COMPARATIVE STUDY ON BUILDING MATERIALS FOR THE CONSTRUCTION OF REFUGE SPACE

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Degree of Master of Science

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Civil Engineering

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DECLARATION

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ABSTRACT

With the effects of climate change, natural disasters are becoming more severe and more frequent, resulting in loss of lives and an impact on a country's economy. Disaster resistant structures play a vital role in preventing loss of lives and damage to the belongings. As a consequence of a whole disaster resistant house being unaffordable, converting a part of the house to a disaster resistant refuge space could be attractive and could pave a way to build resilient communities.

Selecting a suitable building material is a vital decision as they account for almost 60% of the total cost and govern the disaster resistance of the structure. There are many options to choose from alternative materials in addition to conventional building materials. One such alternative material is produced by recycling Expanded Polystyrene (EPS) wastes. It is the EPS based lightweight concrete (LWC) wall panels.

This study aims at evaluating the material properties and characteristics of this construction method. A detailed comparative study was conducted in comparing the strength, durability, thermal performance, embodied energy and carbon footprint of the LWC panels to the conventional building materials: bricks and cement blocks. Furthermore, this study presents details of work study and cost analysis conducted on a full-scale model construction. The potential of LWC panels as a mainstream building material is shown with the comparative study.

Moreover, this study presents the aspects of a survey conducted among experienced and young engineers, professionals, and the general public on the importance of material properties. This thesis also discusses a multi-criterion decision problem solved through the Analytical Hierarchy Process (AHP) in obtaining the most suitable material as a case study.

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LIST OF ABBREVIATIONS

EPS – Expanded Polystyrene

LWC – Lightweight concrete

AAC – Autoclaved aerated concrete

FB – Fired bricks

HCB – Hollow cement blocks

URM – Unreinforced Masonry

NERDC – National Engineering Research Development Centre

BSR – Building schedule of rates

EE – Embodied energy

CF – Carbon footprint

MCDA – Multi-criteria decision analysis

AHP – Analytical Hierarchy Process

INT – Interior

EXT – Exterior

1. INTRODUCTION

1.1 Background

Sri Lanka was one of the countries which did not face severe natural disasters frequently in the past. However, as a tropical county, Sri Lanka is highly vulnerable to climate change effects. With the recent effects of climatic changes due to global warming, natural disasters are becoming more severe and more frequent (Climate Change Secretariat of Sri Lanka, 2015). Flash floods, cyclones, lightning, and earthquakes (rarely) are the major disasters threatening the country. Due to the absence of a past history of severe disasters, houses built in the past are not adequate to resist such disasters. The results are loss of lives and damage to the properties.

According to the National Disaster Relief Services Centre (NDRSC) of Sri Lanka, a total of 65 deaths were recorded in 2018 due to floods, heavy rains, high winds and lightning. In addition, 124,152 families were affected with 1,249 fully damaged houses and 16,541 partially damaged houses due to the same causes. Rs. 2.5 billion is allocated from the total of Rs. 15 billion of Natural Disaster Insurance scheme for the provision of immediate disaster relief as dry ration, cooked food, drinking water and other necessary commodities. Rest of Rs. 12.5 billion is allocated for the aid of damages occur to buildings in housings and small and medium scale industries (Ministry of Disaster Management, 2018). The recorded compensations for the year 2018 as an advance of Rs. 10,000 per household, totalling up to around Rs. 265 million and through an application process a total of Rs. 83.8 million with Rs. 25,000 per household (Ministry of Disaster Management, 2018). From the above statistics, it is evident that a country is largely affected by natural disasters and needs to be prepared in order to reduce the losses.

In order to prevent catastrophic consequences, buildings, especially houses, need to be made disaster-resistant. It might be financially impossible even for a mid-income family to rebuild a house to make it disaster-resistant. In addition, the occupants may need to vacate the house in order to rebuild such a way the house could resist probable forces. This may cause a lot of inconvenience to the occupants. As a solution for this, a refuge space can be introduced. Refuge space can be defined as a room or a part of the house/ building, which is constructed to resist the forces exerted by the above disasters. Converting a part of the building to be disaster-resistant would only add a small percentage to the total cost of the construction which would not be a massive burden in the sense of the financial situation of a family. Furthermore, a part of the house can be built as a refuge space while the residents are still occupying the same house without the need to wait or vacate till the construction is completed and if the room already exists, it could be rebuilt or retrofitted to make it stronger to be disaster-resistant.

One of the important components of the total cost will be the selection of suitable materials. According to Honţuş, (2014), construction materials account for about 70% of the total cost of the house excluding finishes and furnishing and the rest 30% being labour. In Sri Lanka, the cost of materials is around 50-60% of the total cost of construction (Udawatta, 2010). The materials selected for the construction need to possess adequate properties to resist the hazards and forces exerted in the event of disasters of probable types like floods, earthquakes, and cyclones along with the affordability of the materials. It can be widely seen that the construction industry is moving towards sustainability, the use of alternate materials like Autoclaved Aerated Concrete (AAC) and Expanded Polystyrene (EPS) based lightweight concrete are welcomed over the conventional materials such as conventional concrete, burnt clay bricks and cement sand blocks. This study will focus on proposing a selection criterion through which a potential durable, strong and affordable material could be identified for the construction of refuge space by conducting a comparative study between alternative materials and conventional materials.

1.2 Objective

The main objective is to conduct a comparative study on locally available materials to assess the suitability for the construction of a refuge space. Following sub-objectives were formulated:

- Develop the concept for the refuge space

- Develop a framework for the comparative study
- Conduct a comparative analysis of various materials available locally and manufactured as an alternative

1.3 Methodology

The following methodologies were adopted to achieve the above objectives.

- A thorough literature review together with a pilot survey was carried out to explore and filter suitable locally available materials and to identify the parameters need to be considered when selecting a material for the construction of refuge space.
- A well-recognized framework was selected and formulated for the comparative study.
- A comparative study was carried out for EPS based lightweight concrete panels, hollow cement blocks, and fired clay bricks.
- A case study was carried out using the results obtained from the comparative study.

1.4 Arrangement of the Thesis

- Chapter 2 presents the findings of the literature review.
- Chapter 3 describes the concept and features of refuge space and highlights the cost-effective measures which could make the construction of refuge space affordable.
- Chapter 4 provides the results of the survey carried out among a selected group of people on the factors affecting material selection.
- Chapter 5 presents the comparative study along with the experimental studies carried out.
- Chapter 6 presents a case study carried out in selecting material for the construction of refuge space.
- Chapter 7 presents conclusions and recommendations.

2. LITERATURE REVIEW

2.1 Introduction

With the increased scarcity of the natural resources, a rise in studies of alternative materials can be widely seen locally and as well as globally. Numerous materials are introduced by consuming widely available materials and recycled waste products as raw materials for production. Autoclaved Aerated Concrete (AAC), Expanded Polystyrene (EPS) based lightweight concrete panels and Cement Stabilised Earth Blocks (CSEB) are some of the widely available alternative materials.

It is common to compare alternative materials to conventional construction materials to highlight the advantages and disadvantages. Many comparative studies have been carried out between conventional and alternative construction materials on various properties and characteristics. Some materials could perform well in a certain property while lacking another. Therefore, comparative studies considering several properties at once could provide a clearer picture of the pros and cons of using such alternative materials. Although a moderate number of researches have considered more than a property by comparing ratios, very few studies have considered multiple properties at once. This literature review was carried out to identify the properties and methods to conduct a comparative study. In addition, this chapter discusses previous research carried out related to this study.

2.2 Properties and characteristics for the comparative study

Properties and characteristics are crucial in the selection of construction materials for a disaster-resistant structure. However, refuge space being a part of the house, the properties that are considered when selecting materials for construction of house need to be included in addition to that of a disaster-resistant structure.

Honţuş, (2014) carried out a comparative study on the choice of building materials for construction of a house, between brick masonry and AAC block masonry. The study considered the following properties and characteristics of both materials for the comparison:

- Compressive strength of the material
    - For higher bearing capacity
- Bulk density of the material
    - For better thermal insulative properties
    - To reduce the seismic force during an earthquake
    - Less self-weight on the structure
- Thermal conductivity
- Reaction to fire/ fire resistance
- Cost of overall construction including saving on structural elements
- Cost of air conditioning
- Constructability and handling
- CO_2 emission/ Carbon footprint

Olanipekun et al., (2006) considered compressive strength, water absorption capacity and cost per unit volume of concrete for a comparative study of concrete with coconut shells and palm kernel shells as a replacement for coarse aggregates.

While construction time is influenced by various factors such as environmental situation, labour productivity, cash flow, etc., construction time is one of the three factors deciding the success of a construction project along with cost and quality (Walker, 1995).

Dissanayake et al., (2017) conducted a comparative analysis of embodied energy and carbon footprint of EPS based lightweight concrete wall panels with fired bricks and cement blocks for single storey loadbearing construction. In this study, embodied energy consists of energy required for the material production and energy spent on transportation of materials to the respective sites. However, carbon footprint/ CO_2 emission is only considered for material production. Furthermore, the study compared the cost of construction of these materials by considering the cost per unit area.

A similar study has been carried out by Udawattha & Halwatura, (2016a) for cement blocks, fired bricks, and mud concrete blocks by considering three 10 ft x 10 ft wall units out of each material. This study included the embodied energy of materials and energy for the transportation of materials excluding the energy for the foundation as the same type of foundation was used for all the cases. Furthermore, the study included a comparison of the cost of each construction material using standard Building Schedule of Rates (BSR).

Sazedj et al., (2013) carried out a study to compare the costs of structural walls with unreinforced masonry and reinforced concrete structure with masonry infill walls. In the study, a comparison was carried out ensuring similar conditions in the related aspects considered that could have an effect on the comparison. Furthermore, the comparison was carried out considering the cost of the structure excluding the foundation and coatings assuming both functional units will be treated the same. The study omits the comparison of thermal performance as the equivalent heat transfer coefficients for both cases were of almost the same value.

Udawattha & Halwatura, (2016b) compared cement blocks, fired bricks, and mud concrete blocks in terms of thermal performance and structural cooling ability through real-world analysis and simulation analysis. Time lag and decrement factor were used to compare the results and identify the level of performance between the materials of interest. Furthermore, thermal conductivity (thermal transmittance/U-value) and specific heat capacity of the materials were determined through laboratory tests using a thermal conductivity meter.

2.2.1 Cost of construction

Although major contractors have developed their own norms for estimation from the past experiences, most contractors, especially new contractors in Sri Lanka is using the standard Building Schedule of Rates (BSR) as the basis for estimation and material acquisition (Udawatta, 2010). BSR is published and updated time to time by the Construction Industry Development Authority (CIDA) of Sri Lanka. The latest available BSR was released in March 2019 and later amended in September, the same year.

