26).

Figure 3.25: EPS cubes immersed under 200 mm head of water

Figure 3.26: EPS cubes subjected to a controlled temperature of 23 ºC

After 24-hours, the specimens were removed and all excess surface water was wiped off with a dry clean cloth. Each specimen in its wet state was weighed and recorded. The mass of water absorbed by EPS specimen compared to its initial dry mass results in the percentage of water absorbed by the EPS. Their average values were calculated using the following formula:

$$\omega = \frac{m_w - m_d}{m_d} \qquad \text{(Equation 3.5 Water absorption)}$$

3.4 Environmental parameters

The National Building Regulations and Building Standards Act of 1977 (Act No. 103 of 1977) 'c' states that, the objective of legislation in regulating the design and construction of homes is to ascertain that solutions that are used in the process of home construction are environmentally sustainable. From this act, it is evident that environmental considerations should be at the centre of any material advancement. According to the Natural Resource Institute (2018), the consideration of environmental parameters in buildings directly benefits plant and animal life.

The live miniature model comprising 1200 mm diameter x 600 mm carved EPS was used to measure this parameter through observation. Due to a large portion of a dome house being pre-fabricated, it had less impact on the environment compared to conventionally built houses. The observations made in the assessment of the EPS live dome model were used to develop a comparative matrix in Chapter 5.

CHAPTER 4: EXPANDED POLYSTYRENE LIVE MODEL DESIGN

4.1 Introduction

The objective of this chapter is to outline the construction considerations applicable to EPS dome houses. This chapter outlines how building an EPS unit differs from the general building process of a conventional dwelling. This is accomplished by considering four major steps in house construction, namely; the general posture of a dwelling (which largely determines how it will behave towards wind forces), walls, type of roof as well as the type of foundation.

The first distinctive difference in the construction process of EPS dome houses is that all EPS components are prefabricated. There are numerous benefits of prefabrication as opposed to on-site construction. According to Tam, Tam, Zeng and Ng (2007), some of these benefits include:

1) Achieving a shortened construction time as well as lower labour costs;
2) All year-round construction since work is not affected by changes in climate conditions;
3) Precise conformity to building code standards and greater quality assurance;
4) Minimal wastage of materials; and
5) Less theft of material/equipment.

4.2 Analysis of Expanded Polystyrene configured mould

Wind and atmospheric turbulence initiate negative air pressure when they come into contact with the eaves and cornices of conventionally built houses (Stathopoulos, 1980) (Figure 4.1). These often gather underneath the roof and have the potential to destroy the roof leaving the contents of the house exposed. However, the aerodynamic shape of domes and the absence of suction elements offer excellent protection against winds (Da Silva 2016).

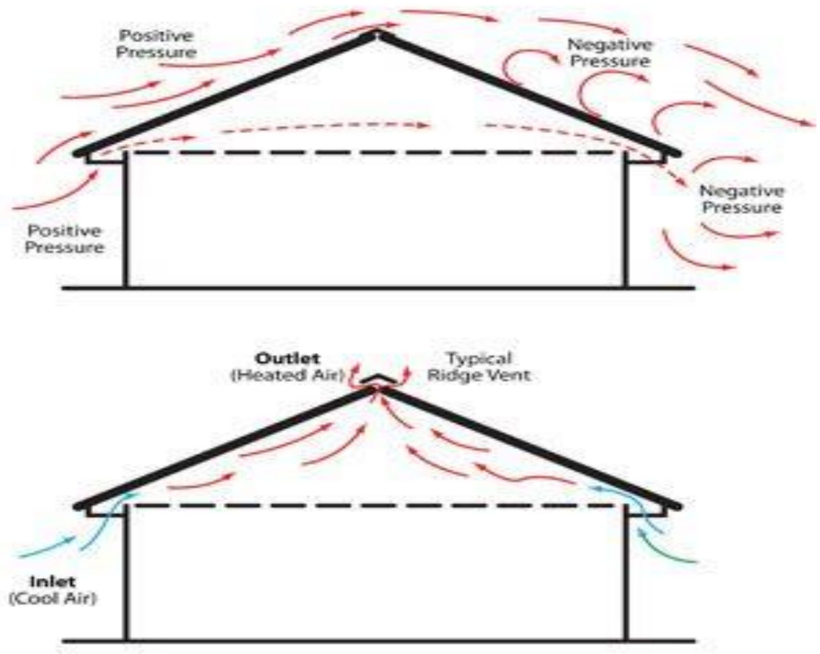

Figure 4.1: Negative and positive wind pressure on a conventional house
Source: Stathopoulos (1980)

The design of a dome house is based on very simple rules of geometry and should therefore be able to withstand any type of wind force (Consumer Guide 1981). Due to the lightweight nature of EPS components, EPS dome houses have a low centre of gravity (Michaeli et al., 2009). This quality of EPS dome houses affirms that they are resistant to collapse.

4.2.1 Insulation, internal walls and finishing

The insulation of all building types is affected by the type of cover they have on the walls and roof. The purpose of insulating a building is to assist in reducing electricity costs as well as to lower greenhouse gas emissions through lowered energy use (Pfundstein, Gellert, Spitzner and Rudolphi 2012).

The most important parts of a house that require insulation are the walls since they generally lose approximately 30 % to 40 % of the total heat lost (Blue Designs 2018). The roof loses approximately 25 % heat and the windows and doors loose approximately 10 % to 15 % heat (Blue Designs 2018).

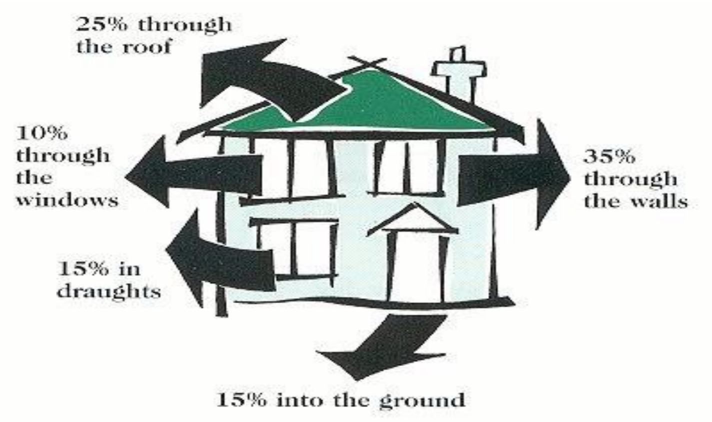

Figure 4.2: The importance of insulation
Source: Blue Designs (2018)

Conventionally built houses are insulated using various strategies which include the use of Epanded Polystyrene inside the wall cavity of the external and internal brick walls (Pfundstein et al. 2012). Various mortar compositions are further used as cladding to protect against water ingress and thus to increase heat retention within the structure. Some mortar compositions that can be used to clad building structures can either be a sand and lime mixture, cement plaster or gypsum plaster (The Constructor 2017).

EPS dome houses being made of EPS material are naturally insulated. The only further insulation that is added is that of a mortar-based plaster to increase the water resistance of the EPS layer (Figure 4.3).

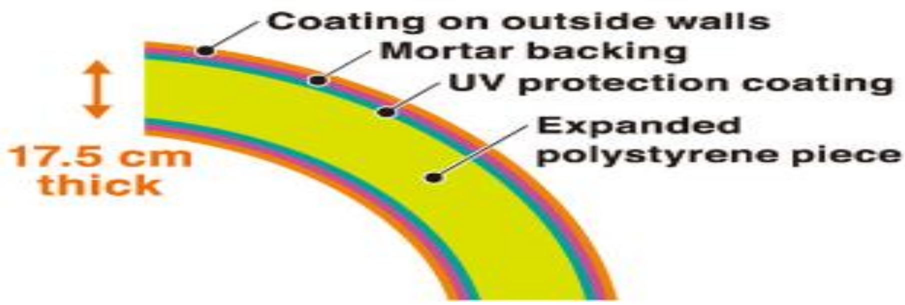

Figure 4.3: Layers of EPS dome house
Source: Japan Dome House Co. Ltd (2018)

4.2.2 Roof

A roof experiences the full effect of all weather conditions and therefore needs to be suitably robust. It is also required to channel water away. The purpose of a roof is to support and maintain the shape of a house as well as to ensure that the stored contents of the house remain dry (Roofing Calculator 2018). The most common types of roofs are shown in Figure 4.4.

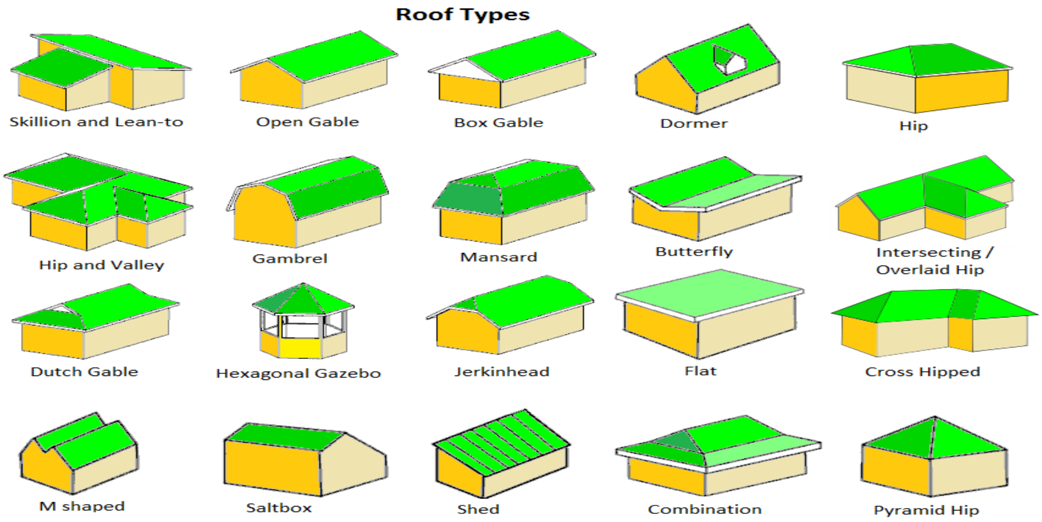

Figure 4.4: Different types of roofs
Source: Roofing Calculator (2018)

The most crucial parameters for choosing a roof structure are those of complexity and cost (Roofing Calculator 2018). These two parameters are linked to each other since the more complex the roof structure, the more expensive it will be to construct.

Since EPS dome houses have a dome structure, the roof will be made of an EPS component that will also be pre-manufactured and assembled along with the wall components. The uniformity of the walls and the roof are an effort to ensure a lower cost as opposed to the conventional roof types where the prevailing disadvantage is that the roof material differs from the wall material.

4.2.3 Foundation

Foundations have three vital functions, namely: carry the entire load of a building; withstand weather conditions; lock moisture away from weakening the structure of the building (Reese, Isenhower and Wang 2006).

Reese et al. (2006) further suggest that foundations can generally be categorized as shallow or deep foundations, as outlined in Table 4.1.

Table 4.1: Difference between shallow and deep foundations

Sources	Shallow Foundation	Deep Foundation
1. Definition	A foundation which is placed near the surface of the earth or transfers the loads at a shallow depth is called a shallow foundation.	A foundation which is placed at a greater depth or transfers the loads to deep strata is called a deep foundation.
2. The depth of foundation	The depth of shallow foundation is generally approximately three meters or the depth of foundation is less than the footing width.	Greater than shallow foundation.
3. Cost	A shallow foundation is cheaper.	Deep foundations are generally more expensive than shallow foundations.
4. Feasibility	Shallow foundations are easier to construct.	The construction process of a deep foundation is more complex.
5. Mechanism of load transfer	Shallow foundations transfer loads mostly by end bearing.	Deep foundations rely both on end bearing and skin friction; with a few exceptions for example end bearing pile.
6. Advantages	Construction materials are available; less labour is required; construction procedure is simple and affordable.	Foundation can be provided at a greater depth; provides lateral support and resists uplift; effective when foundations at a shallow depth are not possible, has the ability to carry a huge load.
7. Disadvantages	Possibility of a settlement, usually applicable for lightweight structure; weak against lateral loads etc.	More expensive; requires skilled labourers; complex construction procedure; time-consuming and some types of deep foundations are not very flexible.
8. Types	Isolated foundation, strip foundation; mat foundation; combined foundation.	Pier foundation; pile foundation; caissons.

Source: Reese et al. (2006)

EPS dome houses require a shallow type of foundation and will therefore be cost effective and easy to construct. The simplicity of the foundation suggests a reduction in the construction time (Figure 4.5).

Figure 4.5: Strip footing for EPS dome house
Source: Japan Dome House Co. Ltd, 2018)

4.2.4 Construction method

All electrical and water connections in an EPS Dome house are installed in a similar way to a conventionally built house. The construction process of an EPS dome house follows the same sequence as that highlighted by Japan Dome House Co. Ltd (2018):

- Site is prepared by clearing any rubble and debris;
- Twelve 180 mm X 1 m strip footings are constructed which will serve as anchors to the EPS pieces;
- A 15 Mpa lightweight surface bed is constructed where tiles or carpet will be placed;
- The toothed joints of EPS piece walls are assembled and joined together by interlocking with each other through a strong adhesive and through bolts;
- The joints are further sealed with a waterproofing agent;
- Internal and external walls are plastered;
- Fittings such as windows and doors are installed; and
- House is painted.

A minimal labour force is required due to the interlocking nature of the EPS pieces. Less activity is observed on construction sites where EPS dome houses are being constructed since the largest components that are delivered are the

EPS pieces. Furthermore, less dust is generated into the atmosphere since excavations for the foundation are concluded at a very early stage in the construction process.

4.2.5 Durability of structure and expected maintenance

The only component that requires maintenance in an EPS dome house is the clad material and paintwork. Similar to most conventionally built walls, regular cleaning will be required at least annually for the EPS walls. Clean warm water is sufficient to remove dirt and to maintain a grime-free surface.

4.3 Conclusion

It can be noted from Chapter 4 that the use of EPS when used for house construction does not differ much from the process of conventionally constructed buildings. The largest distinction is the dome shaped roof instead of other commonly used roof types such as those shown in Figure 4.4. This chapter shows that the adoption of EPS will not signify a complete departure from the conventional building process. This is because the basic activities such as excavation for foundations as well as general finishings such as plastering and painting are still necessary.

CHAPTER 5: USES OF EXPANDED POLYSTYRENE AS WELL AS ITS ASSOCIATED COST IMPLICATIONS

5.1 Introduction

Sustainability is a relationship between many factors that are constantly changing including social, environmental and economic factors (Franklin and Blyton 2011).

There has been an increased focus on sustainability in infrastructure as a result of changing climatic conditions. Climate change therefore remains at the centre of the need for more sustainable alternative building products and processes (Dewick and Miozzo 2004).

The success of alternative building materials is dependent on key factors such as cost, technical input and material availability. The use of any alternative material should be on the basis of all three key factors as an inseparable collective. Reddy and Jagadish (2001) suggest that sustainability within the context of the building industry can therefore be defined as the careful articulation of material technologies which satisfy the felt needs of communities and the development needs of the population without adversely affecting the environment.