According to Udawatta, (2010), around 50-60% of the total cost is spent on materials. Wastages in materials increase the overall cost of construction and make it deviate much from the estimated value. Although wastages are unavoidable in the construction industry, wastages in Sri Lanka was found to be over the acceptable range. It was found concrete and cement mortar displayed 21% and 25% wastages respectively due to the rectification works (Jayawardane, 1992).

Arooz, (2019) conducted a real scale work-study on Mud concrete as a loadbearing wall in a 4.8 m × 4.8 m square (in plan) single storey unit to obtain a unit cost value for Mud concrete walls and the rate was found to be Rs. 61.43 per sq. ft.

2.2.2 Strength of the material

According to Papanicolaou et al., (2011) failures of unreinforced masonry (URM) during an event of natural disaster is a main cause of fatalities and should be given focus to improve nowadays as the natural disasters are becoming more frequent. Therefore, the material's strength is an important factor in material selection.

In an event of natural disaster, a structure could undergo several types of loads due to numerous causes. In terms of direction, loads can be classified as lateral/horizontal loads and vertical loads. Dead loads including self-weight and imposed loads can be considered as vertical loads and wind loads, seismic loads, hydrostatic and hydrodynamic loads caused by floods and impact loads such as impacts of floating debris could be considered as lateral/horizontal loads acting on the structure (Seron & Suhoothi, 2017). In an event of a flood, where flood level difference between opposite sides is greater than 1-1.5 m, hydrostatic lateral load due to the flood could cause excessive deformations, resulting in out of plane failure as flexural capacity is less in common URM walls (Kelman & Spence, 2003). On the other hand, hydrodynamic loads can cause serious damages depending on the velocity and the shape of the building. Impact loads which are originated from coastal floods/Tsunamis and the debris from the flood could cause severe destruction than hydrostatic and hydrodynamic loads. Evaluation of the magnitudes of these loads is very complex and are highly unpredictable to represent in a mathematical model accurately.

Not only the strength of the material reflects the ability to resist forces, but also the quality and durability. It can be widely seen that walls and facades made with stronger materials such as rock walls do not easily deteriorate or decay unlike walls made with low strength earth wall materials (Udawattha et al., 2018). Hence, the strength of the materials also needs to be considered when discussing the durability to the external effects such as rain.

2.2.3 Durability of the unit

Udawattha et al., (2018) carried out a study on natural rain surface erosion of various walling materials used widely in Sri Lanka. The study states that the surface erosion or decay would not cause any structural implications on walling materials unless the erosion is deeper than a quarter of the width of the walling material. However, when considering the aesthetic appeal of the building, surface erosion or decay is a massive issue. In addition, surface decay will damage the quality, the value of the building, and the life span of the walling material (Abeysundara et al., 2009; Ayrilmis, 2007; Udawattha et al., 2018). Figure 1 depicts the decay of various walling materials.

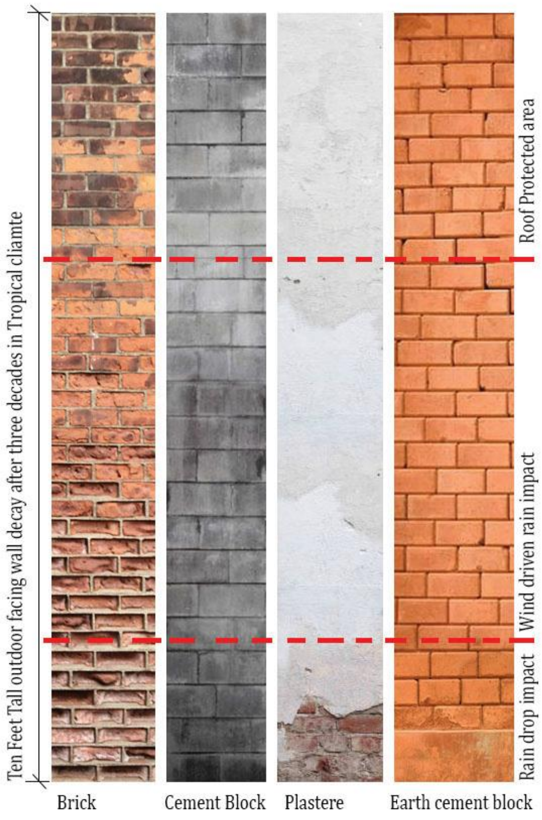


Figure 1: Decays on various wall constructions
Source: (Udawattha et al., 2018)

Udawattha et al., (2018) distinguished rain dropping patterns into three types: direct rain, bouncing drop rain, and the wind-driven rain. Direct rain does not affect the walling material as the drops fall mostly parallel to the wall or the façade. Bouncing drop rain is caused when the drops are bounced from the nearby horizontal surfaces such as ground or walkways. Bouncing drop rain is the most common type of rain that causes decaying of the facades as widely seen in old buildings in Sri Lanka as shown in Figure 1 (Udawattha et al., 2018). The severity of this effect depends on the surface roughness as drops bounce easily on smoother surfaces than rough surfaces (Parra-Saldivar & Batty, 2006; Rydock & Gustavsen, 2007).

The wind-driven rain is the third and a significant cause of decaying or erosion of facades. This is due to the accelerated speed of droplets resulting from extreme weather conditions like heavy rain accompanied by high winds or cyclones. This affects the upper parts of the façade unlike the previously discussed bouncing drop rain. Furthermore, this can hit the wall in different angles depending on the wind direction. The severe one is that of perpendicular to the wall. Proper roof design and provision of eves could minimize the effect of wind-driven rain (Erkal, D'Ayala, & Sequeira, 2012; Udawattha et al., 2018).

2.2.4 Construction time

Construction time is affected by worker attitude, management practices, client experience, procurement type, project organizational type, and site conditions such as access to the site, soil conditions, and groundwater table, etc. (Ireland, 1985; Naoum, 1991; Sidwell, 1982; Walker, 1995).

Reducing labour idling is a key factor to increase the productivity and resulting in reduced construction time. Labour productivity is usually improved through programs which build motivation, teamworking skills, technical skills through training, leadership qualities, etc. (Udawatta, 2010).

One of the key factors deciding the construction time is the type of construction. Rapid constructions/precast buildings and infrastructures are becoming more common as a solution to reduce wastage and construction time (Dissanayake & Jayasinghe, 2015; Fernando et al., 2017; Hieber et al., 2005).

2.2.5 Thermal performance

In order to reduce the direct and indirect heat gains to the dwelling units in tropical countries like Sri Lanka, walling materials need to be selected carefully. As a warm-blooded species, we need to maintain a constant body temperature regardless of the outdoor temperature of the environment. In this case, building envelope acts as a third skin for us (Udawattha & Halwatura, 2016b). Unlike cold climatic countries, the main function of building envelope walls in tropical countries is to reduce the heat gain. Most common walling materials in Sri Lanka can be identified as fired bricks, and solid and hollow cement blocks.

There are various methods to assess the thermal performance of a material. Thermal performance of walling materials can simply be assessed by comparing outdoor and indoor ambient temperatures (Tabatabaei et al., 2017). Thermal conductivity and thermal transmittance (U-value) of a material is another simple identifier of the material's thermal performance (Balaji et al., 2013). Another method is to measure outdoor and indoor surface temperatures through which decrement factor and time lag could be interpreted (Jin et al., 2012). With materials with high lag time and very low decrement factor, a thermally comfortable constant temperature indoor environment which is not much affected by the outdoor temperature swings could be implemented (Asan & Sancaktar, 1998; Duffin & Knowles, 1984).

2.2.5.1 Time lag (φ)

The time it takes for the heatwave to propagate from outside to inside is known as time lag (Asan & Sancaktar, 1998). It depends on thermal mass, reflectivity, thickness, and material density (Asan, 2006; Asan & Sancaktar, 1998; Cheng, Ng, & Givoni, 2005; Wiley & McLaren, 1955). For example, it will take longer for the heatwaves to propagate through thicker denser material than a lighter thin material (Asan & Sancaktar, 1998). Time lag can be calculated as shown in Equation 2.1.

$$\text{Time lag } (\varphi) = t_{T_{in(\max)}} - t_{T_{out(max)}} \qquad \text{Eq. (2.1)}$$

Where: φ – Time lag

$t_{T_{in(\max)}}$ – Time when inside surface temperature is at peak

$t_{T_{out(max)}}$ – Time when outside surface temperature is at peak

2.2.6 Decrement factor

The decreasing ratio of outdoor and indoor surface temperature is defined as the decrement factor (Asan & Sancaktar, 1998; Jin et al., 2012). The decrement factor is measured by Equation 2.2. Figure 2 shows the schematic representation of time lag and decrement factor.

$$Decrement\ factor\ (f) = \frac{T_{in(\max)} - T_{in(min)}}{T_{out(\max)} - T_{out(min)}} \qquad \text{Eq. (2.2)}$$

Where: f – Decrement factor

$T_{in(\max)}$ – Inside maximum surface temperature

$T_{in(min)}$ – Inside minimum surface temperature

$T_{out(\max)}$ – Outside maximum surface temperature

$T_{out(min)}$ – Outside minimum surface temperature

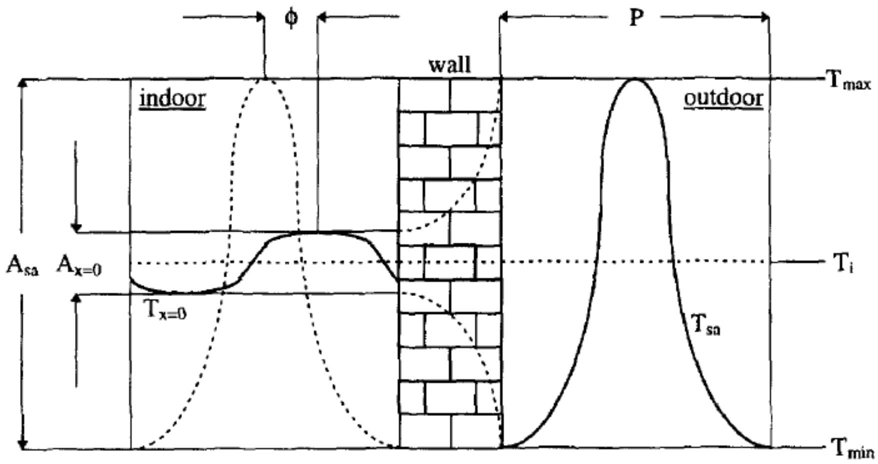


Figure 2: Schematic representation of time lag and decrement factor
Source: (Asan & Sancaktar, 1998)

2.2.7 Eco-friendliness and sustainability

As the world is concerned about sustainability in every field with the Millennium Development Goals (MDG) and Sustainable Development Goals (SDG), the construction industry holds a major role in managing natural resources. In regard to this, sustainable materials and buildings are getting more attention and attraction among investors. A successful sustainable building addresses economic, environmental issues and social parameters (Anastaselos et al., 2009). In essence, a sustainable material should be able to fulfil the following: does not require massive investment to produce, environment friendly and affordable. If the production of a product needs a lot of investment for components such as raw materials or machinery, it is not economically sustainable.

Sustainable building materials needs to be less energy-consuming in manufacturing and also in the operational cycle of the building (Kariyawasam & Jayasinghe, 2016). In a tropical country like Sri Lanka, operational energy is not dominant compared to the energy required for the production. Using natural resources that deplete over time, increases the risk in the environmental department as well as a rise in cost and affordability. The construction industry, on the top list of consumers of natural resources, using wastages from the building demolitions or other recycled waste materials is becoming more and more popular and welcomed (Jayasinghe et al., 2016) as it addresses the economic, environmental and social aspects of sustainability.

2.2.7.1 Embodied energy and carbon footprint

The total energy of a building can be classified into two components; embodied energy and operational energy (Dixit et al., 2010). Embodied energy is the energy consumed in all forms to produce a product, from the acquisition of natural resources to the delivered product (Park & Clair, 2009). This consists of all the energy components related to its raw material extraction, manufacturing and transporting. The operational energy is the energy required to run the building for lighting, air conditioning and heating, etc. In a tropical country like Sri Lanka, embodied energy plays a major role than the operational energy unlike in colder countries where heating is required in most of the times round the year.

Similarly, carbon footprint consists of embodied carbon and operational carbon describing the same as in terms of the total emission of carbon dioxide gas instead of energy. Embodied carbon refers to the total greenhouse gas emitted in terms of carbon dioxide equivalents – CO2e, during the stages of raw material extraction, manufacture and transport of the product (Sansom & Pope, 2012).

Embodied energy can be calculated in several methods. According to Dissanayake et al., (2017), for the Sri Lankan context, the process analysis method is more applicable considering the data available. In the process analysis, the embodied energy of each material in every stage of production is assessed along with any other energy required for production.

2.3 Potential materials identified

Commercially available materials can be classified into two categories as conventional building materials and alternative building materials.

2.3.1 Conventional building materials

In Sri Lanka, fired brick masonry and cement block masonry constructions are widely used construction method for house construction with hollow cement blocks gaining popularity in recent years. These can be classified as unreinforced masonry (URM) constructions. In the global context as well, URM buildings contain a considerable portion of existing buildings (ElGawady et al., 2005). Buildings can be divided into two categories as engineered and non-engineered. According to Mendis et al., (2014) about 70% of the URM structures around the world could be classified as non-engineered. These structures are common due to their less requirement for skilled labourers, durability, low cost and availability of materials. URM structures are the leading form of construction in rural areas of developing countries where the population is generally comprised of low-income people with limited knowledge of construction or engineering practices (Bhattacharjee & Behera, 2018).

2.3.2 Alternative materials

Commercially widely available alternative materials in Sri Lanka are Expanded Polystyrene (EPS) based lightweight wall panels and Autoclaved aerated concrete (AAC) blocks (Dissanayake et al., 2017; Fernando et al., 2017; Ranasinghe & Jayasinghe, 2019). Disposal of fly ash has been a problem in Sri Lanka; using this as a construction raw material is well appreciated as it disposes of the waste. AAC is such a material that turns waste into useful construction material. Although AAC blocks are preferred for seismic resistant structures due to their lightweight character, it is not recommended to use in flood-prone areas where submersion of units for several days is a possibility due to high water absorption ability of AAC (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006; Honţuş, 2014).

EPS based lightweight concrete (LWC) panels are manufactured by sandwiching LWC between two cement fibre boards. It uses EPS, which is a waste product generated in a large amount from packaging in various industries. It is not decomposable in nature and causes environment problems (Kan & Demirboğa, 2009a). EPS is a lightweight material of spherical shape which has 2% of polystyrene and about 98% of air (Aciu et al., 2015). Earlier, research has been done by (Dissanayake et al., 2017; Eric et al., 2019; Fernando et al., 2017; Vishnu et al., 2017) for lightweight concrete produced using virgin EPS and recycled EPS in 50/50 ratio. However, due to the increased cost of virgin EPS, currently recycled EPS is used fully for the production of LWC wall panels (Gunawardana et al., 2019).

The local manufacturer (EPCI homes (Pvt) Ltd.) decided to use recycled EPS alone as the waste material since it is available in large amount and various industries situated in the area are contributing by dumping the EPS waste at the factory itself. The recycled EPS is obtained from crushing waste polystyrene used for packaging. The lightweight aggregates affect the properties of concrete such as density, water absorption and thermal conductivity which can be considered as advantages compared to conventional concrete aggregates (Kan & Demirboğa, 2009a; Sayadi et al., 2016). In addition, fly ash is added to the lightweight concrete, which provides a durable concrete with fewer pores and helps lifelong strength gaining of concrete when added to the concrete (Chousidis, Rakanta, Ioannou, & Batis, 2015).

Consequently, varieties of buildings such as office buildings and apartments are widely utilizing lightweight wall panels for partitioning. These panels are also used as load-bearing walls in single-storey buildings (Fernando et al., 2017). Therefore, much research has been done to compare the use of lightweight panels and conventional materials (Dissanayake et al., 2017). Coppola et al., (2016) stated that the use of EPS as aggregates showed benefits such as reduction in the usage of sand, less self-weight and reduction of waste in the environment. There will be a reduction in concrete strength as the EPS has strength nearly zero (Kan & Demirboğa, 2009b), however, the lightweight concrete showed strengths greater than the minimum required for structural concrete (Dissanayake et al., 2017).

2.4 Frameworks for comparison

The decision of selecting the suitable material depends on the beneficiary after considering the properties of available materials with available budget (Honţuş, 2014). Material selection is considered as a multi-criteria decision problem and is widely seen as an experience-based task due to the absence of formal and available measurements (Nassar et al., 2003). As the material selection process is a multi-layered problem often with complex connections between them, a suitable solution could be found in the family of multi-criteria decision analysis (MCDA) methods (Alibaba & Özdeniz, 2004; Barker & Zabinsky, 2011; Shapira & Goldenberg, 2005; Zavadskas et al., 2008).

Analytical Hierarchy Process (AHP) is one of the widely used methods for handling multi-criteria decision problems in real-world situations (Saaty, 2002; Zavadskas et al., 2011). Reza et al., (2011) used AHP method as a multi-criteria tool for the selection of sustainable flooring system. Furthermore, the authors state that AHP provides a strong framework that complies with sustainable construction practices. Due to its simplicity and popularity, many researchers have used AHP in material selection (Akadiri et al., 2013; Nadoushani et al., 2017; Yang & Ogunkah, 2013).

2.5 Summary

Due to the time and resource limitations the study was narrowed to consider some of the material properties found to be vital to the refuge space. Summary and main findings of the literature study are given in Figure 3.

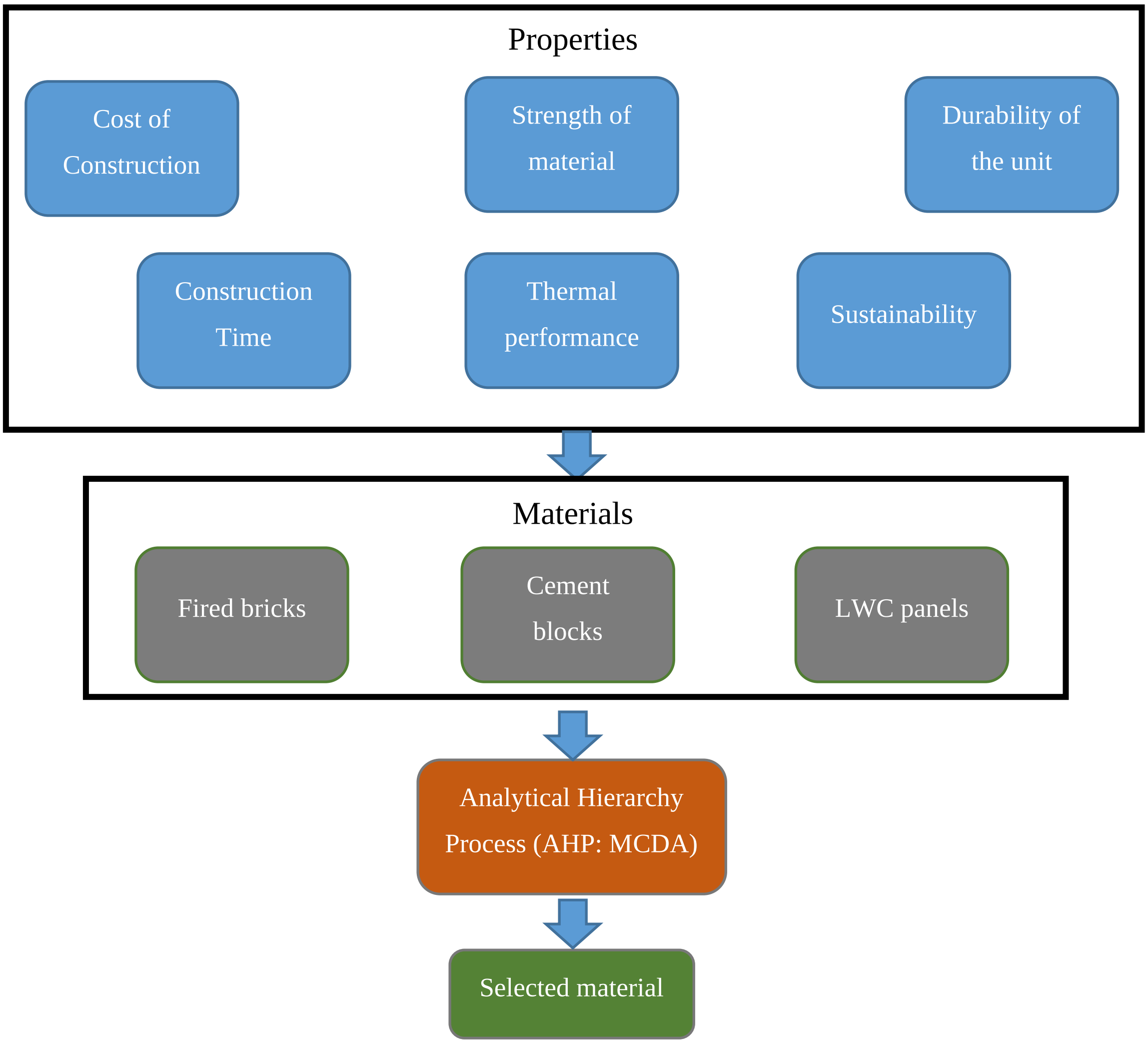


Figure 3: Summary of literature review

3. CONCEPT OF REFUGE SPACE

3.1 Introduction

Development of refuge space needs to be carried out carefully so that it could withstand the forces of nature while being feasible to construct in every aspect. In order to develop and design any disaster-resistant houses or building, it is vital to identify the probable causes of failures. Once the expected events are identified, it is possible to come up with engineered solutions where the building designed will have the correct architectural and structural forms, the proper use of materials through which the strength and durability needed to survive any event that could cause the following forms of damage can be ensured:

1. Liquefaction of soil surrounding and underneath the foundation,
2. scouring around foundations that could lead to foundation failures,
3. damages to the structure in the event of earthquakes,
4. damages to the roof from any cyclones,
5. excessive damages due to lightning striking the facility,
6. and to resist any other form of the destructive effects that could cause loss of lives.