5.1.1 Expanded Polystyrene companies in South Africa

The Expanded Polystyrene Association of Southern Africa (EPSASA) represents three sectors of EPS in South Africa, namely equipment suppliers, raw material suppliers and manufacturers (Expanded Polystyrene Association of Southern Africa, 2018). The main aim of EPSASA is to promote the growth of the expanded polystyrene market in South Africa. According to the EPSASA (2018), seven companies are currently registered with the association (Table 5.1).

Table 5.1: Companies that are currently registered with the Expanded Polystyrene Association of Southern Africa

Company	Description
Automa Multi Styrene (Pty) Ltd	Automa Multi Styrene (Pty) Ltd is a market leader in EPS and Expanded Polypropylene (EPP) mouldings, EPS sheets and Polyphen fire resistant sheets. The services offered by Automa Multi Styrene (Pty) Ltd are manufacturing, product development and in-house computer-aided design and manufacturing (CAD–CAM) enabled tool room
Global Polymer Industries (Pty) Ltd	Global Polymer Industries (Pty) Ltd is located in Namibia. It is a manufacturer of innovative polymer products and in particular for the building and packaging sector. The services offered by Global Polymer Industries (Pty) Ltd are product design, development and manufacturing.
Isover	Isover's foam division manufactures industrial, commercial and domestic EPS products. These can range from refrigeration cold stores, roofs & ceilings and packaging. The services offered by Isover include thermal & acoustic design.
Isolite	The Isolite Group manufactures and distributes EPS products throughout Southern Africa. The services offered by Isolite are that of manufacturing.
ISO Moulders	Iso Moulders (Pty) Ltd is located in KwaZulu-Natal. Iso Moulders are manufactures of EPS products. The services offered by Iso Moulders are that of manufacturing.
Isowall	Isowall Southern Africa (Pty) Ltd. (ISA) has branches based in Cape Town, Isithebe, Ladysmith, Durban, Matsapha and Accra. The services offered by Isowall are that of manufacturing.
Technopol	Technopol is a producer of EPS products which it suppliers locally and also exports. Technopol manufactures bulk EPS block stock which further gets converted into numerous products. The services offered by Technopol are that of manufacturing.

Source: Expanded Polystyrene Association of Southern Africa (2018)

5.2 Industry use of Expanded Polystyrene

EPS is a very diverse material which has a wide range of uses; however, the public perception often only limits it to packaging. DS Smith (2018) lists at least 101 uses for EPS which are categorized as shown in Table 5.2.

Table 5.2: Miscellaneous industry uses of EPS

Industries	Examples of uses
Automotive	Bumper cores, void fillers and head rests
Protective packaging	Appliance packaging
Food	Hot & cold catering boxes, egg boxes and drink cups
Construction	Ceiling tiles, road construction and sound deadening
Consumer products	Surfboards, baby seats and shelving
Advanced shapes	3D lettering, signage and beanbags
Insulation and HVAC	Heating components, air-conditioning components and fridge components
Horticulture	Seed trays, plant pots and raised beds
Seating	Outdoor seating, aircraft seating and horse saddles
Safety and transport	Bike helmets, medical supports and chemical storage
Prototypes, hobbies and crafts	Block for prototypes & custom modelling, sculpting marquette's and model boats

5.3 Comparative study between existing systems

The performance of EPS will be benchmarked against three existing industry models, namely, Moladi, Khaya ReadyKit and Fischer Housing.

The following three principles of universal design as developed by Mace (1998) were considered in evaluating the effectiveness of the existing innovative housing designs in South Africa:

- Simple and intuitive- Is the design easily understandable?
- Low physical effort- Is the design simple to implement and construct?
- Size and space- Is the design of the appropriate specifications?

5.4 Assumptions made for comparative study

In order for the comparison between the various building models to be admissible, the following assumptions were made:

- Variations in price were not considered over the duration of the research;
- Soil conditions were assumed to be that of compacted sand;
- The cost of land is not included in the results; and
- Electrical and water services are not included in the results.

5.5 Comparison of costs

5.5.1 Moladi system

The Moladi system is a construction system that was founded in 1986 in South Africa. The objective of the system is to achieve rapid house construction by means of recyclable, re-usable and removable formwork moulds. Mortar fills the formwork to form the wall structures of the house. The formwork panels can be re-used up to 50 times therefore making the system cost effective as it can be repeatedly applied (Moladi 2018).

The Moladi construction system includes a raft foundation, superstructure, Moladi bonding agent, windows, doors, ceilings and a roof (Moladi 2018) (Figures 5.1 to 5.3). A complete Moladi unit costs R39,017.13 (Annexure A).

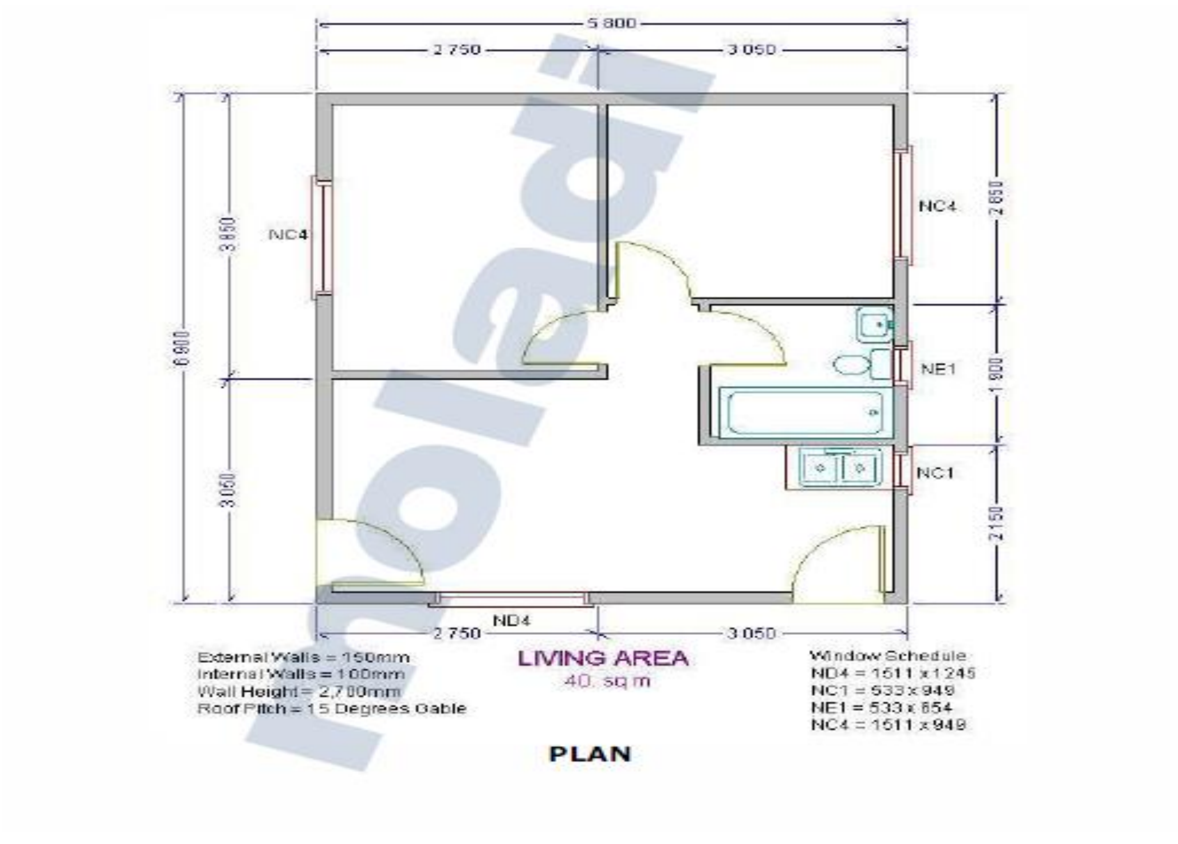

Figure 5.1: Plan view of a Moladi unit
Source: Moladi (2018)

Figure 5.2: Moladi formwork moulds
Source: Moladi (2018)

Figure 5.3: Newly constructed walls using Moladi formwork
Source: Moladi (2018)

5.5.2 Khaya ReadyKit system

The Khaya ReadyKit system was developed in 1993. It constitutes timber panels that are a standard width of 1 m. There are also 1.5 m and 2 m widths which are manufactured if required. Dried and cured Sap with dimensions of 114 mm x 38 mm is prepared to be 2500 mm high and either 1000 mm or 1500 mm wide. The timbers main role is to perform a structural function (ReadyKit Construction, 2018) (Figures 5.4 to 5.5).

A 40 m^2 pre-packaged 'kit' house costs R104 000.00 (Annexure B).

Figure 5.4: Khaya ReadyKit timber panels
Source: ReadyKit Construction (2018)

Figure 5.5: Complete house constructed using Khaya ReadyKit system
Source: ReadyKit Construction (2018)

5.5.3 Fischer Housing

Fischer Profile South Africa was founded in 1979. It consists of two models, namely; type 21 and type 40. Type 21 is a 21 m^2 one bedroomed house whereas type 40 is a 40 m^2 two bedroomed house. Both types have an open plan kitchen, lounge area as well as a bathroom. The standard width and height of the house are 2600 mm and 2850 mm. All the units of the house are supplied in knock-down condition, ready for assembly by the appropriate professionals on-site (Fischer Housing, 2018) (Figures 5.6 and 5.7).

The 40 m^2 unit costs R96,370.00 (Annexure C).

Figure 5.6: Complete Fischer housing unit
Source: Fischer Housing (2018)

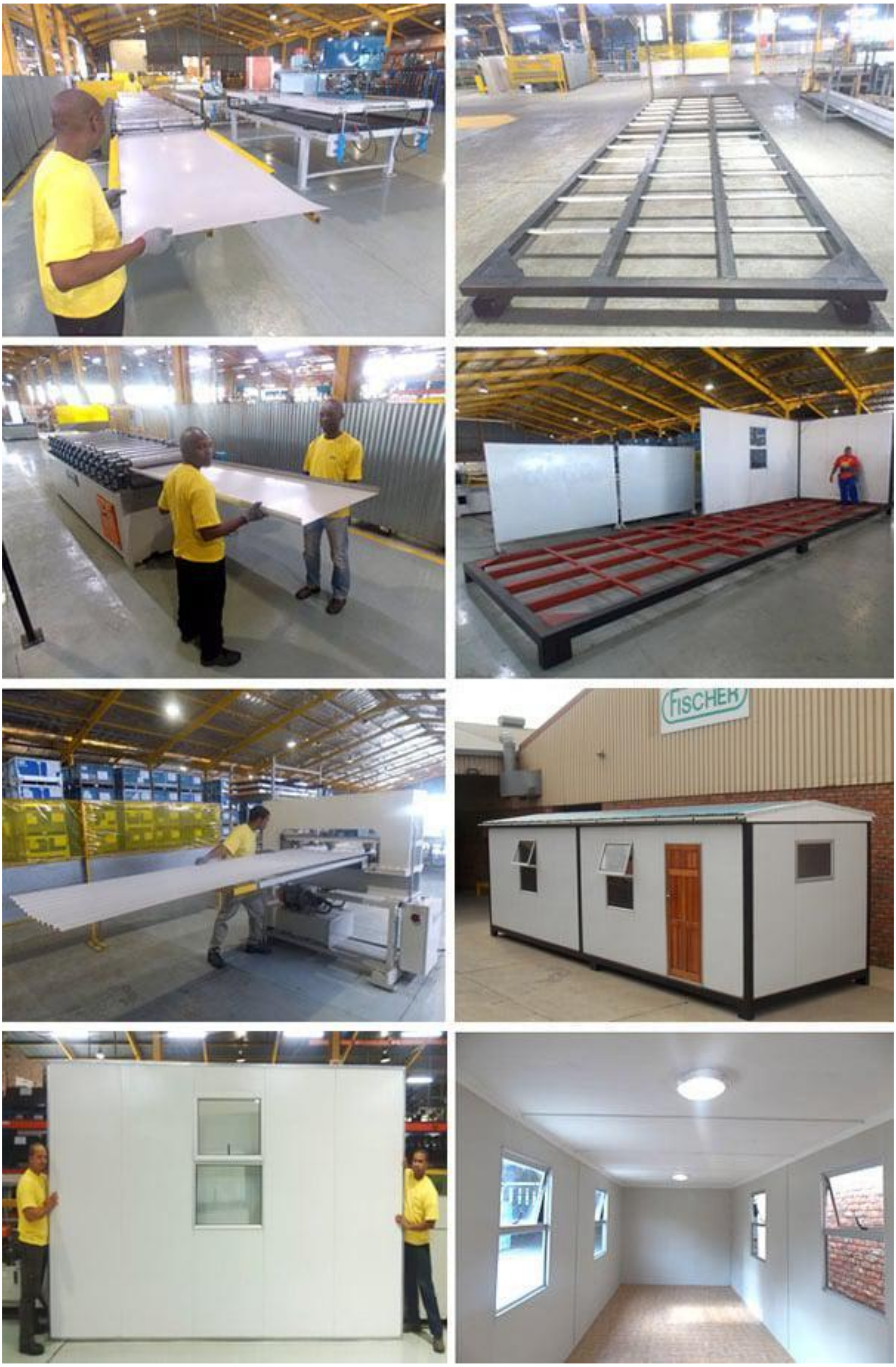

Figure 5.7: Assembly process of a Fischer housing unit
Source: Fischer Housing (2018)

5.6 Comparison of construction time

The construction times for each of the considered models are as follows:

- Moladi- One day (Moladi 2018)
- Khaya ReadyKit- Two days (ReadyKit Construction 2018)
- Fischer housing- One day (Fischer Housing 2018)
- EPS dome house- Seven days (Japan Dome House Co. Ltd 2018)

5.7 Quantifying environmental sustainability and wastage

Protection of the environment is fundamental in sustaining the quality of human life. Any possible adverse impact on the environment and on health is critical in selecting construction methods and materials that are environmentally friendly. It is therefore important to consider the various components that are required to make up each individual model.

5.7.1 Moladi

Moladi requires “one cubic metre of Moladi mortar (which consists of 1800kg or 0.720m^3 of local decomposed granite/river sand), 250kg of 42,5N Ordinary Portland Cement (OPC), 5 litres of moladiCHEM, a non-toxic, water based chemical cocktail as well as 200 litres of water” (Moladi 2018).

5.7.2 ReadyKit

The ReadyKit system requires polystyrene insulation boards and strengthening wire mesh, plaster sand as well as timber for roof trusses (ReadyKit Construction 2018).

5.7.3 Fischer building system

The Fischer building system consists of sections that are manufactured from coiled steel and Zincal produced on Fischer’s roll-forming machines (Fischer Housing 2018).

From the above it is evident that there are some environmental concerns with the above three models. For the Moladi system, the use of 200 litres of water, particularly in areas affected by drought, may be a challenge during mass production of the units. Timber used for roof trusses in the Readykit system fails to contribute to efforts aimed at tree preservation. Finally, the process of mining iron ore from the ground before it is smelted for use in the Fischer building system is a costly and energy intensive process and further depletes the earth's natural resources.

The major components needed to construct an EPS dome house are as follows:

- Water
- Sand
- 19 mm stone
- Two lengths of 23 m of R8 rebar for the foundation
- 125 m^3 of EPS

Detailed quantities can be seen in the Bill of Quantities (Annexure D).