However, there could be many other consequences of planning such houses and buildings. One of the primary factors will be the additional cost of construction and another will be the time coupled with the aesthetic appeal of such houses and buildings to fulfil the aspirations of the owners. In this context, making the facility totally disaster-resistant would not be a feasible solution when the constructions are undertaken with a limited budget as usually occur with the construction of living spaces in developing countries. It is usual to have houses built in stages while occupying a part of the house by the owner while other parts are gradually completed as permitted by the available finances. In such situations, the provision of refuge spaces in the form of a disaster-resistant room could be very attractive. The reason is, that part of the limited budget available initially could be earmarked for the construction of the refuge space. It is also possible to provide government assistance in the form of grants or subsidies for such a facility since its presence in a house could prevent fatalities. The benefits of this facility, if implemented, could provide a financial significance and hence such investments could be undertaken as special investments on disaster resilience.

Considering all the above requirements, the refuge space must have the following features:

1. It should be constructed in a very cost-effective way so that majority of the population could afford its construction while increasing the disaster resilience of the nation.
2. The layout used should allow it to be easily used as part of the occupied space when the house is used after either partial or full completion of it.
3. It should have a foundation system that will resist liquefaction or scouring.
4. The super-structure of the refuge space must be earthquake, flood and cyclone-resistant
5. The structural form should be of such a nature that it will not attract lightning.
6. It should have upper floors so that in case of river floods or flash floods or tsunami waves, the occupants could easily escape to the upper floors to save their lives.
7. It is preferable if an upper floor of the refuge space could be provided with a water supply and sanitary facilities.

At the point when flood waves arise due to heavy and prolonged rain, generally in flat terrains, the water levels will rise slowly. Hence, if the doors and windows are not completely watertight, the flood level tends to equalize inside and outside even when the openings are kept closed. However, the typical guidance is to keep the doors and windows open when the floods occur even on an event of flash floods. Therefore, the chances of excessive lateral loads exerted on the walls are very less.

However, flash floods could cause scouring of the foundation that could prompt the failure of the refuge space particularly when the soil is of sandy nature without sufficient clay particles to have enough impermeability to resist scouring. In this way, this aspect must be given sufficient consideration when the refuge spaces are developed to secure the lives if there is a possibility of flash floods or river floods.

The houses found exceptionally near the sea coast could experience the ill effects of tsunami waves which might be of totally different scale and subsequently it is viewed as that the refuge spaces proposed for river floods should be situated at least 1.0 km away from the sea coast in flat terrain areas above the coastal elevations. The explanation is that the refuge spaces having the fundamental features for river floods could tolerate if there is a possibility of tsunami waves. However, it must be noted there needs to be precautionary measures to be taken in order to implement refuge spaces for tsunami-prone areas. Implementation of refuge space in tsunami-prone areas needs an extensive study on probable failures and the precautionary measures to prevent those catastrophic failures.

3.2 Development of a layout for the refuge space

Along these lines, when the possibilities of super and substructure failures are evaluated, the consideration could be paid to the layout for a refuge space which could save lives from floods. Figure 4 (a) shows the ground floor layout developed for the refuge cell indicating the staircase. Figure 4 (b) depicts the first-floor layout indicating the ladder that can be used to climb to the roof level in case of a severe flood, the washroom and the pantry on wall arrangements. The dimensions mentioned in the layout is only for the illustrative purposes and can be changed accordingly to match the requirements of the owners, although it is highly recommended to have a dimension similar to what is shown in the figure to ensure adequate structural robustness of the refuge space. The appliances shown in the plan demonstrates that the refuge space could be utilized for everyday activities under typical conditions.

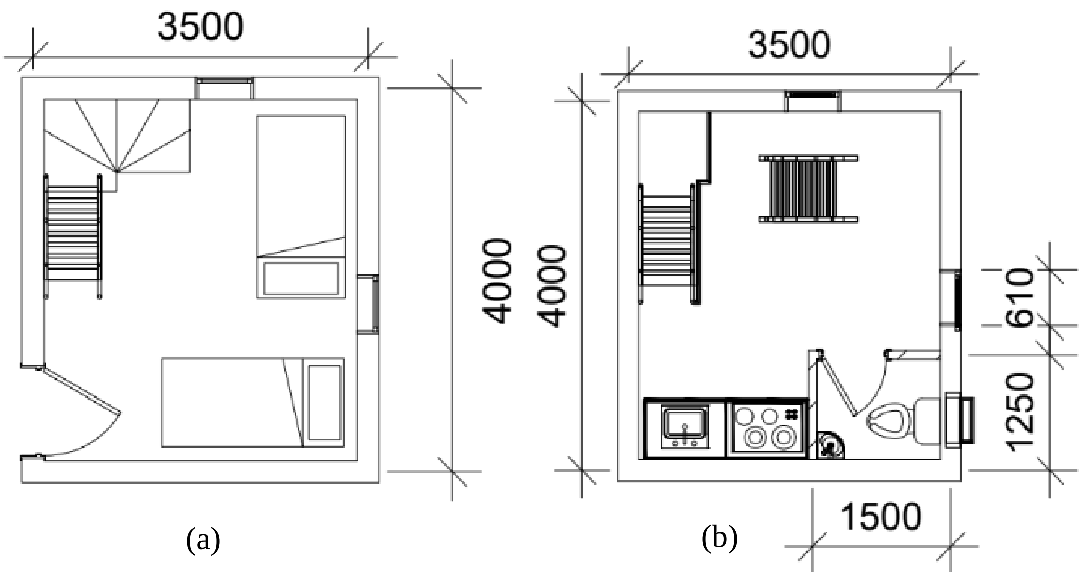


Figure 4: a) Ground floor layout b) First-floor layout

3.3 Main features included in the proposed refuge space

The main desirable features of the proposed refuge space are as follows:

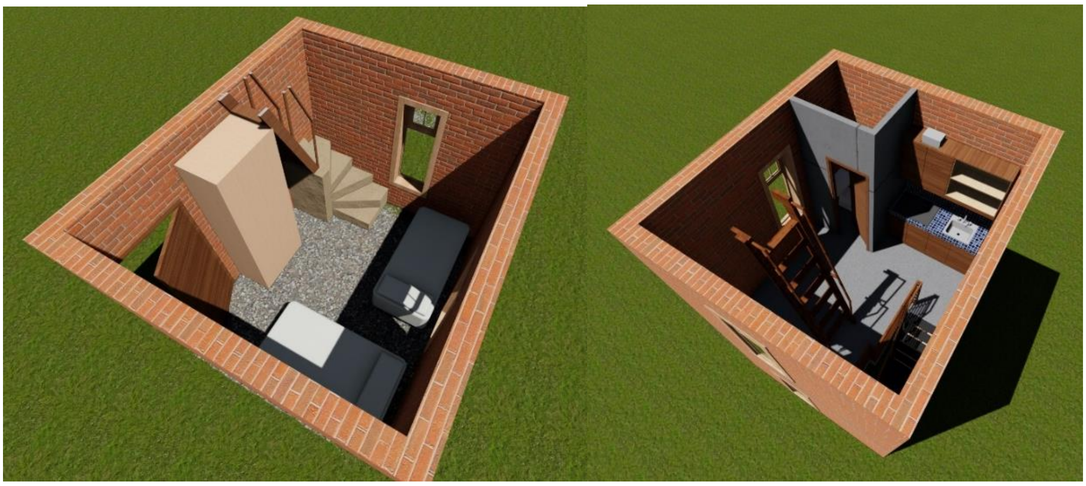
1. It could be square or rectangular in plan with a predetermined number of openings where the area and the size of each opening must be chosen carefully to guarantee that there would not be any structural implications.
2. It must have an upper floor accessed by a staircase which could resist floods (timber, steel or cement with the initial steps could be made out of cement stabilized rammed earth to reduce the cost) and the floor height could be decided between 3.0-3.5 m by considering 50 or 100 year return period flood height.
3. The upper floor must have a rooftop that can withstand a cyclone of the most probable extent to happen at a given area and consequently a solid concrete slab or a beam slab system could be used.
4. In an instance of floods of unforeseen water levels, the tenants must have the option to access the rooftop level to prevent any loss of lives and therefore, the roof slab must be designed for a higher live load in the range of 2-3 kN/m^2.
5. The rooftop should be of nature that would not attract lightning strikes.
6. It is desirable to have sanitary facilities as shown in Figure 4 (b), which could be utilised in case of prolonged floods where the rescue operation could take

longer to reach the occupants of refuge space. In addition, it is advisable to have reasonable storage space with a kitchen sink in the pantry on wall concept as shown in Figure 5. This could be used to prepare food on a stove that can be powered by Liquid Petroleum Gas (LPG) cylinders along with fresh water from the water tank situated on the rooftop.

Figure 5: Pantry on a wall with some storage facility

7. It should have a dependable water supply which should be made sure to prevent contamination of floodwater. Therefore, the water tank can be situated on the rooftop slab ensuring a continuous water supply for the whole house.

A conceptual 3D model developed using Revit software is shown in Figure 6. Figure 6 (a) shows the ground floor indicating the solid first few steps of the staircase, the small openings for enhanced robustness and the space available for arranging the furniture. Figure 6 (b) illustrates the first floor indicating the ladder that is available to reach the roof level in case of severe flooding and the washroom space and the pantry on wall concept with adequate storage. A 3D view with two adjacent walls hidden for better understanding shows the integration of above-discussed aspects of refuge space is given in Figure 7.



(a) (b)

Figure 6: (a) 3D view of the proposed ground floor layout (b) 3D view of the first floor

Figure 7: Exploded view of the refuge space

3.4 Precautious measures against scouring

From the above Figure 4, 6, and 7 it can be seen that the requirements mentioned in section 3.1 have been integrated into the refuge space except for the cost-effective solutions against scouring of soil around foundation when the existing soil is sandy. When the soil composition contains 10-15% clay and slit particles, the permeability of the soil reduces significantly resulting from the cohesion of clay particles when the soil is not fully dry nor saturated (Gunaratne et al., 2007). Once such soil is laterite soil that is found in tropical countries, which contains gravel, sand, clay, silt and some impurities like organic matter from vegetation and roots of trees.

Due to the presence of clay, such soils with low permeability will have enough time lag to ensure the initial flood waves would not cause scouring and hence preventing the failure of the foundation. Therefore, even if sandy soil is seen in a place where scouring is susceptible, an additional clayey soil layer of 150-200 mm can be introduced as a well-compacted soil layer to prevent flood induced scouring of soil. This can be combined with the layout discussed above to provide a cost-effective refuge space for every household in flood-prone areas.

3.5 Earthquake resistant features for the two-storey refuge space

When earthquakes are considered, it is vital to know about the probable types and magnitudes of that can hit the area of interest. Regarding Sri Lanka, it is located well within the Indo-Australian tectonic plate. Therefore, Sri Lanka is only susceptible to be hit by intraplate earthquakes. The historical deposits state an occurrence of a major event of earthquake only in 14^{th} of April in the year 1615. From the damages reported and documented, the magnitude has been assessed as about 6.0 on the Richter scale. Other than this event, most recent records indicate earthquakes with magnitudes that are less than 5.5 in Richter scale.

Another important fact is that the epicentre of these occurred earthquakes is more than 100 km away from the western coasts of Sri Lanka. Earthquake events occurring at this far will not be able to cause liquefaction of saturated sandy soil. Liquefaction will never occur in saturated sandy clayey soils or partially dry sandy clayey soils which are the main type that the lateritic soil found in abundance inland falls into. Sandy soils without much clay can be found only close to the coast and hence can be easily improved by mixing with clay if liquefaction is ever suspected (Gunaratne et al., 2007; Jayasinghe, 1999; Mallawaarachchi et al., 2007).

There is no need to have additional precautious measures for loadbearing masonry walls against earthquakes affecting refuge spaces when such favourable conditions prevail. However, the following precautious measures can be implemented in refuge spaces to adopt even in countries where moderate to severe earthquakes are susceptible (D'Altri, Messali, Rots, Castellazzi, & de Miranda, 2019; Dilhani & Jayaweera, 2016; Franco, Sheth, & Meyer, 2013; Hussain & Mahendran, 2010; Jayasinghe et al., 1997; Khazai et al., 2006).

1. Openings must not be placed near the edge of any wall.
2. Reinforced concrete band beams with a minimum of 2 Nos. of 8 mm high yield steel bars must be provided at windowsill level, lintel level on both ground and first floors.
3. Tie beam should be provided at the ground floor level at the plinth level to ensure the whole foundation to function as one unit in case of an earthquake.

3.6 Lightning resistance of two-storey refuge cell

Due to the use of a reinforced concrete slab, the chances of lighting hitting a flat roof will be extremely rare when other taller houses or buildings or trees are located surrounding it. In addition, to increase the level of thermal comfort in the refuge space, Expanded Polystyrene (EPS) based lightweight concrete panels can be used as an insulative material for the flat roof slab.

3.7 Cost-effective materials for the construction of the refuge cell

In order to make this facility accessible for the whole population, especially low to mid-income families whose houses are situated in flood-prone areas, the cost of construction needs to be kept minimal while ensuring adequate safety. Since the cost of construction materials influences the overall cost as a significant percentage, discovering economical solutions and materials is vital. Some of the technologies are listed below:

1. The foundation of the refuge space must rest on firm ground with sufficient depth to avoid excessive settlements from having two stories. If sandy soil is found to be present below the foundation on the site, it is advisable to follow the above-discussed method by excavating deeper than required and making a soil layer by mixing clayey soil with the excavated soil and backfilling the trench before constructing the foundation. This will minimize the probabilities of failure by scouring and liquefaction of soil.
2. Since reinforced concrete frames with masonry infill walls could be more expensive, it is preferable to use loadbearing masonry as structural elements to minimize the cost of construction. The lateral load resistance of walls specified in the building regulations (minimum thickness of 100 mm) (Dilhani & Jayaweera, 2016; Franco et al., 2013; Jayasinghe et al., 1997) in practice nowadays in Sri Lanka is much low, it is advisable to use one brick thick walls with a wall thickness of above 200 mm when completed. When cement blocks are used, the walls could be constructed out of 150 mm or preferably 200 mm blocks. Bricks passing basic quality checks such as ringing sound and dropping a brick on another from 1.2 m height could easily achieve characteristics strengths above 1.5 MPa when constructed with 1:5 or 1:6 cement sand mortar (Jayasinghe, 1998). Therefore, with the careful selection of wall thickness and quality ensured walling units to resist lateral loads, walls at the ground level can function as a loadbearing structural member regardless of the type of masonry unit used comprising of fired bricks, cement blocks, and etc.
3. The floor slab is another important aspect that determines the overall cost of construction. Hence, it is necessary to have cost-effective floor systems for the refuge space. The floor could be made of timber, reinforced concrete, or any other suitable material. However, in order to ensure the stability against buckling induced compressive failures of loadbearing masonry walls, it is preferred to have a slab system that would effectively reduce the effective height of the wall. In this context, it is preferred to have a stiff slab system such

as reinforced solid slab, reinforced concrete beam slab composite system or a precast prestressed beam with in situ cast reinforced concrete slab system (Sanjaya, Srilal, Perera, & Sooriyaarachchi, 2015). A suitable system can be chosen from one of the above-mentioned systems or any other suitable system depending on the aesthetic appeal and the financial status. Having such a system would enhance the lateral load resistance of the stiff masonry wall due to the vertical stresses acting on the walls. However, one shortcoming is the earthquake-induced forces are affected by the increased mass of the floor.

4. Access to the top floor must be provided with a suitable staircase. Parameters like the rise, going and the number of steps must be selected carefully while providing the staircase to reduce the loss of valuable useable space. In this context, the floor to floor height could be maintained between 3.0 m to 3.5 m. This will ensure that the minimum height requirement of 2.7 m specified in the building regulations adopted to suit the tropical climatic conditions are met. The rise could be selected between 175 mm to 200 mm. The going must be a minimum of 225 mm with 250 mm being preferred to ensure safe usage. When 225 mm going is provided, a 20-25 mm nosing can be provided to extend the going to reach 250 mm. In order to minimize the cost, the first 6 steps of the staircase could be constructed with cement stabilized earth as illustrated in Figure 8. In the construction of these initial steps of the staircase, any construction debris of masonry or concrete origin could also be mixed with the soil prior to the stabilization. It should be made sure that at least 5% of cement is used for the stabilization of the soil (Venkatarama Reddy & Prasanna Kumar, 2011). The rest of the staircase could be made from either precast or in situ cast reinforced concrete. It is also possible to use a strong and durable locally grown timber variety to construct the staircase as shown in Figure 8.

Figure 8: First few solid steps of the staircase out of CSRE

Figure 9: Steep stairs made with timber or steel to contain the cost

5. The upper floor roof must be out of concrete slab with enough weight in order to provide adequate cyclone resistance to the refuge space. This would ensure that the wind-induced uplift forces will not be critical to damage the refuge space. In this context, the roof can be either a reinforced concrete solid slab or a precast beam slab system (Eric et al., 2019; Gunawardana et al., 2019; Sanjaya et al., 2015). Generally, the use of loadbearing masonry for walls with relatively small plan dimensions will ensure that the wind-induced lateral loads will not have any significant effect even under the cyclonic conditions. However, this roof will need a covered opening with a steep staircase at an angle about 60^o to horizontal or a ladder to provide access to the rooftop in case of extreme flood events where the flood height could easily exceed the 50-100 year return period flood levels to which the first floor height is decided.
6. The upper floor slab with limited access can be used to provide a water tank of adequate capacity around 500 -1000 litres. This can be connected to the main water supply of the house so that fresh water will be available always without stagnation due to the constant daily use. A separate outlet can be provided for the supply of water is preferred to the refuge space to ensure no contamination with floodwater due to back-siphonage from the submerged pipes and faucets of the ground floor in an event of flood.
7. It is preferred to have a small washroom at the first-floor level as shown in Figure 10 for usage when the occupants are stuck in the refuge space waiting for rescue services to reach. Since the walls of the washroom are supported by the slab itself, it is advisable to use suitable lightweight partitions such as Expanded Polystyrene (EPS) based lightweight concrete (density 650-750 kg/m^3) panels. Such panels can be easily used for partitions without inducing excessive stresses on the supporting slab system.

Figure 10: Lightweight Partition walls of the washroom to prevent the overloading of the first-floor slab

All these features will ensure a safe refuge space that will have all the basic facilities whilst keeping the cost of construction relatively low. The main advantage of having a similar refuge space is that both ground and first floor of the refuge space could be utilised under the normal day to day activities and therefore, it must not be considered as a burden on the newly constructed house.

3.8 Summary

One of the key needs of disaster resilience is saving the lives. The most vulnerable category for flood-related disasters is children since there is a high chance for them to be carried away by the flash floods even of small magnitudes. In some instances, flash floods could occur over the night while the occupants are asleep, and it may be too late to escape to high grounds. Having a refuge space in each house could save the lives and valuables of occupants.

The vital features required for the refuge space were identified and the layout is developed accordingly. Precautious measures to prevent scouring of soil due to flowing water were discussed. Features to resist not only floods but also hazards like earthquakes, cyclones, and lightning were included in developing the concept. An additional escape route to the rooftop that could be utilised in an event of extreme weather condition was discussed. Furthermore, cost-effective materials and technologies which could make the refuge space affordable for most of the population was discussed in brief.

4. SURVEY CARRIED OUT

4.1 Pairwise comparison

An online survey was carried out among a selected group consisting of 70 people which included civil engineers, academics, professionals from various fields and the general public. The purpose of this survey was to identify the preference of level of importance of each factor over the other to formulate the multi-criterion decision making process framework. In addition, the survey was used to discover any other parameter that a decision maker would consider in selecting a construction material and needs to be included in the study. The survey included a pairwise comparison of the following listed parameters.

1. Cost of construction
2. Strength of the material
3. Durability of the unit
4. Construction time
5. Thermal comfort level
6. Greenness and sustainability

An extract of the questionnaire is shown in Figure 11. Similarly, pairwise comparison for each parameter was followed.

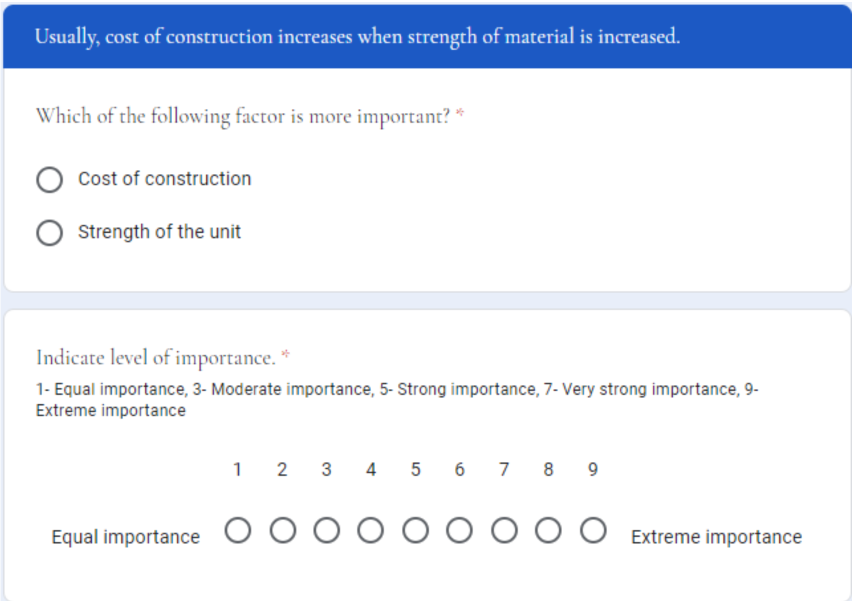


Figure 11: Extract of the questionnaire

In addition to what parameter the survey participant prefers out of the given two parameters, the importance level is also recorded from the participant as in the scale as shown in Table 1.