5.8 Waste generation

According to the National Environmental Management Waste Act of 2008 (South Africa, 2009), waste is described as any substance that:

- Is excess, unwelcome, disallowed, castoff or abandoned;
- The producer has no additional use of for;
- Must be disposed of or treated; and
- Encompasses waste created by the medical, mining or other sectors.

The four most common types of waste in South Africa include "non-recyclable municipal waste (35 %), construction and demolition (C&D) waste (20 %), organic waste (13 %) and metals (13 %)" (Department of Environmental Affairs 2012). The contributions of both EPS as well as conventional materials such as concrete and masonry into the waste stream will be examined below.

a) EPS waste

EPS is 100 % recyclable (Rakhshan, Friess and Tajerzadeh 2013) and, according to the EPSASA (2006b), an EPS-related municipal solid waste stream will have:

- Paper and paper board (37.1 %);
- Glass (9.7 %);
- Metals (9.6 %);

- Plastics (6.9 %);
- Polystyrene foam (0.26 %) (Expanded Polystyrene);
- Rubber and leather (2.5 %);
- Textiles (2.1 %), wood (3.8 %);
- Food wastes (8.1 %);
- Garden refuge (17.9 %); and
- Miscellaneous organic waste (1.8 %).

The above indicates that EPS contributes minimally towards the filling up of landfills.

b) Concrete and masonry waste

Concrete along with bricks and asphalt contribute 23.3 % of waste in the general waste stream (Council for Scientific and Industrial Research 2014). Muigai, Alexander and Moyo (2013) stated that an average of 8.69 million m^3 (20.9 Mt) of ready-mix concrete was produced per year for the period 2005-2008 in South Africa. Muigai et al. (2013) further stated that “8.17 million m^3 (19.6 Mt) of concrete was used in the production of concrete products: paving blocks, roof tiles, masonry, floor slabs, retaining blocks and infrastructure products.” When compared to the contribution that EPS makes in the general waste stream, these are tremendous amounts of concrete which continue to advance the depletion of the earth’s resources.

5.9 Environmental impact of conventional homes

5.9.1 Environmental impact of concrete

The main concern with using cement and concrete for infrastructure development is the energy it consumes and the subsequent environmental impact that it makes on the environment. Cement production is one of the most energy intensive industrial manufacturing processes in the world (Schneider, Romer, Tschudin and Bolio 2011). Cement and concrete production generate considerable air-pollutant emissions (Schumacher, Domingo and Garreta 2004). Emissions include: sulphur dioxide (SO_2) and nitrous oxides (NO_x). SO_2 emissions (and to a lesser extent SO_3, sulphuric acid, and hydrogen sulphide) result from sulphur content of both the raw materials and the fuel (Babor, Plian and Judele 2009). In addition to air-pollution, another environmental impact of cement and concrete production is water pollution. Ragheb (2011) states that on a global scale "they [the cement industry] account for one-sixth of the world's freshwater withdrawals." There are also health concerns related to handling and working with concrete and cement. Wet concrete requires that the skin be protected from the high alkalinity of concrete (Babor et al. 2009).

5.9.2 Environmental impact of masonry

Masonry is often not perceived as an environmental threat and is usually a large part of "green building" strategies (Adedeji and Fa, 2012). However, mortar mixing and stone cutting can generate airborne particulate waste such as silica dust (Flanagan et al. 2010). According to the Department of Labour (2018), silica can be associated with fibrosis of the lungs (i.e. silicosis). It is therefore critical to take these concerns into account in the use of masonry.

5.10 Environmental impact of EPS Houses

EPS has a negligible impact on the environment in comparison to other pollutants (Rakhshan et al. 2013). For example, the energy source for the manufacture of EPS is steam (Doroudiani and Omidian 2010). The steam is produced in boilers through natural gas as fuel. The Isowall Group (2018) affirms that the amount of "water consumption used in the manufacture of EPS is very low as the water is reused continuously in the manufacturing process".

According to Kore (2014), "The European Manufacturers of Expanded Polystyrene (EUMEPS), estimates that for every litre of oil used to produce EPS insulation, 150 litres of oil is saved in heating costs over the lifetime of any constructed building."

Expanded polystyrene does not contain chlorofluorocarbons (CFCs) or hydro chlorofluorocarbons (HCFCs) when it is manufactured, and therefore does not damage the ozone layer (Eaves 2004).

One negative aspect of EPS is that it is non-biodegradable (Horvath 1994), which means that there is a risk that when it breaks apart it can be transported to various vicinities by the wind. Horvath (1994) further suggests that wherever EPS is blown by the wind, it can cause harm in the form of polluting water bodies or being eaten by animals. If EPS is eaten by animals or marine life, it is possible that it could be a potential hazard for humans who may consume these animal and marine products.

5.11 Cost and construction time of conventionally built houses

The construction time of a conventionally built house is dependent on numerous factors, including the accessibility of material and the location where the house is to be built. The construction process commonly lasts for a period of two weeks (Moladi Framework 2009). In 2014, according to the Department of Human Settlements (2014), the average construction cost of a conventionally built house was approximately R91,650.00 (R2,291.25 per square metre). Due to escalation, in 2016, Statistics South Africa (2016) reported that constructing a freestanding house per square metre had increased to approximately R5,932.00. This signifies an increase of 61 % in material costs in two years.

5.12 Comparative matrix

A comparative matrix was compiled based on three criteria, namely, construction feasibility, technical viability and legal feasibility. Details of the considered models against the proposed model of EPS dome houses are tabulated in Figure 5.8. The researcher has assigned percentages to the three categories as follows: legal feasibility has been assigned 35 % since all building models have to be sufficiently congruent with all statutory laws before any of its other qualities may be considered; technical viability has been assigned 40 % since although a model may meet all legal requirements, its success also hinges on the availability of its particular resources; construction feasibility has been assigned 25 % since it is only once the legal and technical characteristics of a housing model have been sufficiently analysed can the ease of construction can be considered.

Figure 5.8: Comparative matrix comparing EPS Dome, Moladi, Khaya Readykit and Fischer Housing

Characteristics	Wt. %	EPS Dome House	Moladi	Khaya Readykit	Fischer Housing
Construction feasibility An assessment of the ease to construct each solution based on whether any training is required prior to assembly.	25	No prior training is required to toothed joints of EPS dome pieces.	Training on the use of Moladi formwork is required.	Training on the assembly of the timber panels is required.	No prior training is required since the Fischer unit is prefabricated and is delivered in an assembled state.
Technical viability An assessment of the practicality of the solution and the environmental sensitivity of the solution.	40	Expanded Polystyrene is factory manufactured and is therefore readily available. Impact on the environment is negligible.	Moladi still makes use of reinforcing steel and the system is therefore not entirely environ-mentally friendly.	Khaya Readykit requires numerous panels of dried and cured timber. Timber is a scarce resource and the system is not entirely environ-mentally friendly.	Fischer housing low cost units are made of stainless steel and stainless steel is a green product since it is recyclable. Impact on the environment is negligible.
Legal Feasibility An assessment of how well the solution can be implemented within existing legal and contractual obligations.	35	Concept is compliant with all minimum requirements of legislation such as size and number of rooms.	Concept is compliant with all minimum requirements of legislation such as size and number of rooms.	Concept is compliant with all minimum requirements of legislation such as size and number of rooms.	Concept is compliant with all minimum requirements of legislation such as size and number of rooms.

5.13 Conclusion

The researcher considered each solutions complexity of design as discussed in this chapter as well as each component that is used in each solution's composition. By way of overall summary, the performance of each solution with regards to Ronald Mace's three principles of design (Mace, 1998), is presented in Figure 5.9.

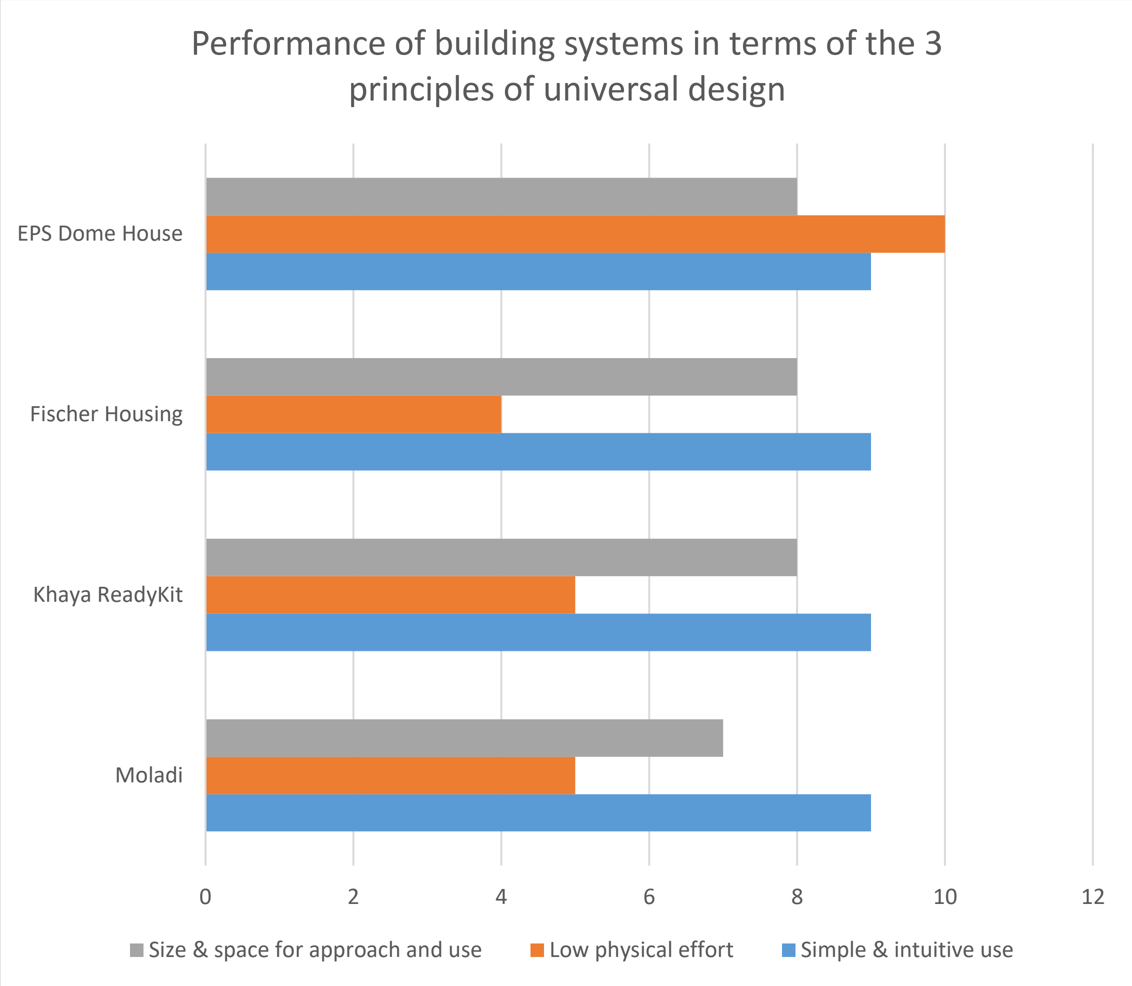

Figure 5.9: Performance of building systems in terms of the three principles of design

It has often been thought that achieving sustainability in construction is only limited to the consideration of cost, quality and time. This is a very limited approach to sustainability since construction sustainability should also consider degree of environmental impact and consumption of matter/energy (Hussin, Rahman and Memon 2013).

A cost analysis based on all the combined costs for each system is displayed as a pie chart in Figure 5.10. It is evident from this figure that EPS dome houses would be R33,582.00 more affordable than conventionally built houses.

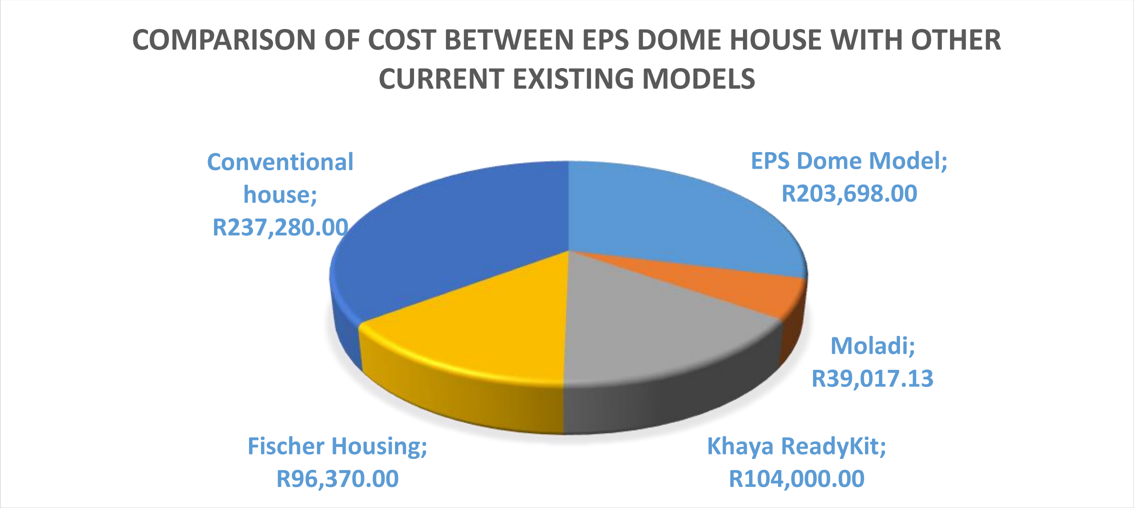

Figure 5.10: Comparison of cost between EPS dome house with other current existing models

CHAPTER 6: SUMMARY OF FINDINGS, CONCLUSION AND RECOMMENDATIONS

6.1 Findings

6.1.1 Live model findings

The highest recorded temperature, rainfall and wind speed in the location of the live model are shown in Table 6.1. Observations made on the model on the 3rd of February 2018 indicate that the high temperature of the previous day did not alter the structural composure of the model. Observations made on the 17th of March after heavy rains indicated no collapse due to water penetration. A photo taken on 11th of March 2018 indicates that the surface texture remained unaltered (Figure 3.10). Although water is only able to partly penetrate EPS due to the material properties of EPS, a large contributing factor of the minimal penetration is the shape of the model. Surface water run-off is maximized with a dome shape compared to a conventional box-shape. Wind speeds observed on the 2nd of February 2018 did not collapse the model as wind gusts flowed easily over the curvatures of the model; there is a lack of sufficient surface area for the wind to force itself against, therefore it flowed past the model to continue on its path.

Table 6.1: Highest recorded temperature, rainfall and wind speed

Date Recorded		
02 February 2018	Highest Temperature	36°C
02 February 2018	Highest Wind Speed	39km/hr
16 March 2018	Highest Rainfall	28mm

Since the live model was exposed to the natural environment for six months from February to July 2018, it experienced three out of the four seasons of the year (i.e. one month of Summer, three months of Autumn and two months of Winter). The live model would be plastered on the inside and outside when constructed for the purposes of inhabitancy, but it was a point of interest to study the material in its most natural state. An aspect which can be extrapolated to better understand what would happen in the structure of an EPS body shell for a second six months would be its discoloration potential. The sun emits ultraviolet or UV light, and any change of the surface colour of any material indicates that a chemical reaction is taking place. The discoloration of the live model was assessed over the six-month period and extrapolated over the remaining six months. Figure 6.1 shows that from the first month through to the sixth month there was a continuous trend of discoloration in the live model. This suggests there would be a continuous process in which the live model absorbs water during rainy days and dries during sunny days. The EPS live model went through the six-month period having undergone varying levels of wetting and drying but did not show any signs of deformation in its structure. This emphasises the resilience of a dome shaped structure in response to naturally varying levels of heat and rain. The discoloration of the EPS and indicative wetting and drying would all be minimized through appropriate cladding material such as a waterproofing coat, plaster coat, and paint coat.

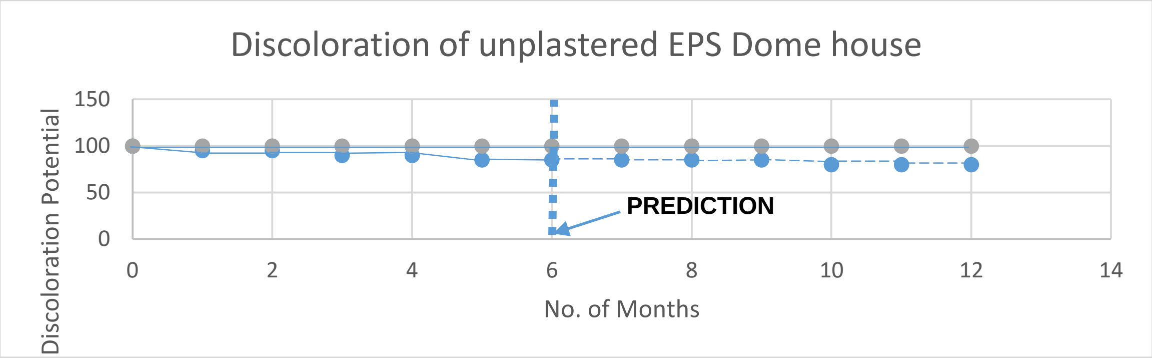

Figure 6.1: Discoloration potential of EPS

The live model demonstrates the viability of EPS dome shaped houses. However, the hot-wire system cannot be used for mass production of EPS dome houses due to the inconsistency and inaccuracy with which each EPS component is carved.

The live model also demonstrated that a conservative density of EPS can satisfactorily withstand environmental elements. However, mortar mix cladding is advised in order to protect against discolouration of the EPS since discoloration was noted over the six-month observation. The advantages of a dome shaped house are that it can provide adequate protection to the contents and users of the house without any risk of collapse, as was observed throughout the six-month period.

6.1.2 Laboratory test findings

6.1.2.1 Microscopic analyses

Figures 6.2 to 6.7 show the results of microscopic analyses.

Output of instrument:

- **Analysis of 15 kg/m^3**

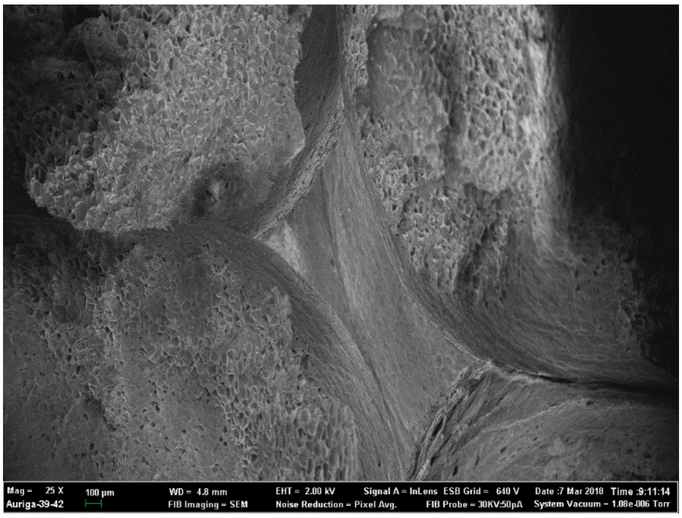

Figure 6.2: Extent of void in 15 kg/m^3 EPS

- **Analysis of 15 kg/m^3**

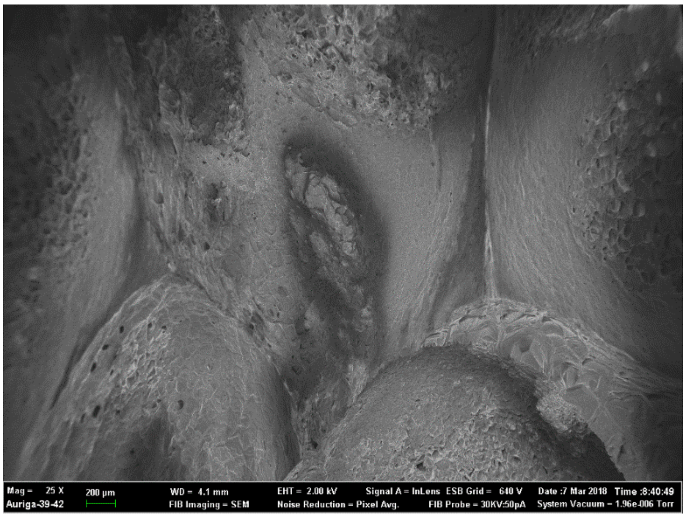

Figure 6.3: Configuration of EPS beads in 15 kg/m3 density sample

➢ Analysis of 20 kg/m^3

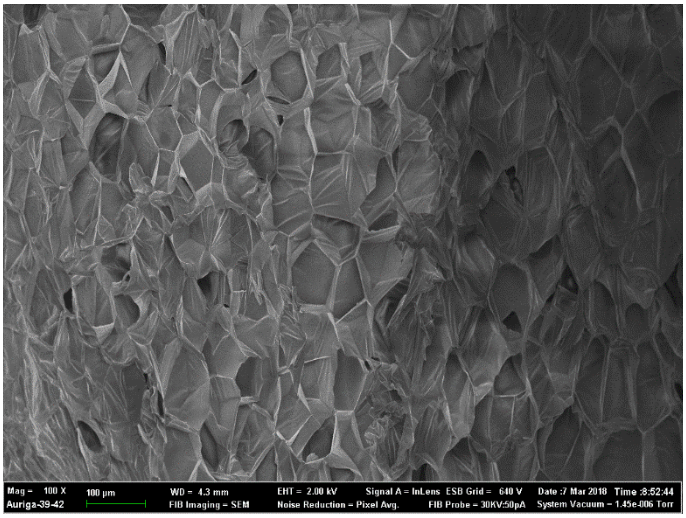

Figure 6.4: Configuration of EPS beads in 20 kg/m^3 density sample

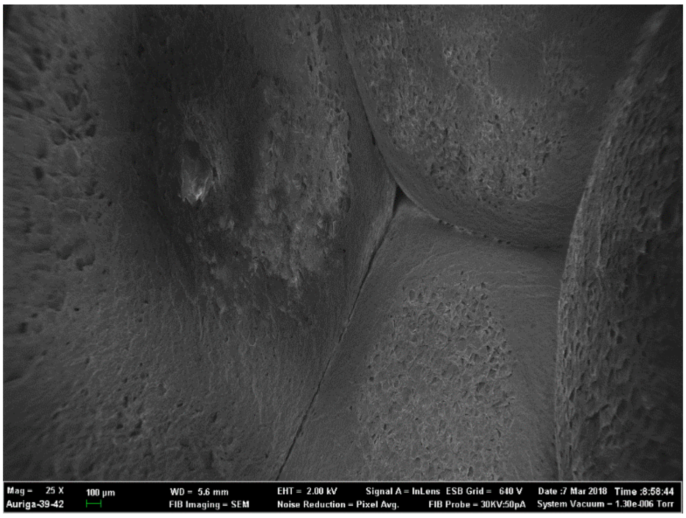

Figure 6.5: Voids in EPS sample of 20 kg/m3

➢ **Analysis of 30 kg/m^3**

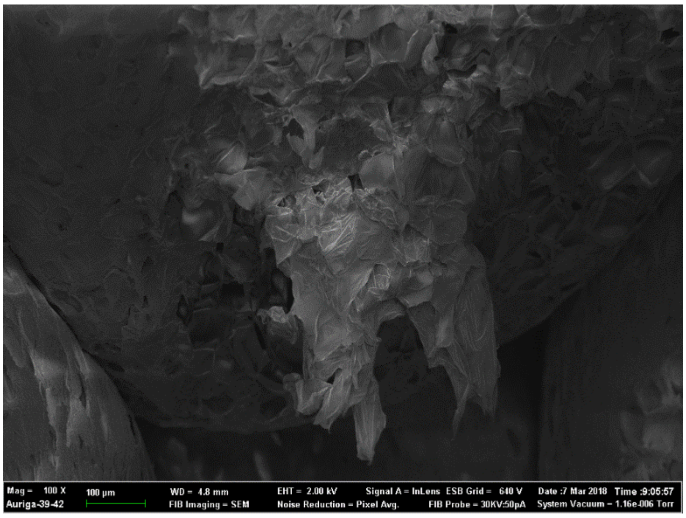

Figure 6.6: Ruptured EPS beads in sample of 30 kg/m^3

Figure 6.7: Voids which exist in 30 kg/m^3 sample

The appearance of EPS samples is such that it does not appear that any voids would be found in its microstructure. However, Figures 6.2, 6.5 and 6.7 depict the extent of the voids in each different density category. Voids are an immediate potential avenue for water ingress. From Figure 6.6 it is also evident that EPS beads have the potential to rupture as they converge in the process of increasing their density. Figure 6.6 is a sample of 30 kg/m^3 EPS where it is evident that beads have ruptured. This occurrence was not observed in densities of 15 kg/m^3 and 20 kg/m^3. Contrary to what is commonly believed regarding the density of materials, the use of lower densities of EPS has certain merits, the greatest being the retention of the circular composition of the beads. The rupture of individual beads in in the 30 kg/m^3 density EPS reveals that there is a risk of such occurrences which might lead to a compromise in strength and reliability in performance.

6.1.2.2 Compressive strength test

The Instron 5966 display unit was used to plot compressive stress versus compressive strain graphs for all processed samples for each density type (Figures 6.8 to 6.10 and Tables 6.2 to 6.4).

- **Density of 15 kg/m^3**

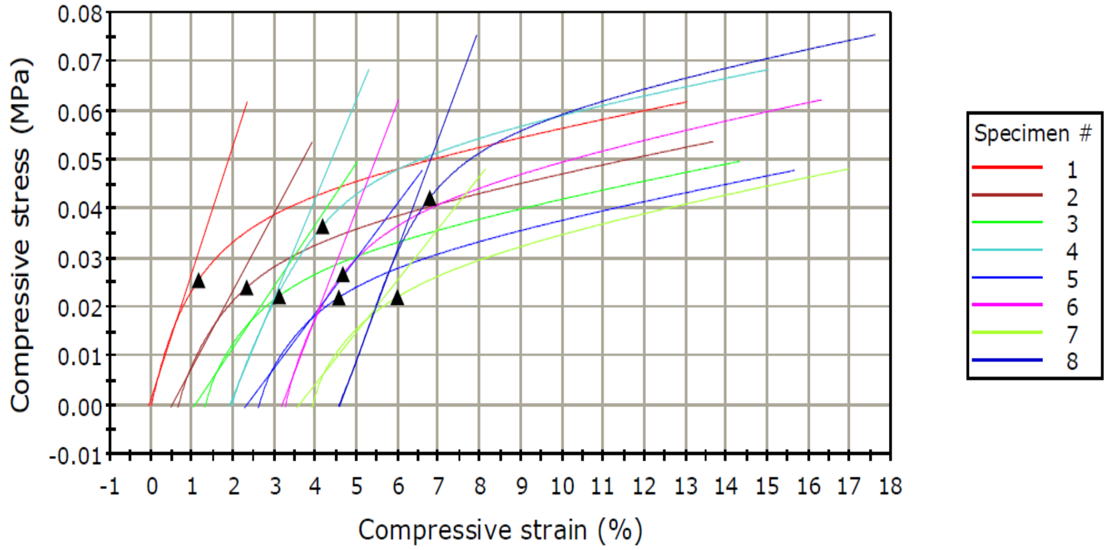

Figure 6.8: Compressive stress vs strain graph for 15 kg/m^3

Table 6.2: Modulus results for 15 kg/m³

	Modulus (E-modulus) (MPa)	Compressive stress at Tensile Strength (MPa)	Compressive stress at Yield (Zero Slope) (MPa)
1	2.57653	0.06176	0.02556
2	1.56708	0.05365	0.02405
3	1.25471	0.04966	0.02229
4	2.00629	0.06831	0.03654
5	1.11647	0.04783	0.02197
6	2.19101	0.06216	0.02686
7	1.05562	0.04814	0.02210
8	2.26020	0.07539	0.04228
Mean	1.75349	0.05836	0.02771
Standard Deviation	0.58136	0.01020	0.00758

- **Density of 20 kg/m³**

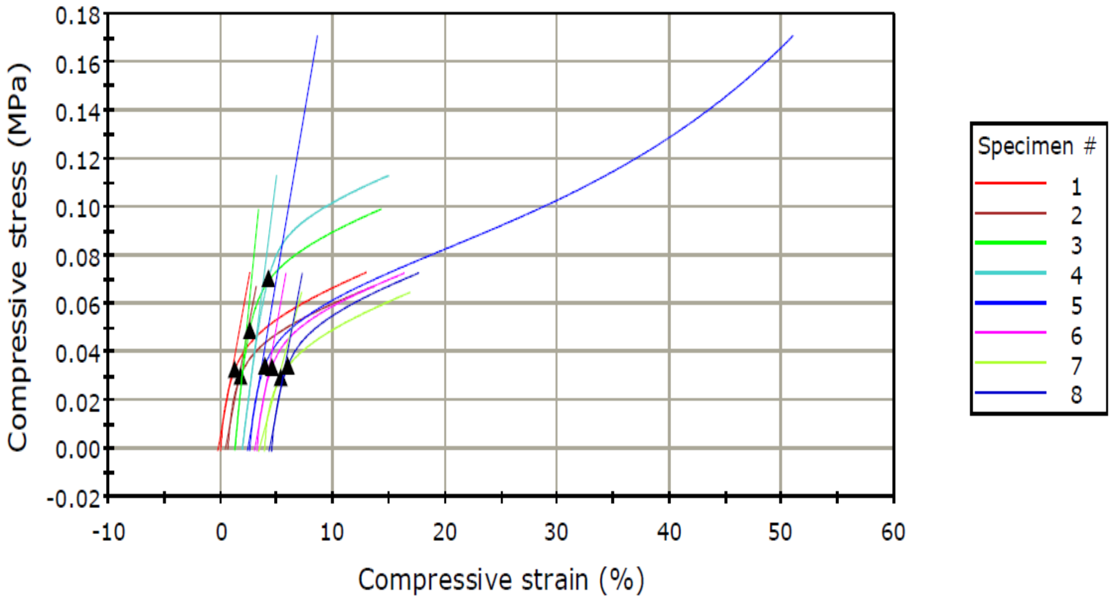

Figure 6.9: Compressive stress vs strain graph for 20 kg/m³

Table 6.3: Modulus results for 20 kg/m³

	Modulus (E-modulus) (MPa)	Compressive stress at Tensile Strength (MPa)	Compressive stress at Yield (Zero Slope) (MPa)
1	2.61037	0.07299	0.03291
2	2.41700	0.06720	0.03023
3	4.63297	0.09914	0.04890
4	3.66630	0.11300	0.07061
5	2.76923	0.17075	0.03436
6	2.64164	0.07259	0.03380
7	1.71743	0.06476	0.02956
8	2.49446	0.07268	0.03433
Mean	2.86868	0.09164	0.03934
Standard Deviation	0.89015	0.03618	0.01399