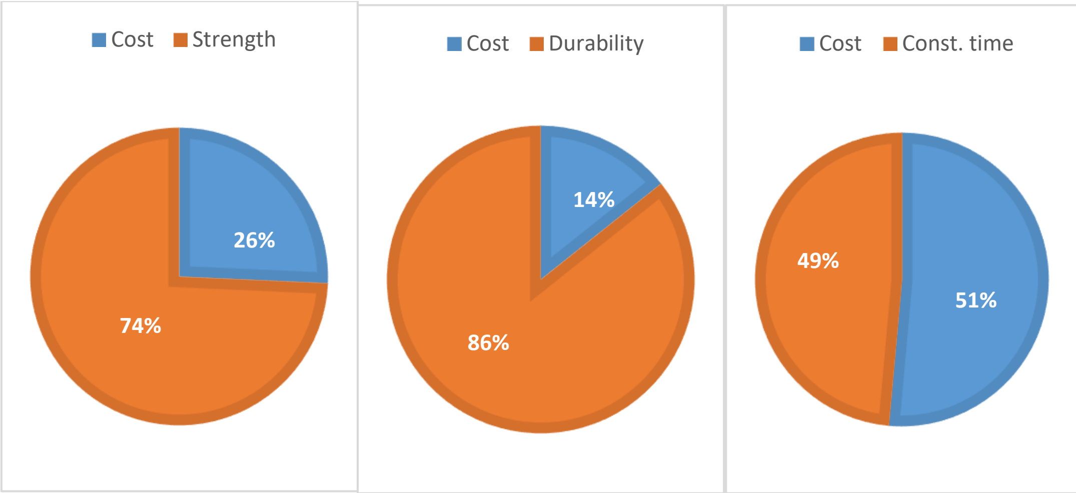
Table 1: Interpretation of the scale used in the survey

Intensity of importance on absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favour one activity over another
5	Strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	Activity is strongly favoured, and it is dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

The summary of the responses received is tabulated in Table 2. The number of people who preferred each factor over the other in each pairwise comparison is depicted as pie charts in percentages.

Table 2: Summary of responses received

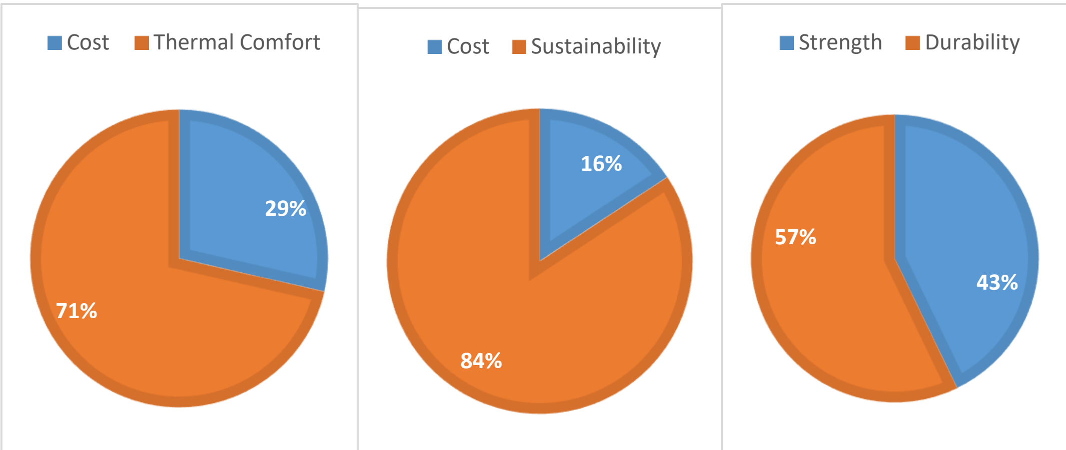
Pair	Total responses	Number of Importance factor responses								
		1	2	3	4	5	6	7	8	9
Cost	18	3	0	4	0	4	3	2	0	2
Strength	52	5	4	6	0	6	7	9	6	9
Cost	10	1	1	0	3	1	3	0	0	1
Durability	60	9	3	7	1	9	5	16	4	6
Cost	36	5	3	4	3	7	3	5	3	3
Const. time	34	5	1	0	2	11	5	5	3	2
Cost	20	2	2	0	2	10	1	1	1	1
Thermal Comfort	50	5	0	5	6	7	2	11	6	8
Cost	11	0	0	1	2	3	0	3	0	2
Sustainability	59	0	4	8	3	7	4	8	6	19
Strength	30	9	3	0	0	6	6	4	0	2
Durability	40	6	2	2	2	11	6	8	2	1
Strength	49	3	1	7	2	9	8	11	3	5
Const. time	21	1	2	1	1	6	2	4	1	3
Strength	33	2	1	5	2	10	2	7	0	4
Thermal Comfort	37	5	1	2	2	10	2	7	3	5
Strength	20	5	1	2	0	1	4	4	0	3
Sustainability	50	2	0	9	2	8	10	8	3	8
Durability	50	1	2	10	1	12	9	7	5	3
Const. time	20	2	0	0	2	5	4	2	3	2
Durability	30	3	3	3	4	7	3	3	3	1
Thermal Comfort	40	2	1	5	5	4	8	4	5	6
Durability	18	3	1	2	1	2	2	3	4	0
Sustainability	52	6	3	5	4	9	6	6	7	6
Const. time	18	4	1	6	1	0	1	4	1	0
Thermal Comfort	52	0	2	4	2	13	7	7	10	7
Const. time	12	2	0	2	0	1	1	3	3	0
Sustainability	58	3	0	4	4	13	8	10	4	12
Thermal Comfort	19	2	0	3	1	1	1	6	4	1
Sustainability	51	5	3	6	3	4	3	7	7	13



(a) (b) (c)

Figure 12: Pairwise comparison percentages

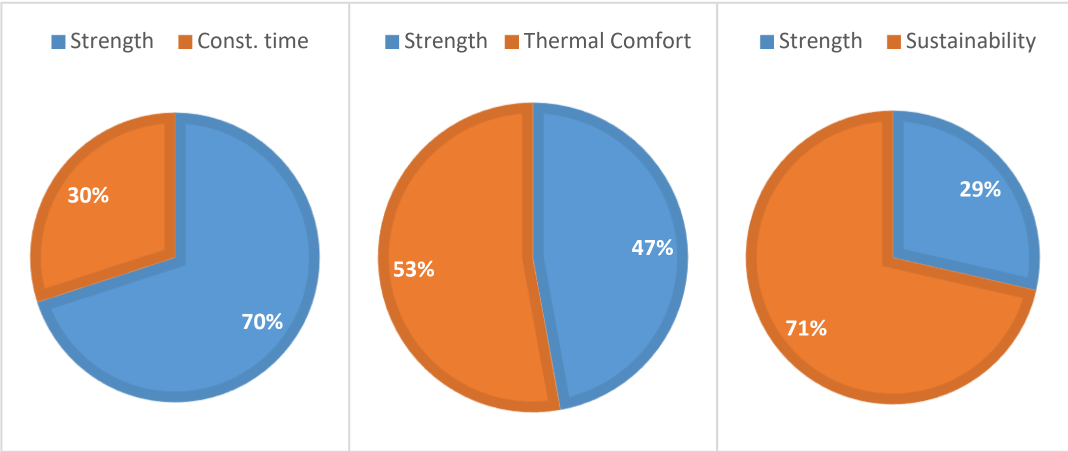
It can be seen from Figure 12 (a) and (b), and Figure 13 (d) and (e), that almost 75 % of the respondents prefer to have stronger, durable, sustainable material that could provide a thermally comfortable space over a cheaper alternative that could perform less in the above-mentioned properties. However, when it comes cost and construction time, half of the respondents preferred cost over construction time and the rest of them, vice versa (See Figure 12 (c)).



(d) (e) (f)

Figure 13: Pairwise comparison percentages

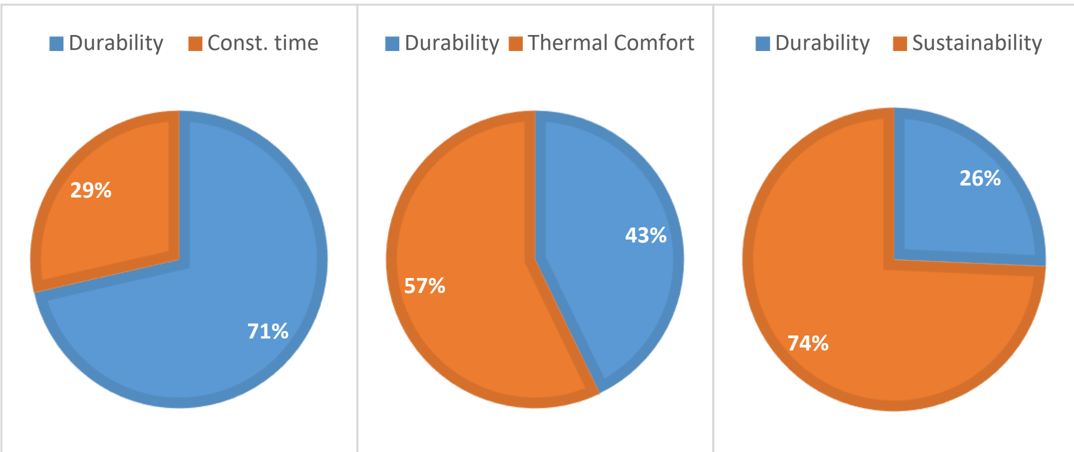
Regarding strength, about 70% of the respondents chose strength over construction time (see Figure 14 (g)) and nearly 55% of the respondents prefer to have a durable and thermally comfortable space over a stronger one (Figure 13 (f) and Figure 14 (h)). Furthermore, it can be seen that about 70% of respondents prefer a more sustainable material than a stronger less sustainable alternative (Figure 14 (i)).