- **Density of 30 kg/m³**

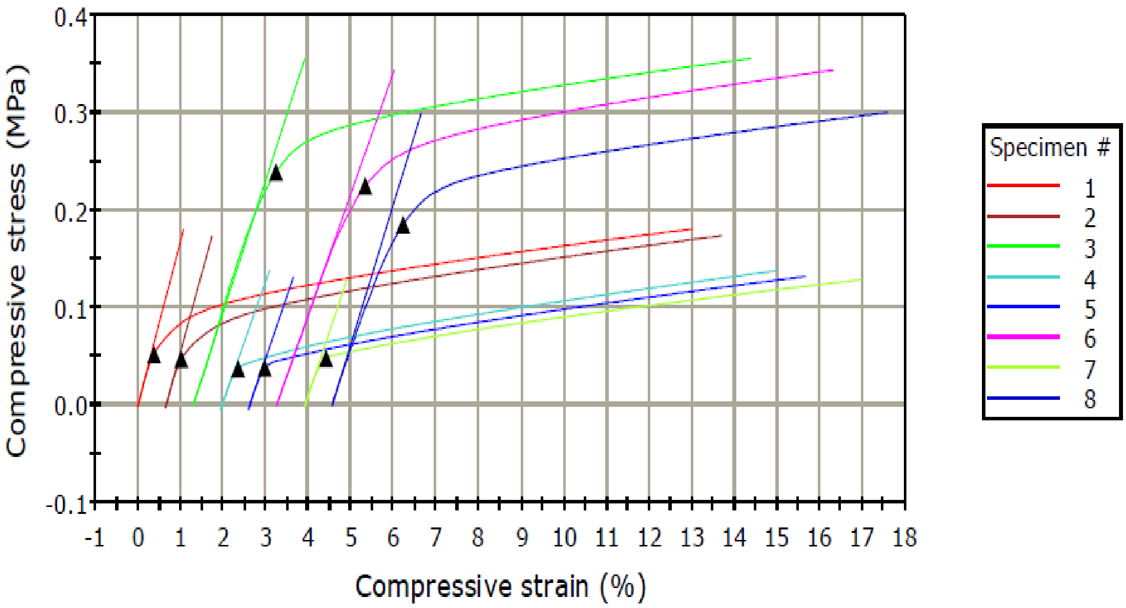

Figure 6.10: Compressive stress vs strain graph for 30 kg/m³

Table 6.4: Modulus results for 30 kg/m^3

	Modulus (E-modulus) (MPa)	Compressive stress at Tensile Strength (MPa)	Compressive stress at Yield (Zero Slope) (MPa)
1	17.00000	0.18057	0.05188
2	16.24066	0.17364	0.04752
3	13.58269	0.35513	0.23854
4	12.40905	0.13778	0.03734
5	12.80508	0.13195	0.03819
6	12.45292	0.34333	0.22426
7	13.13191	0.12858	0.04816
8	14.29810	0.29986	0.18518
Mean	13.99005	0.21885	0.10889
Standard Deviation	1.74801	0.09740	0.09005

From the eight specimens for each different density, the three most comparable results from each were considered (Tables 6.5 to 6.7).

Table 6.5: Modulus for density of 15 kg/m^3

	Modulus (E-modulus) (MPa)	Compressive stress at Tensile Strength (MPa)	Compressive stress at Yield (Zero Slope) (MPa)
1	1.25471	0.04966	0.02229
2	1.11647	0.04783	0.02197
3	1.05562	0.04814	0.02210
Mean	1.14226	0.04854	0.02212

Table 6.6: Modulus for density of 20 kg/m^3

	Modulus (E-modulus) (MPa)	Compressive stress at Tensile Strength (MPa)	Compressive stress at Yield (Zero Slope) (MPa)
1	2.61037	0.07299	0.03291
2	2.41700	0.06720	0.03023
3	2.49446	0.07268	0.03433
Mean	2.50727	0.07096	0.03249

Table 6.7: Modulus for density of 30 kg/m^3

	Modulus (E-modulus) (MPa)	Compressive stress at Tensile Strength (MPa)	Compressive stress at Yield (Zero Slope) (MPa)
1	12.40905	0.13778	0.03734
2	12.80508	0.13195	0.03819
3	12.45292	0.34333	0.22426
Mean	12.55568	0.20435	0.09993

Figure 6.11 shows the compression strength investigation of clay bricks (Shodhganga 2013).

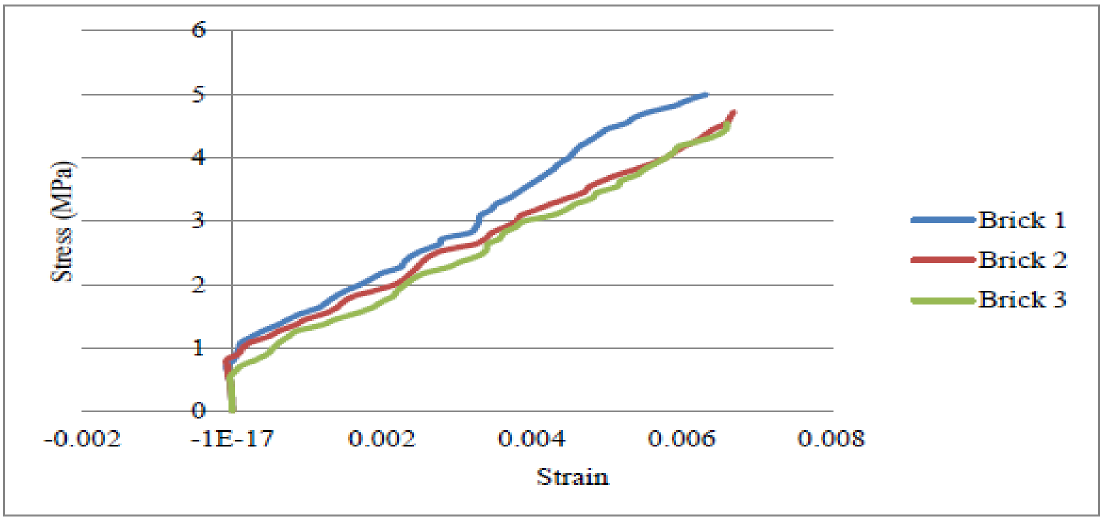

Figure 6.11: Compression test results for clay bricks
Source: Shodhganga (2013)

Shodhganga (2013) states that the modulus of elasticity for the three clay brick samples considered during the investigation was “600.6 MPa, 559.2 MPa and 574.2 MPa”. This shows that the modulus of conventional materials such as clay bricks is significantly higher than the modulus of standard grade EPS. The recommended thickness for construction of EPS dome houses using modified EPS is 17.5 cm, but from the compressive strength test it is evident that the thickness of EPS dome houses using standard grade EPS would need to be extended to at least 25 cm in order to increase the compressive strength of the dwelling.

6.1.2.3 Flexural test

The Instron 5966 display unit was used to plot flexural stress versus flexural strain graphs for all the processed samples for each density type (Figures 6.12 to 6.14 and Tables 6.8 to 6.10.

- **Density of 15 kg/m³**

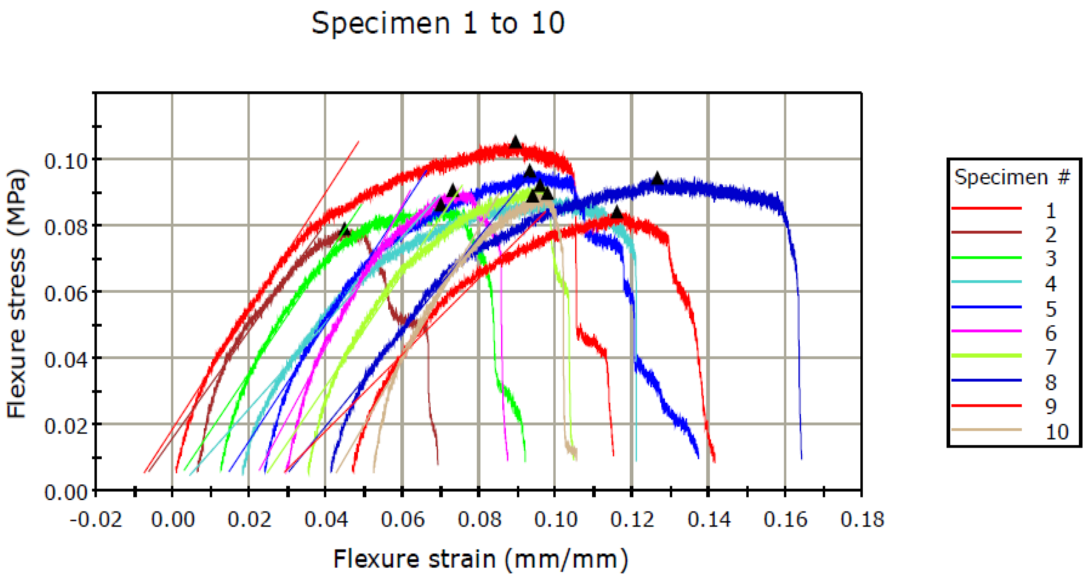

Figure 6.12: Flexural stress vs flexural strain graph for density of 15 kg/m³

Table 6.8: Modulus for density of 15 kg/m³

Thickness (mm)	Width (mm)	Modulus (E-modulus) (MPa)	Flexure stress at Yield (Zero Slope) (MPa)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)
10.00000	40.00000	1.78454	0.10541	0.08947	0.10541
10.00000	40.00000	1.62018	0.07910	0.03919	0.07910
10.00000	40.00000	1.73276	0.08644	0.05858	0.08644
10.00000	40.00000	1.29497	0.08919	0.07685	0.08919
10.00000	40.00000	1.76062	0.09664	0.07044	0.09664
10.00000	40.00000	2.14485	0.09083	0.04469	0.09083
10.00000	40.00000	1.70844	0.09235	0.06172	0.09235
10.00000	40.00000	1.42463	0.09450	0.09628	0.09487
10.00000	40.00000	1.15230	0.08421	0.07027	0.08421
10.00000	40.00000	1.97986	0.08989	0.04647	0.08989

- **Density of 20 kg/m³**

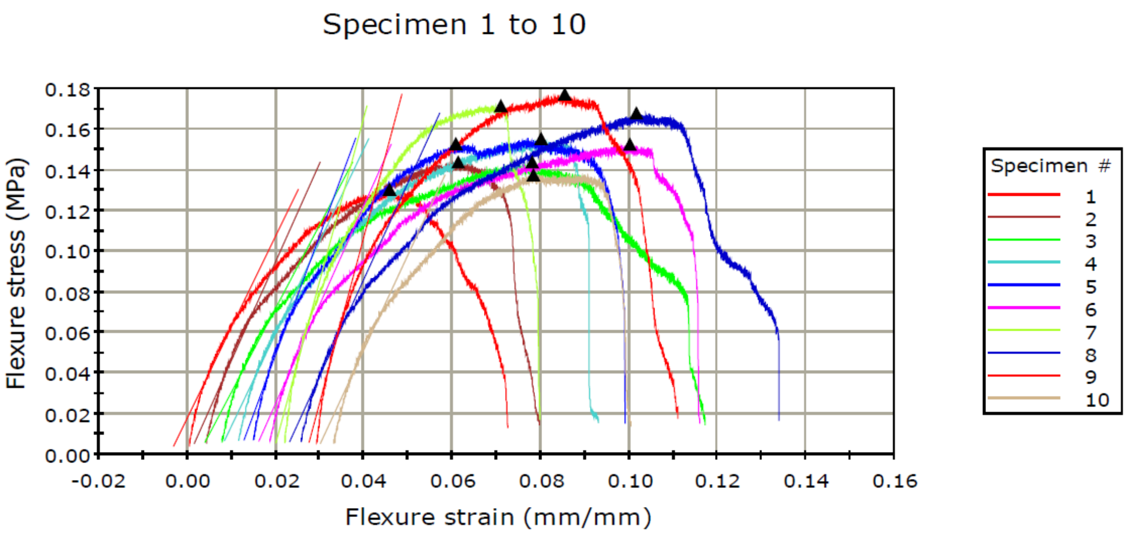

Figure 6.13: Flexural stress vs flexural strain graph for density of 20 kg/m³

Table 6.9: Modulus for density of 20 kg/m³

Thickness (mm)	Width (mm)	Modulus (E-modulus) (MPa)	Flexure stress at Yield (Zero Slope) (MPa)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)
10.00000	40.00000	4.47752	0.13044	0.04582	0.13044
10.00000	40.00000	4.86656	0.14386	0.05774	0.14386
10.00000	40.00000	4.12392	0.14395	0.07086	0.14395
10.00000	40.00000	4.54843	0.15528	0.06926	0.15528
10.00000	40.00000	5.86103	0.15296	0.06266	0.15557
10.00000	40.00000	4.87139	0.15260	0.08209	0.15260
10.00000	40.00000	8.04629	0.17141	0.04931	0.17141
10.00000	40.00000	4.75709	0.16807	0.07642	0.16807
10.00000	40.00000	8.13434	0.17717	0.05653	0.17717
10.00000	40.00000	4.66835	0.13771	0.04596	0.13771

- **Density of 30 kg/m³**

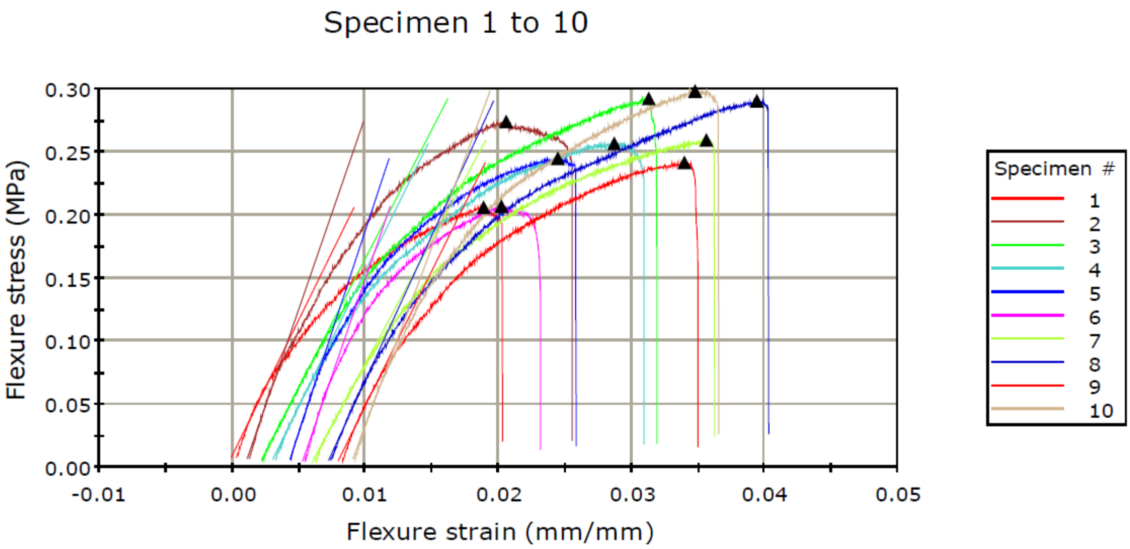

Figure 6.14: Flexural stress vs flexural strain graph for density of 30 kg/m³

Table 6.10: Modulus for density of 30 kg/m³

Thickness (mm)	Width (mm)	Modulus (E-modulus) (MPa)	Flexure stress at Yield (Zero Slope) (MPa)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)
10.00000	40.00000	21.51992	0.20609	0.01888	0.20609
10.00000	40.00000	30.68129	0.27415	0.01958	0.27415
10.00000	40.00000	20.48518	0.29203	0.02927	0.29203
10.00000	40.00000	21.48149	0.25689	0.02569	0.25689
10.00000	40.00000	31.94205	0.24480	0.02047	0.24480
10.00000	40.00000	30.73390	0.20692	0.01523	0.20692
10.00000	40.00000	19.53697	0.25933	0.02961	0.25933
10.00000	40.00000	23.00018	0.29047	0.03241	0.29047
10.00000	40.00000	21.36165	0.24152	0.02597	0.24152
10.00000	40.00000	28.25827	0.29830	0.02578	0.29830

The standard requires that at least four specimens be tested, therefore, only four output results of a similar nature were considered (Tables 6.11 to 6.13).

➢ Density of 15 kg/m^3

Table 6.11: Reduced sample size for 15 kg/m^3

Thickness (mm)	Width (mm)	Modulus (E-modulus) (MPa)	Flexure stress at Yield (Zero Slope) (MPa)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)
10.00000	40.00000	1.78454	0.10541	0.08947	0.10541
10.00000	40.00000	1.73276	0.08644	0.05858	0.08644
10.00000	40.00000	1.76062	0.09664	0.07044	0.09664
10.00000	40.00000	1.70844	0.09235	0.06172	0.09235

➢ Density of 20 kg/m^3

Table 6.12: Reduced sample size for 20 kg/m^3

Thickness (mm)	Width (mm)	Modulus (E-modulus) (MPa)	Flexure stress at Yield (Zero Slope) (MPa)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)
10.00000	40.00000	4.86656	0.14386	0.05774	0.14386
10.00000	40.00000	4.87139	0.15260	0.08209	0.15260
10.00000	40.00000	4.75709	0.16807	0.07642	0.16807
10.00000	40.00000	4.66835	0.13771	0.04596	0.13771

➢ Density of 30 kg/m^3

Table 6.13: Reduced sample size for 30 kg/m^3

Thickness (mm)	Width (mm)	Modulus (E-modulus) (MPa)	Flexure stress at Yield (Zero Slope) (MPa)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)
10.00000	40.00000	21.51992	0.20609	0.01888	0.20609
10.00000	40.00000	20.48518	0.29203	0.02927	0.29203
10.00000	40.00000	21.48149	0.25689	0.02569	0.25689
10.00000	40.00000	21.36165	0.24152	0.02597	0.24152

The differences in the modulus of rupture from a higher density to a lower density was significantly large. Difference from the lowest modulus of 30 kg/m^3 to the lowest modulus of 20 kg/m^3 was 15.81683 Mpa. Differences between the lowest modulus of 20 kg/m^3 to 15 kg/m^3 was 2.95991 Mpa. A study conducted in

Maharashtra in India determined the modulus of rupture for clay bricks (Shodhganga 2013) (Figure 6.15).

Figure 6.15: Clay bricks set-up on flexural instrument
Source: Shodhganga (2013)

The modulus of rupture was calculated using the following formula:

$$fr = \frac{(1.5 * P * l)}{(b * t2)}$$

(Equation 6.1 Modulus of Rupture)

Where,

fr = Modulus of Rupture

P = Maximum Load taken by Specimen

l = Span of Member

b = Width of Specimen

t = Thickness of Specimen

The average value of the modulus of rupture calculated using the above formula was 1.185 MPa (Shodhganga 2013). The average value of the modulus of rupture for the lowest density of EPS considered during the above tests was 1.74659 MPa. This demonstrates that the modulus of rupture of EPS is comparable to that of conventional materials such as clay bricks.

6.1.2.4 Thermal resistance test

The Thermo-gravitational monitor was used to plot the weight (%) versus temperature (°C) graphs for the varying densities subjected to heat (Figures 6.16 and 6.17 and Table 6.14).

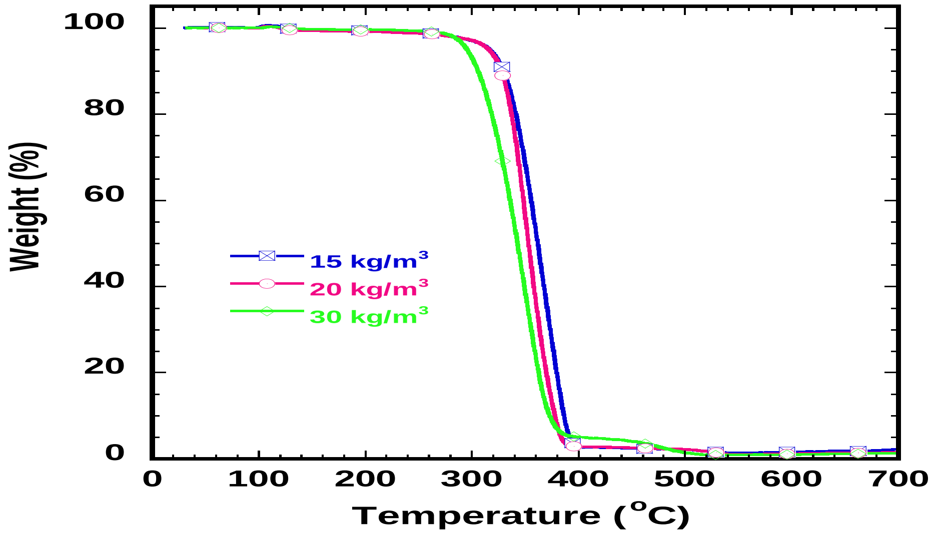

Figure 6.16: Weight vs temperature graph of EPS samples of different densities when subjected to heat

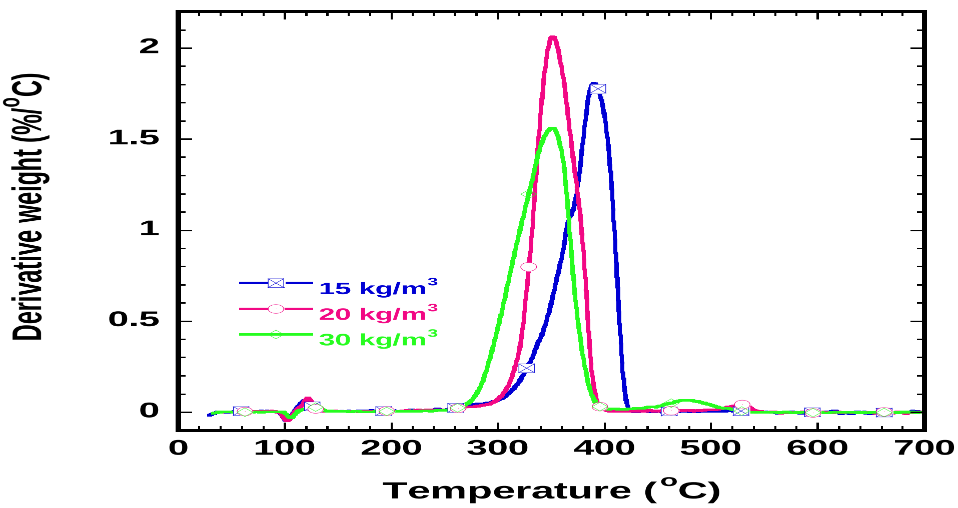

Figure 6.17: Derivative weight vs temperature graph of EPS samples of different densities

Table 6.14: Average degradation of EPS for various densities

	Density (kg/m^3)		
	15	20	30
Run	**Temperature (°C)**		
1st	366,40	356,41	340,50
2nd	398,72	342,98	345,47
3rd	390,30	351,79	351,17
Average degradation	384,14	350,39	345,71

It is evident from the above figures that as the density increases, the maximum degradation decreases (Annexure E). This is contrary to what would naturally be expected. A natural assumption would be that the higher the density, the lower the susceptibility to being consumed by fire. Fires range up to values in excess of 1000 °C (Doran and Cather 2013). The above degradation values suggest that the natural face of EPS would need to be reinforced with a clad layer on the outside surface in order to increase its resistance to heat, and also to off-set its degradation value to a greater value. Data from the thermogravimetric analysis shows that if EPS is exposed to temperatures in excess of 300 °C it begins to soften and melt. However, even as EPS burns, it does not present a severe fire hazard since the toxicity of EPS is significantly less than that of other frequently used building materials (Expanded Polystyrene Association of Southern Africa, 2018).

6.1.2.5 Water absorption test

The percentages of the water absorbed for each sample tested are presented in Tables 6.15, 6.17 and 6.19.

Table 6.15: Water absorption results for density of 15 kg/m^3

15 kg/m^3			
	Sample 1	**Sample 2**	**Sample 3**
Before (mg)	1788,74	1791,72	1740,87
After (mg)	4231	4483	4387
Percentage (%)	136,5352	150,2065	152,0004

Table 6.16: Standard deviation for density of 15 kg/m^3

Average Value (%)	**Standard Deviation**
146,2473856	8,458679

Table 6.17: Water absorption results for density of 20 kg/m^3

20 kg/m^3			
	Sample 1	**Sample 2**	**Sample 3**
Before (mg)	2247,74	2136,6	2221,26
After (mg)	2919	2831	2946
Percentage (%)	29,86377	32,50023	32,62743

Table 6.18: Standard deviation for density of 20 kg/m^3

Average Value	**Standard Deviation**
31,66381 (%)	1,560175

Table 6.19: Water absorption results for density of 30 kg/m^3

30 kg/m^3			
	Sample 1	**Sample 2**	**Sample 3**
Before (mg)	5176,39	5179,59	4998,25
After (mg)	6341	6423	6174
Percentage (%)	22,4985	24,00595	23,52323

Table 6.20: Standard deviation for density of 30 kg/m^3

Average Value	Standard Deviation
23,34256 (%)	0,769797

Padade and Mandal (2012) conducted a similar investigation using EPS and found the following water absorption average percentages for samples with densities of 12 kg/m^3, 15 kg/m^3 and 20kg/m^3 (Table 6.21).

Table 6.21: Water absorption results for densities of 12 kg/m^3, 15 kg/m^3 and 20 kg/m^3

Densities (kg/m^3)	Percentages (%)
12	4.41
15	3.6
20	2.88

Source: Padade and Mandel (2012)

Vėjelis and Vaitkus (2006) further demonstrated that the water absorption of EPS continues to decrease as the density increases (Figure 6.18). This is consistent with the study observations made during the microscopic analysis. Such detail is encouraging because through the analysis of short-term absorption data, it is possible to affirm that EPS can sufficiently protect against water ingress.

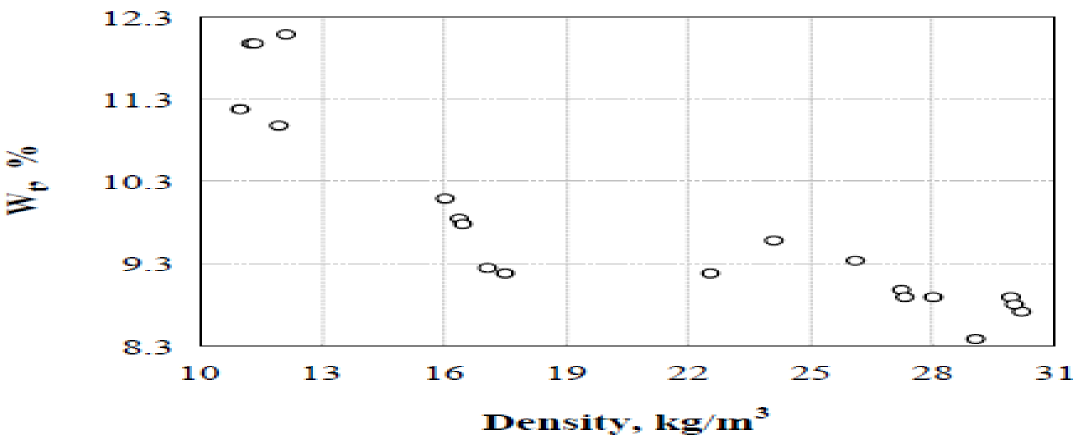

Figure 6.18: Scatter graph of how water absorption of EPS continues to decrease as the density increases
Source: Gnip et al. (2004)

According to Shodhganga (2013), the average water absorption for clay bricks is 16.16 %. The lowest water absorption for 30 kg/m^3 of EPS was recorded as 22.4985 %, this implies that the water absorption characteristics of EPS are comparable to that of other construction materials.

6.2 Recommendations for future research

- It will be prudent in future research related to EPS to consider investigating the social acceptance of structures such as dome shapes. Social acceptance surveys are important as they provide a gauge of the community's views on any arising issue.

- Alternative materials such as bamboo have been found to have high tensile strength properties and are currently being used by various countries to create shelter, furniture as well as musical instruments (Jain, Kumar and Jindal 1992). Bamboo is light weight and is fast growing. Future research should therefore consider how materials such as bamboo can be incorporated in the use of EPS products in low-cost housing. The objective would be to further investigate an alternative to concrete and masonry construction, but also to strengthen EPS's tensile properties.

6.3 Conclusion

6.3.1 Conclusion regarding the strength qualities of EPS

The investigation into the structural suitability of standard grade EPS as an innovative building construction material has shown that it is feasible to use standard grade EPS in the construction of dome house facilities. Flexural strength tests conducted on EPS revealed that the modulus of rupture for EPS is comparable to that of conventional materials such as masonry. Additionally, observations of the constructed EPS model showed that the advantage that dome structures have over conventionally shaped houses is resilience even in unfavourable weather conditions.

6.3.2 Conclusion regarding the construction methodology of EPS dome houses

This study has shown that EPS dome houses can be constructed through a change in construction method (i.e. hot-wire tool) as opposed to the use of intricate commercial moulding equipment. However, individually carving the dome pieces with a hot-wire tool would not meet the required efficiency levels of delivery as required by the current existing housing demand. Although carving

EPS dome house components with a hot-wire tool would not be ideal in terms of efficiency, it would still be a highly beneficial option due to the cost savings that would be made when compared to the use of conventional building models.

6.3.3 Conclusion relative to housing policies in South Africa

There is a need for national government in South Africa to develop a new policy regarding housing assistance. The new policy should have an emphasis on government's influence on the price mechanisms for all major building materials. The new policy must also emphasise a much-needed shift in focus from conventional housing models to alternative models such as EPS dome houses for the purposes of promoting environmentally friendly and economically sustainable communities.