(g) (h) (i)

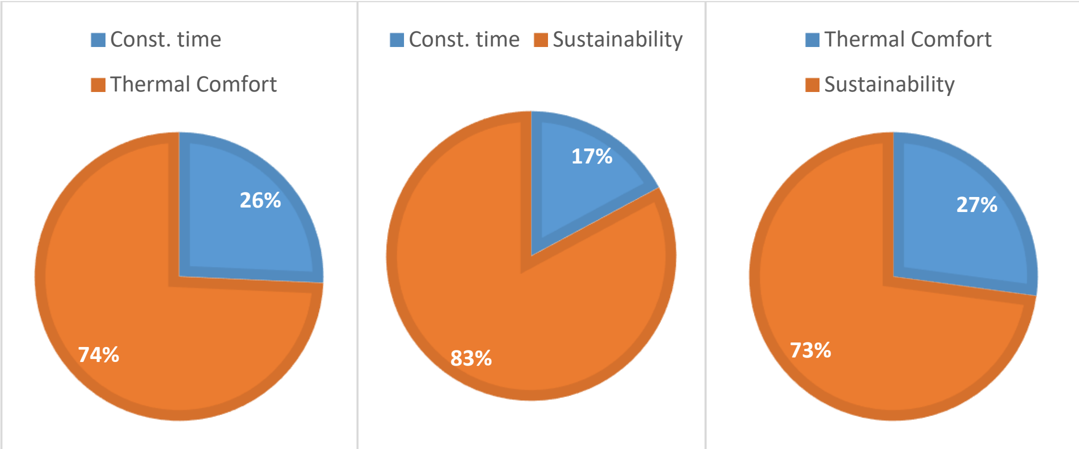
Figure 14: Pairwise comparison percentages

While 70% of the respondents prefer a durable material that takes longer to construct than a lesser durable material which might be a rapid construction method (Figure 15 (j)), about 75% and 60% of the respondents prefer sustainable material and better thermally comfortable space, respectively over durability (Figure 15 (l) and (k)).



(j) (k) (l)

Figure 15: Pairwise comparison percentages



(m) (n) (o)

Figure 16: Pairwise comparison percentages

More than 70% of the respondents have chosen thermally comfortable space and a sustainable material over the construction time of the space (see Figure 16 (m) and (n)). Although thermal comfort is closely connected to sustainability, 73% of the respondents have chosen a sustainable material over a thermally comfortable space.

From the above results, it is evident that sustainability, durability, thermal comfort, and strength were seemed to be the factors attracting a decision maker while cost and construction time were given only a little focus.

4.2 Additional comments

The response received as additional comments for any other factors that should be considered for the selection of material are listed below.

1. Constructability
2. Availability of materials
3. Material handling
4. Aesthetic appearance and visual comfort
5. Water Absorption
6. Permeability
7. Acoustic comfort

Most of the above-mentioned factors are covered in the selected properties either directly or indirectly. For example, availability of the material would be included as in embodied energy and embodied carbon spent on transportation of the material. Some of the parameters such as water absorption, permeability, acoustic comfort, and visual comfort were not included considering the time limit and the unavailability of the suitable instruments to carry out the required experiments.

5. COMPARATIVE STUDY

5.1 General

In order to compare the performance of each alternative in a parameter listed above, appropriate property/properties of materials which represents the level of performance of the respective parameter clearly, were carefully selected. The details are discussed here as in the following topics.

1. Cost of construction
2. Strength of the material
3. The durability of the unit
4. Construction time
5. Thermal comfort level
6. Greenness and sustainability

The comparative study is conducted between lightweight concrete wall panels as an alternative material and hollow cement blocks and fired clay bricks as conventional materials as these were identified as the most suitable and widely available in the country for consumers.

5.2 Cost of construction

A cost analysis was carried out in order to compare the total cost of construction of all three alternatives. This includes the cost for materials and transportation if applicable, labour cost and rentals of equipment and services wherever applicable. The standard building schedule of rates (BSR) was used along with the work studies carried out to fulfil the task. It is notable that there was no standard schedule of rate for the LWC panel construction in Sri Lanka. Work studies and cost analysis of the full-scale model were used to establish the rates for the LWC panel constructions and NERDC slab system. In order to make the comparison fair, rates from the year that the BSR was prepared were used. Tables 3, 4, and 5 show the summary of the findings from the work-study on the full-scale model.

The BSR rate of 150 mm blockwork masonry including wall plaster on both sides was calculated to be Rs. 4,974 per m^2 compared to Rs. 4,332 per m^2 for LWC panels construction which is about 12.9 % cheaper. The BSR rate for 100 mm (4") thick HCB and brick construction was found to be Rs. 3,703 per m^2 and Rs. 4,656 per m^2 correspondingly, compared to Rs. 3,679 per m^2 making the LWC panel construction 0.7% and 21% cheaper than HCB and brick construction, respectively.

Table 3: 150 mm (6") thick LWC panels in cement and sand mortar 1:5, cement paste and 2 Nos of 6mm mild steel dowel bars per panel in the ground floor

No	Item Description	Unit	Quantity	Rate	Amount
1.01	6" Thick LWC panels	No	6.25	5,600.00	35,000.00
1.02	Allow 5% of Items (1.01) for Wastage	-	-	-	1,750.00
1.03	Cement	Bag	0.45	1,005.00	452.25
1.04	Sand	Cube	0.006	17,000.00	102.00
1.05	6 mm mild steel	kg	1.03	68.00	70.04
1.06	Mason	Day	0.5	2,000.00	1,000.00
1.07	U / SK Labourer	Day	1.5	1,200.00	1,800.00
1.08	Allow 3% of Items (1.05, 1.06) for Scaffolding	-	-	-	84.00
	Total for	1	Sqr		40,258.29
	Rate for	1	Sqr		40,258.29
-	**Rate (Say)**			**1 Sq**	**40,258.00**
-	**Rate (Say)**			**1ft²**	**402.58**
-	**Rate (Say)**			**1m²**	**4,331.76**

Table 4: 100 mm (4") thick LWC panels in cement and sand mortar 1:5, cement paste and 2 Nos of 6mm mild steel dowel bars per panel in the ground floor

No	Item Description	Unit	Quantity	Rate	Amount
1.01	4" Thick LWC panels	No	6.25	4,800.00	30,000.00
1.02	Allow 5% of Items (1.01) for Wastage	-	-	-	1,500.00
1.03	Cement	Bag	0.3	1,005.00	301.50
1.04	Sand	Cube	0.004	17,000.00	51.00
1.05	6 mm mild steel	kg	1.03	68.00	70.04
1.06	Mason	Day	0.5	2,000.00	1,000.00
1.07	U / SK Labourer	Day	1	1,200.00	1,200.00
1.08	Allow 3% of Items (1.05, 1.06) for Scaffolding	-	-	-	66.00
	Total for	1	Sqr		34,188.54
	Rate for	1	Sqr		34,188.54
	Rate (Say)			**1 Sq**	**34,188.54**
	Rate (Say)			**1ft2**	**341.89**
	Rate (Say)			**1m^2**	**3,678.69**

Table 5: Placing precast prestress NERDC beams including preparation, transportation, and filling gaps with cement slurry

No	Item Description	Unit	Quantity	Rate	Amount
1.01	NERDC precast beams	No	1	265.00	265.00
1.02	Allow 5% of Items (1.01) for Wastage	-	-	-	13.25
1.03	Cement	Bag	0.01	1,005.00	10.05
1.04	Sand	Cube	0.0002	17,000.00	51.00
1.05	Mason	Day	0.005	2,000.00	10.00
1.06	U / SK Labourer	Day	0.01	1,200.00	12.00
1.07	Boom truck operator	Hour	0.02	500.00	10.00
1.08	Allow 5% of Items (1.05, 1.06) for Scaffolding	-	-	-	1.10
	Total for	1	Lft		372.40
	Rate for	Lft			372.40
-	**Rate (Say)**			**1 Lft**	**372.40**
-	**Rate (Say)**			**1m**	**1,221.47**

Using the results obtained and the BSR, cost comparison is carried out as shown in Table 6. It should be noted that plumbing, wiring, and installation of the prefabricated staircase were not included in the study due to the lack of data and as they will be the same for each building type. The detailed cost analysis is attached in appendix A.1.

Table 6: Summary of cost analysis

No.	Description	LWC panels (Rs.)	HCB (Rs.)	FB (Rs.)
1	Foundation	60,403	60,403	60,403
2	Floor (GF)	32,882	32,882	32,882
3	Walls (GF)	179,168	205,925	259,837
4	Lintel beams	3,212	3,889	3,889
5	Floor slab (FF)	77,833	84,317	84,317
6	Walls (FF)	234,353	248,713	314,958
7	Lintel beams	3,271	3,963	3,963
8	Roof slab	101,988	118,841	118,841
9	Painting	100,048	100,048	100,049
10	Doors and windows	129,677	129,677	129,677
11	Tiling	133,784	133,784	133,784
	Total	**1,056,622**	**1,122,442**	**1,242,601**
	Cost/m^2	**39,250**	**41,695**	**46,159**

The LWC panel construction was observed to be 5.86% cheaper than HCB and 14.97% cheaper than brick construction. The cost reduction is mainly from the wall construction with lesser influence from the precast slab system. Therefore, it can be concluded that LWC panels are performing better than HCB and brick construction in two-storey refuge space construction followed by HCB in second place and bricks being the third.

5.3 Strength of the material

Strength of the material covers numerous topics. Generally, for walling materials, especially loadbearing masonry walls, compressive strength is the widely discussed topic as the wall transfers its self-weight and the load from the upper floors to the ground through the foundation. Since loadbearing masonry structures are commonly seen only in low rise buildings, lateral load resisting capacity is not generally focused as wind loads are not much significant. However, the refuge spaces are suspected to undergo lateral loads in the form of floodwater pressure, cyclone induced forces and seismic forces at rare instances. Therefore, this study has been carried out considering both the compressive strength and the flexural strength.

Fernando et al., (2017) conducted compression and flexural load tests on 100 mm thick LWC panels. In this study, both short and full height panels were tested to distinguish the buckling effects, as with the height increase slenderness of the panel will increase. The height of the short panels were 690 mm and 2400 mm for full height panels. The compressive strengths were observed to be 4.06 N/mm^2 for short panels and 2.89 N/mm^2 for full height panels. The slenderness ratios were found to be about 7 and 24 for short and full height panels, respectively.

A similar study was conducted by Abhayawickrama, (2017) on 150 mm thick full height LWC panels to establish the strength properties of the 150 mm wall panel. Since the slenderness ratio of the 150 mm panels was less than the 100 mm panels, short panels were not tested. The compressive strength of the 150 mm panels was found to be 2.33 N/mm^2.