6.3.4 Key findings

- When standard grade EPS is moulded to form a dome house, it manifests similar performance qualities to commercially modified EPS. This is highly beneficial since commercially modified EPS is much more expensive than standard grade EPS.
- In the midst of the stagnant housing backlog in South Africa, EPS dome houses would be of benefit since they are more affordable than conventionally built houses.
- When put side by side with other alternative building models available in the South African market, EPS has been shown to have certain advantages such as extreme ease of assembly since no prior training is required for anyone to erect an EPS dome house.
- Environmentally, it was found that the advantage that EPS dome houses have over other building models is that their use of the earth's natural resources is minimal. This is due to the bulk of the structure being composed of EPS.

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ANNEXURES

ANNEXURE A: Preliminary cost summary of Moladi

PRELIMINARY COST SUMMARY

moladi
building communities

REF: TJ40
moladi Generic Costing

Amortisation: 50 UNITS

To erect **moladi** - 12 labourers at 4 hours
To fill **moladi** - 11 labourers for 2 hours (using buckets to pour the mortar mix – site mix)
A pump can also be used (2 hours) reducing labour and time
To strip **moladi** - 8 labourers for 2 hours

* 8 hour production cycle

Based on these inputs, an average cost per square metre of 150 mm External wall will cost R217.19.
Based on these inputs, an average cost per square metre of 100 mm Internal wall will cost R149.11.

The complete shell/superstructure for the 40 square metre unit is calculated at R 25, 074.30 including the amortized amount of R 6, 040.38 for the cost/use of **moladi** formwork

REF:TJ 40.0 TJ40 - moladi Generic Costing

SUMMARY

5-Oct-17	%	COST PER M² FLOOR AREA	LABOUR	MATERIAL		TOTAL
RAFT FOUNDATION	32.9%	320.31	1,090.31	11,728.45		12,818.76
SUPERSTRUCTURE	48.8%	475.61	2,923.57	16,110.35		19,033.92
moladi	15.5%	150.93		6,040.38		6,040.38
WINDOWS	1.0%	9.43	-	377.39		377.39
DOORS	0.6%	5.50	-	220.28		220.28
ROOF	0.1%	0.66	-	26.40		26.40
CEILING	0.0%	0.00	-	-		-
PLUMBING	0.0%	0.00	-	-		-
ELECTRICITY	0.0%	0.00	-	-		-
PAINT	0.0%	0.00	-	-		-
PRELIMINARY AND GENERAL EXPENSES	0.0%	0.00	-			-
ENGINEERING FEE	1.3%	12.49	500.00			500.00
LABOUR COST	11.6%	112.79	4,513.88			
MATERIAL COST	88.4%	862.15		34,503.24		
TOTAL	100%	974.94				39,017.13
SUGGESTED CONTRACTORS PROFIT	0%	0.00				-
SUB TOTAL		974.94 RAND			RAND	39,017.13

PLEASE NOTE: These ABOVE items (if specified) are based on our South African Suppliers and prices are to be replaced by local material costs.
The ABOVE items do not include VAT

ANNEXURE B: Preliminary cost summary of Khaya ReadyKit

Peter A <padlard@gmail.com>

to me

10/16/17

Dear Bonke,

I do apologise for the delay in responding to your request for information posted from the Readykit website.

Readykit is going through a restructuring process due to increased demand. Please refer to the attached brochures for information.

The Alternative Building Company is being created to handle requests for one-off and bespoke buildings. For mass-prooduction Mike Hill is the person you should contact.

Khaya Readykit, based in Durban, recently shipped its entire production facility to the Free State to service a large RDP project, so your order would most likely be met by the Somerset West factory and the shipping cost would be from Cape Town.

In brief, a 40sqm pre-packaged 'kit' house would cost you R104 000.00, a 52sqm house would cost R135 200.00, which includes everything except the sanitaryware, tiling, transport, labour required to plaster the walls, and the cost of the floor slab, which is impossible to provide over distance or to give a price for as we have no indication of topography or founding conditions. The purchaser must contract locally to build a suitable foundation and slab for the Readykit house to stand on. Instructions are included in the delivered package.

If you have any queries or requests after browsing this information please don't hesitate to contact me.

Sincerely,

Peter Adlard
Professional Architect
The Alternative Building Company

ANNEXURE C: Preliminary cost summary of Fischer Housing

FISCHER
HOUSING (Pty) Ltd

Type 13 special edition – transportable unit(13 square meters)
Kitchen sink and cupboard, flush toilet, small shower with glass doors, small wash basin, two ceiling lights, two double plugs, switches and DB board, electric outside geyser and painted floor

Ex-factory guide line price excl. vat: **R 41 800.00**

Type 13 standard – transportable unit
Kitchen sink and cupboard, flush toilet, standard wash basin on pedestal, two ceiling lights, two double plugs, switches and DB board and painted floor

Ex-factory guide line price excl. vat: **R 38 700.00**

Type 13 basic – transportable unit
One ceiling light, double plug, DB board and painted floor. To be used as a site office or storeroom.

Ex-factory guide line price excl. vat: **R 34 500.00**

Type 21 – supplied in knocked down sub assemblies
One bedroom, lounge / kitchen with kitchen sink and cupboard, three ceiling lights, one bathroom with shower, flush toilet and wash basin, five aluminium framed windows, one outside mounted hot water geyser, fixed floor cover. Five aluminium framed windows and one door are included in the outside panel assemblies. Internal foamed panels and two doors are used for partitioning purpose. Concrete slab and erection of house are excluded.

Ex-factory guide line price excl. vat: **R 59 640.00**

Type 40 – supplied in knocked down sub assemblies (40 square meters)
Two bedroom, one lounge / kitchen with kitchen sink and cupboard, five ceiling lights, one bathroom with shower, flush toilet and wash basin. Five aluminium framed windows. Concrete slab and erection of house are excluded.

Ex-factory guide line price excl. vat: **R 83 800.00**

Lead time and payment terms to be negotiated pending order quantities.

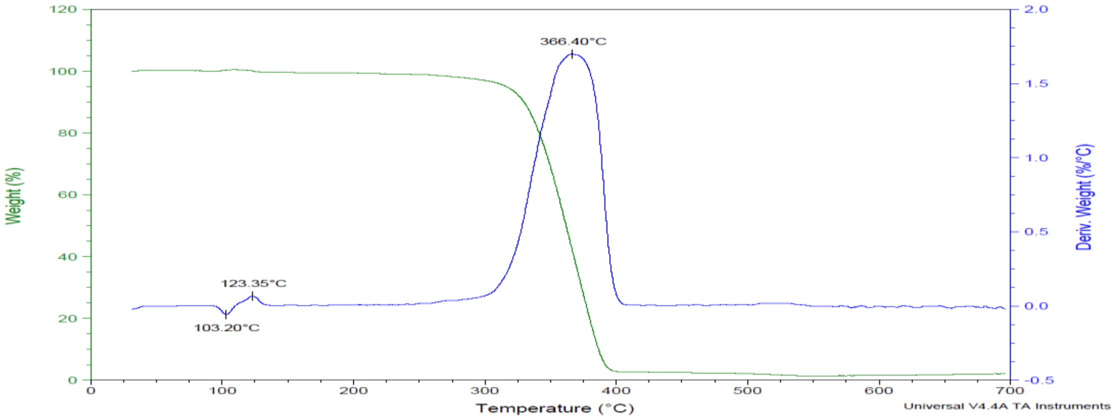
ANNEXURE D: Preliminary cost summary of EPS dome house

No.	Scope of Work	Unit	Quantity	Rate	Total Price (incl. VAT)
1	***EARTHWORKS***				
1.1	Digging up and removing rubbish, debris, vegetation, hedges, shrubs, bush, etc and trees not exceeding 200mm girth.	m^2	100	5,00	500
1.2	Strip average 150mm thick layer of topsoil and stockpile on site.	m^2	100	5,00	500
1.3	Excavation in earth not exceeding 2m deep: Trenches average 750mm deep, including risk of collapse and keeping excavations free of water.	m^3	7	40,00	280
1.4	Extra over all excavations for carting away: Surplus material from excavations and/or stock piles on site to a dumping site to be located by the Contractor.	m^3	2	50,00	100
1.5	Filling with selected material from the excavations and compacted in 150mm thick layers to a density of at least 95% Mod AASHTO maximum density for: Backfilling to trenches, holes, etc.	m^3	3	210,00	630
1.6	Earth filling supplied by the Contractor, including compaction in 150mm layers to 95% Mod AASHTO density, including scarifying and compaction of existing ground surface to a depth of 150mm: Under floors.	m^3	2	280,00	560
1.7	Surface preparation: Compaction of ground surface, including scarifying for a depth of 150mm, breaking down oversize material, adding suitable material where necessary and compacting to 95% Mod AASHTO density.	m^2	3	14,00	42
1.8	Soil insecticide in accordance with SANS 5859: Under floors etc. including forming and poisoning shallow furrows against foundation walls etc., filling in furrows and ramming.	m^2	41	18,00	738
1.9	To bottoms and sides of trenches etc.	m^2	60	18,00	1080
2	***CONCRETE STRUCTURES***				
2.1	UNREINFORCED CONCRETE CAST AGAINST EXCAVATED SURFACES 10 MPa/19mm Concrete: Strip footings foundations including formwork for blinding, etc.	m^3	1	1 200,00	1200
2.2	REINFORCED CONCRETE 20 MPa/19mm Concrete: Surface bed and strip footings.	m^3	3	1 350,00	4050
2.3	CONCRETE SUNDRIES Finishing top surfaces of concrete smooth with a steel float: Surface beds, slabs, etc.	m^2	41	20,00	820
3	***EXPANDED POLYSTRENE***				
3.1	7140mmX7140mmX2400mm of 20kg/m3	Sum	1	R155,040.00	155,040,00
4	***WATERPROOFING***				
4.1	DAMPPROOFING OF WALLS AND FLOORS One layer of 375 micron "Consol Plastics Brikgrip DPC" embossed damp proof course: In walls, cills.	m^2	10	15,00	150
4.2	One layer of 250 micron green polyethylene waterproof sheeting (SANS 952-1985 type C) sealed at laps with PVC self-adhesive tape: Under surface beds.	m^2	41	13,00	533
5	***IRONMONGERY FIXED TO DOORS ETC.***				
5.1	LOCKS: Two lever "CZ 69424955" mortice lockset complete with lockset and door furniture.	No.	2	150,00	300
5.2	Three lever "CZ 69424955" mortice lockset complete with lockset and door furniture.	No.	3	180,00	540
5.3	BATHROOM FITTINGS				
	Stainless steel:				
	Toilet roll holder plugged.	No.	1	150,00	150
6	***METALWORK***				
6.1	PRESSED STEEL DOOR FRAMES 1mm Thick "Durowin" rebated frames suitable for 90mm wide brick walls, with and including ironmongery and red oxide paint finish: Frame for door 813 x 2032mm high.	No.	3	910,00	2730
6.2	1mm Thick "Durowin" rebated frames suitable for 140mm wide brick walls, with and including ironmongery and red oxide paint finish:				
	Frame for door 813 x 2032mm high.	No.	2	950,00	1900
6.3	STEEL WINDOWS, DOORS, ETC.				

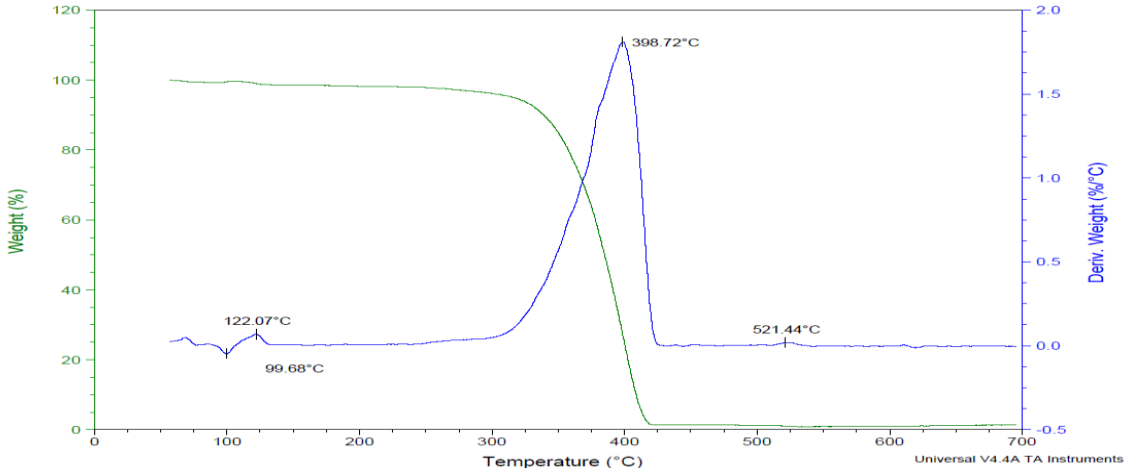
No.	Scope of Work	Unit	Quantity	Rate	Total Price (incl. VAT)
	1mm Thick "Durowin Type F7" residential windows complete with ironmongery, paint, etc. and fixing to brickwork or concrete:				
6.3a	Window, type NE1, size 533 x 654mm high.	No.	1	480,00	480
6.3b	Window, type NC4, size 1511 x 949mm high.	No.	2	1 520,00	3040
6.3c	Window, type ND54F, size 1511 x 1245mm high.	No.	2	1 640,00	3280
7	**PLASTERING**				
	EXTERNAL PLASTER				
	One coat "Cemcrete-Stipplecoat" waterproof cement based textured finish to approved colour, prepared and applied in strict accordance with the manufacturer's instruction				
7.1	On walls including narrow widths.	m^2	100	100,00	10000
8	***PLUMBING AND DRAINAGE***				
8.1	SANITARY FITTINGS Sanitary fittings: Ceramic flush toilet with close couple cistern including plumbing and drainage, installed complete.	No.	1	3 500,00	3500
8.2	Vaal Bantam white ceramic wash hand basin including plumbing and drainage, installed complete.	No.	1	2 500,00	2500
8.3	800 x 460 Kwikot stainless steel sink and drainer unit including plumbing and drainage, installed complete.	No.	1	1 900,00	1900
8.4	Shower including plumbing and drainage, installed complete.	No.	1	1 200,00	1200
9	**ELECTRICAL WORK**				
9.1	PREPAID ELECTRICITY METER Prepaid electricity meters: Prepaid ready board electrical unit complete with one light point and one plug point together with the supply cable.	No.	1	3 500,00	3500
10	**GLAZING**				
10.1	GLAZING TO STEEL WITH PUTTY 3mm Clear float glass:				
	Panes exceeding 0,1m² and not exceeding 0,5m².	m^2	9	180,00	1620
10.2	3mm Obscure float glass:				
	Panes exceeding 0,1m2 and not exceeding 0,5m2	m^2	1	200,00	200
11	**PAINTWORK**				
11.1	Prepare and apply one coat polyurethane varnish for exterior use: On doors.	m^2	2	70,00	140
	ON METAL SURFACES Prepare and apply one coat primer and two coats enamel paint.:				
11.2	On door frames.	m^2	3	65,00	195
11.3	On window frames	m^2	5	60,00	300
	TOTAL PRICE (Incl. VAT)				**R203,698,00**

ANNEXURE E: Thermogravimetric test run results

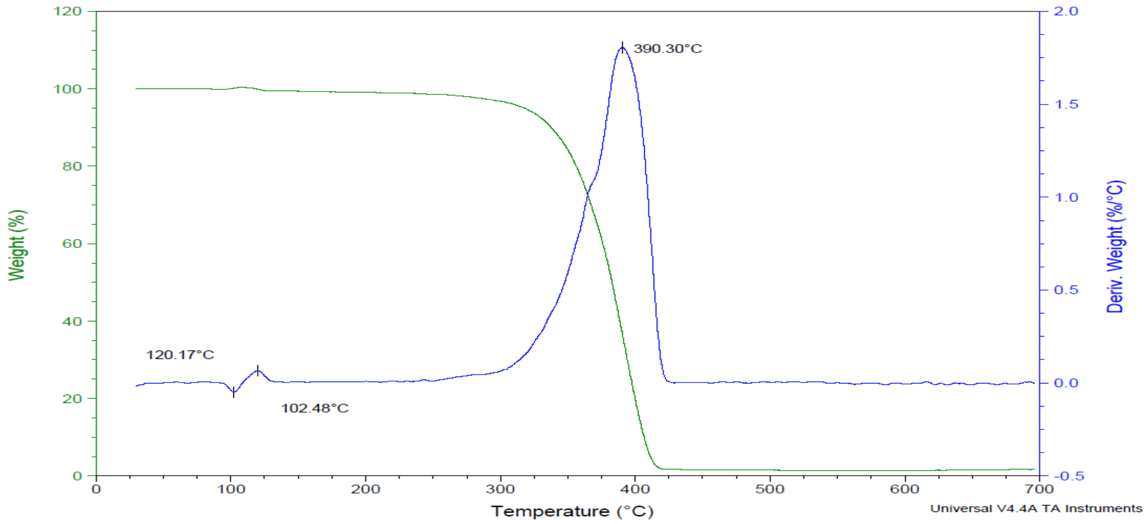
THERMOGRAVIMETRIC TEST RUN RESULTS



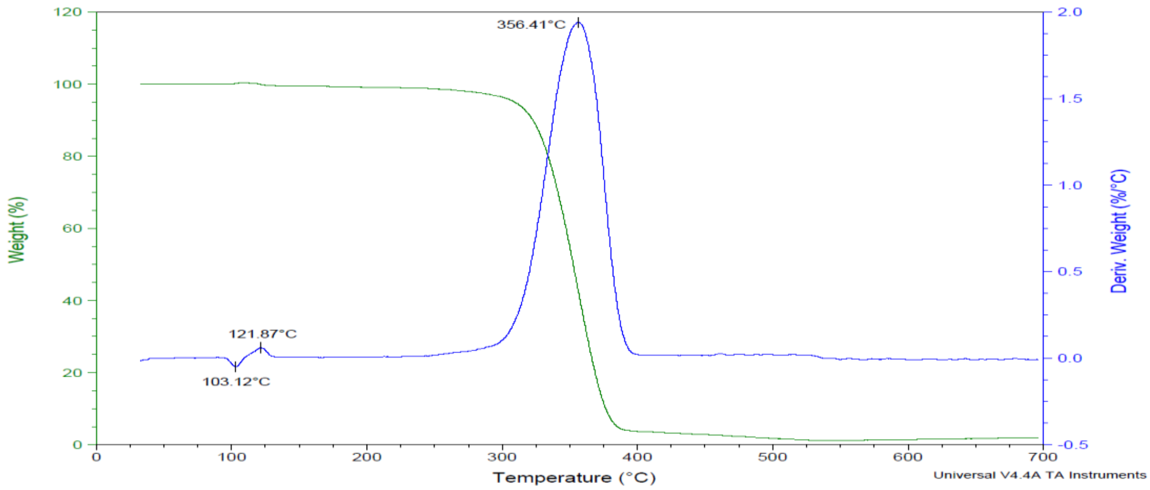
1st Run- 15kg/m^3



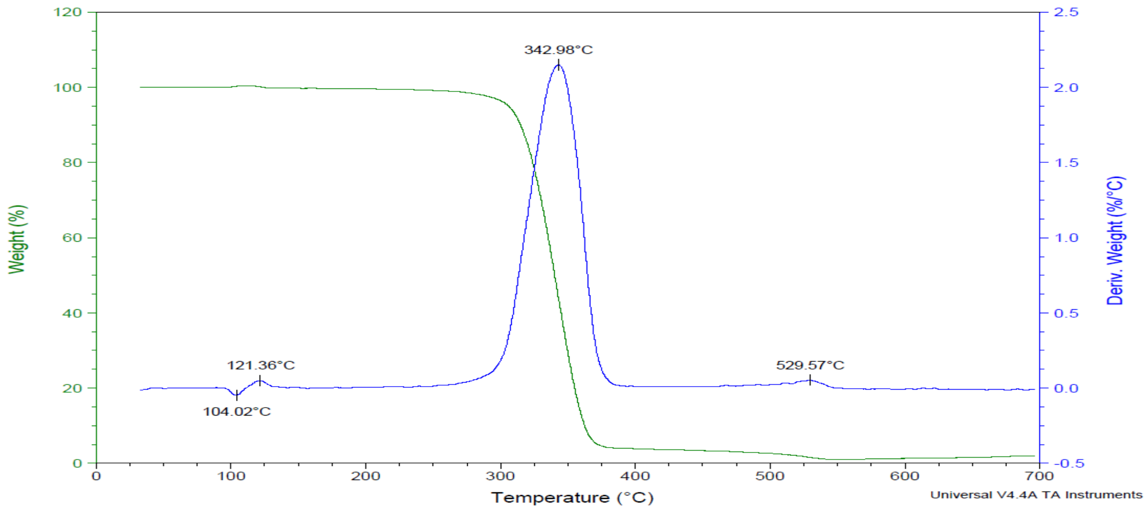
2nd Run- 15kg/m^3



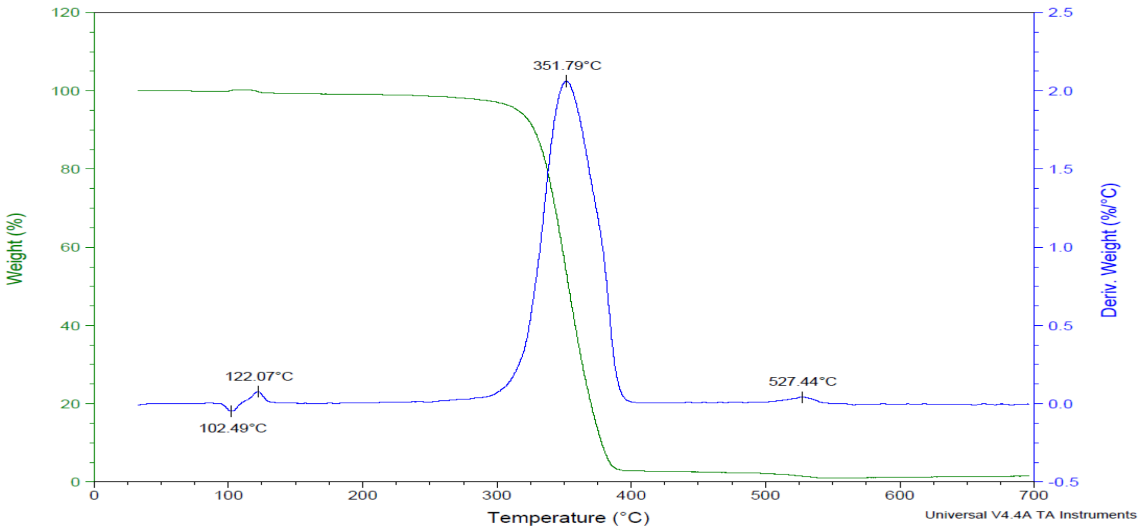
3rd Run- 15kg/m^3



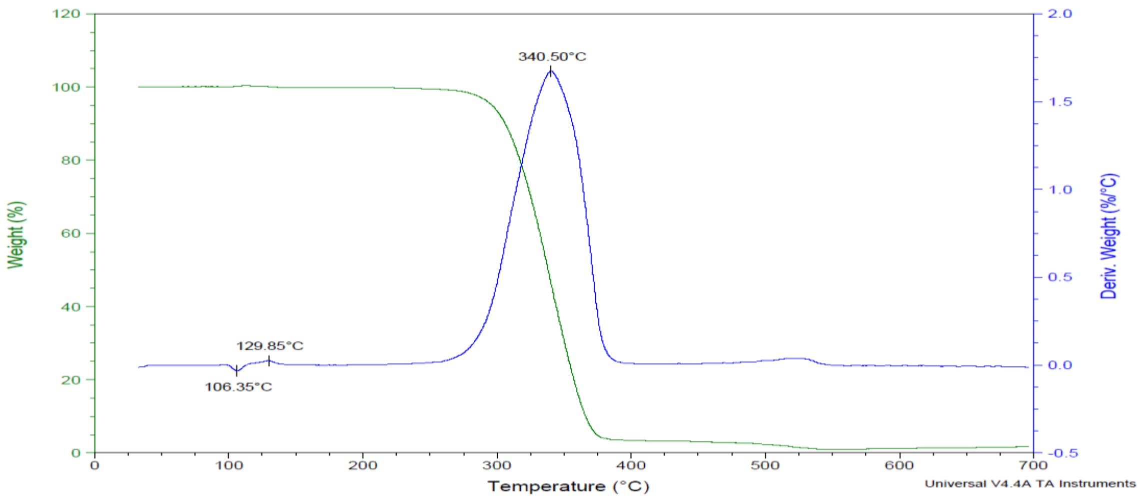
1st Run- 20kg/m^3



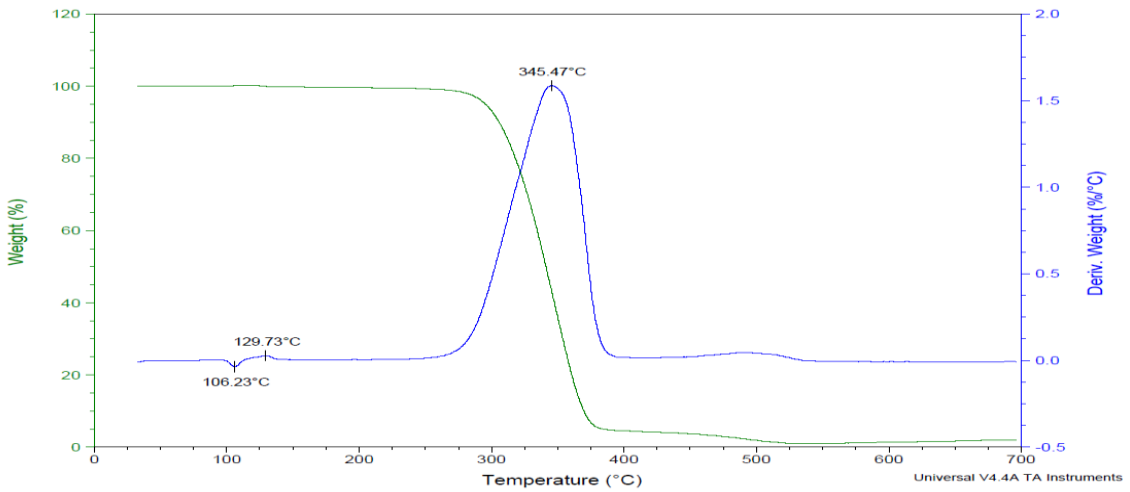
2nd Run- 20kg/m^3



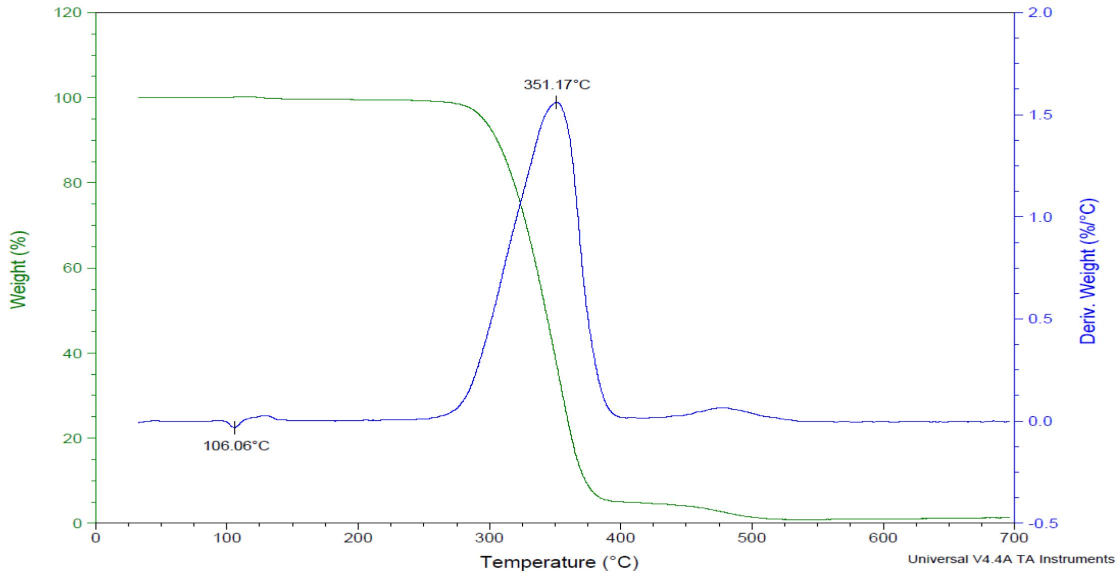
3rd Run- 20kg/m^3



1st Run- 30kg/m^3



2nd Run- 30kg/m^3



3rd Run- 30kg/m^3

ANNEXURE F: List of Publications and Conference Proceedings

List of Publications and Conference Proceedings

Publications

Mncwango, B. and Allopi, D., An investigation into the structural suitability of Expanded Polystyrene (EPS) as an innovative building construction material, International journal of engineering, business and enterprise applications, Volume 1, Issue 20, May 2017, pg. 1-5, ISSN 2279-0020

Mncwango, B. and Allopi, D., The link between housing, public health and the quality of life thereof, American International Journal of Research in Humanities, Arts and Social Sciences, Volume 1, Issue 22, March-May 2018, pg. 112-116, ISSN 2328-3734

Mncwango, B. and Allopi, D., The structural suitability of expanded polystyrene (EPS) using comparative analysis, Journal of construction, Volume 11, Issue 2, December 2018, pg. 38-46, ISSN 1994-7402

Conference proceedings

Mncwango, B. and Allopi, D., The structural composure and water absorption properties of Expanded Polystyrene, Proceedings of the 480th International Conference on Science, Technology, Engineering and Management, November, 2018, Cape Town, South Africa

Mncwango, B. and Allopi, D., A laboratory investigation and an appraisal of the viability of expanded polystyrene dwellings, Proceedings of the Wessex Institute Materials Characterisation Conference, May, 2019, Lisbon, Portugal

Mncwango, B. and Allopi, D., A conservative approach to low-cost housing through the use of expanded polystyrene, Proceedings of the 8th International Conference on Civil Engineering, November, 2019, Paris, France

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EDITING CERTIFICATE

Re: **Bonke Mncwango**
Master's dissertation: **AN INVESTIGATION INTO THE STRUCTURAL SUITABILITY OF STANDARD GRADE EXPANDED POLYSTYRENE (EPS) AS AN INNOVATIVE BUILDING MATERIAL**

I confirm that I have edited this dissertation and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). During my 13 years as a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology I supervised numerous Master's degree dissertations.

Dr Richard Steele
12 May 2019
per email