Fired bricks are available in various strengths depending on the manufacturing quality. According to Perera et al., (2015), the minimum compressive strength specified by the Sri Lankan Standards Institute is 2.8 N/mm^2 and it is not met by many manufacturers. Compressive strength of 2.64 N/mm^2 was observed in study carried out by Konthesingha et al., (2007). Therefore, the compressive strength of brick unit is assumed to be 2.8 N/mm^2 for the comparative study. The hollow cement block considered in this study is produced by International Construction Consortium (ICC) Pvt. Ltd. The compressive strength of this unit was found to be 8.5 N/mm^2 in a study carried out by Baskaran et al., (2019). The widely used mortar in Sri Lanka is cement sand mortar with 1:5 ratio and a joint thickness around 12-17 mm.

The characteristic compressive strengths of masonry units are converted to normalised compressive strengths according to BS EN 772-1:2000 standard and the compressive strengths of the masonry walls are calculated according to Eurocode 6 (BS EN 1996-1-1:2005). The detailed calculations are given in appendix A.2. Compressive strengths of different materials are compared in Table 7.

Similarly, the flexural strengths of the walling materials were obtained using the UK national annex for Eurocode 6 as EC 6 provides more generalised values for the flexural strength. The flexural strengths of the materials are compared in Table 8.

Table 7: Compressive strengths of walling materials

Material	Compressive strength (N/mm^2)	Source
Fired bricks	1.39	(Konthesingha et al., 2007; Perera et al., 2015)
HCB	3.96	(Baskaran et al., 2019)
LWC panel – 150 mm	2.33	(Abhayawickrama, 2017)
LWC panel – 100 mm	2.89	(Fernando et al., 2017)

From the above results, both 100 mm and 150 mm panels have a higher compressive strength than the brick masonry. However, the hollow cement block masonry was observed to be performing better in terms of compressive strength than the LWC panels.

Table 8: Flexural strengths of walling materials

Material	Flexural strength (N/mm^2)	Source
Fired bricks	0.4	UK National Annex for EN 1996-1-1:2005
HCB	0.22	UK National Annex for EN 1996-1-1:2005
LWC panels – 150 mm	1.03	(Abhayawickrama, 2017)
LWC panels – 100 mm	1.64	(Fernando et al., 2017)

Regarding flexural strengths, it was observed that the LWC panels are performing better than both brick and hollow block masonry constructions which is a crucial property for refuge space where the wall could be expected to resist lateral loads from the floods. This is followed by brick masonry and then hollow blocks having the least flexural strengths.

5.4 Durability

The durability of walling materials could be assessed in different methods according to the environment that the material will be subjected to or used. However, for a tropical country like Sri Lanka, considering the environment, the refuge space will be mostly subjected to decay and erosion due to the effects of rain such as bouncing drop rain and wind-driven rain. Hence, accelerated surface erosion test was chosen for the comparative study.

The durability of the EPS based lightweight concrete panels was assessed with accelerated surface erosion test according to ASTM C744 along with SLS 1382-2-2009. A set of well-cured samples were obtained from the manufacturer and three samples with 200 mm × 200 mm dimensions were obtained from different wall panels. These samples were oven-dried for 24 hours at 105 ± 5 °C followed by saturation by immersion for another 24 hours. The samples were left to dry in room temperature and then tested in the erosion test apparatus as shown in Figures 17 and 18.

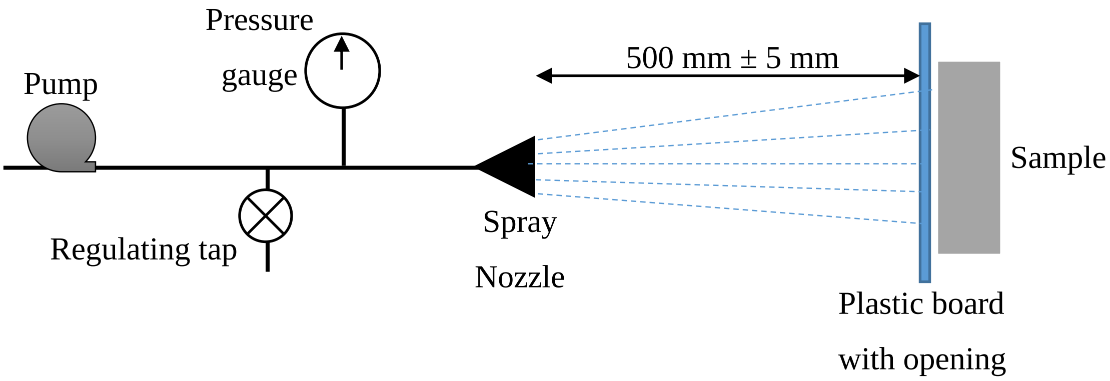
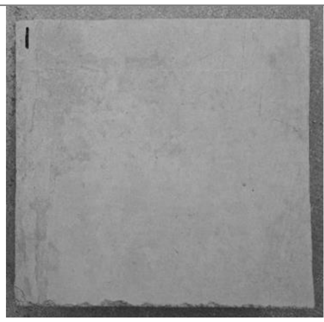
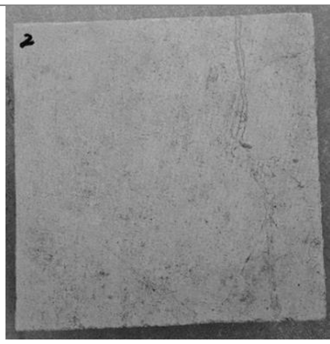


Figure 17: Schematic of erosion test apparatus

Figure 18: Erosion test on progress

The testing procedure can be explained as follows. The sample was placed 500 mm away from a spray nozzle and water was sprayed horizontally at a constant pressure of 50 kPa. The area exposed to the water spray was limited to a circle of 150 mm diameter by placing a transparent plastic board with an opening of the same dimensions. Each sample was exposed to the spray for a total of 60 minutes (1 hour) with pit depths observed in 15 minutes interval. Usually, LWC panels are manufactured by sandwiching fresh lightweight concrete between two cement fibre boards and hence, the erosion test was carried out on samples with cement fibre boards on both sides. Although it is a highly unlikely occurrence for the cement fibre board to be removed from the panel when used as walls, a sample was exposed to erosion test without the cement fibre boards. The pit depth was measured using a Vernier calliper's depth measuring face by recording initial and final readings. Table 9 shows the photographic records and the observed pit depths of the accelerated erosion test.

Table 9: Photographic records of erosion test

Sample No.	**Before the test**	**After the test**
1		
	Pit depth = 0.0 mm	
2		
	Pit depth = 0.0 mm	

3		
	Pit depth = 0.0 mm	
4 (without cement fibre board)		
	Pit depth = 0.8 mm	

Samples with cement fibre boards did not show any observable erosion after water spraying for 60 minutes. However, the sample without the boards showed a mild erosion of 0.8 mm after 60 minutes of spraying. Udawattha et al., (2018) carried out the accelerated erosion test on various other walling materials following the same methodology and apparatus. The comparison of pit depths over a period of 60 minutes in 15 minutes interval is tabulated in Table 10.

Table 10: Comparison of pit depths of different materials (Source: Udawattha et al., 2018)

Material	Pit depths (mm)			
	15 mins	**30 mins**	**45 mins**	**60 mins**
Fired bricks	0.2	0.6	0.8	1.1
Cement blocks	0.0	0.0	0.0	2.1
Cement plaster	0.2	0.8	1.6	2.1
Rough cement plaster	0.0	0.0	0.0	0.0
Lightweight wall panels	0.0	0.0	0.0	0.0
Lightweight wall panels (without fibre board)	0.0	0.0	0.0	0.8

From the results, the lightweight wall panels showed less erosion than cement blocks and fired bricks in both cases with and without fibreboard. Fired bricks observed to be performing better than the cement blocks leaving maximum erosion in cement blocks. However, it should be noted the durability of bricks and cement blocks could be improved with a cement plaster rendering.

5.5 Construction time

Construction time varies with many factors such as climate conditions, availability of equipment and machinery, skill level and experience of workers, technological knowledge, etc. Established work norms on the requirement of labour days per unit amount of common construction works in Sri Lanka were used to evaluate the construction time requirement. These data are widely used in industry for the preparation of estimations to get an approximate time and labour requirement. The labour requirements are based on a normal workday of 8 hours.

In this study, the two-storey refuge space developed in the previous chapters with the dimensions of 4 m × 3.5 m and floor to floor height of 3 m was constructed to see the labour requirement of this method of construction. Figures 19 and 20 show the construction process of the wall.

Figure 19: Construction process

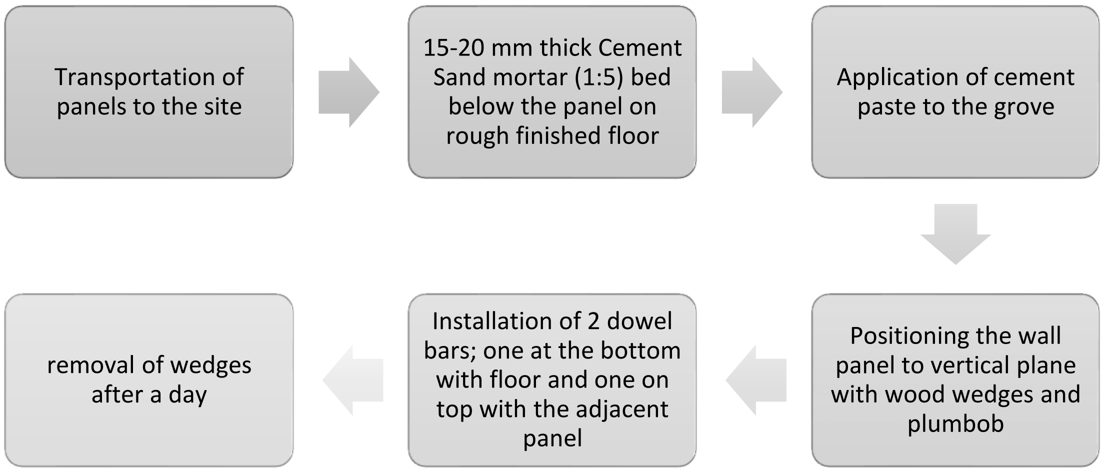


Figure 20: Construction process of walls

The summary of labour required for the LWC panel construction of a 3.048 m × 3.048 m (10 ft × 10 ft) is compared with other wall constructions found in established work norms in Table 11.

Table 11: Labour requirement for different wall constructions (10 ft x 10 ft)

Construction type	Skilled (labour days)	Unskilled (labour days)
LWC panels 100 mm	0.5	1
LWC panels 150 mm	0.5	1.5
HCB 100 mm w/ plaster on both sides	3	4.5
HCB 150 mm w/ plaster on both sides	3.5	4.5
HCB 200 mm w/ plaster on both sides	3.5	5
Bricks 110 mm w/ plaster on both sides	3.5	4.5
Bricks 220 mm w/ plaster on both sides	4.25	6.25

The total construction time in terms of labour days for each construction type was studied and compared in Table 12. The detailed calculations are attached in appendix A.3.

Table 12: Labour requirement for different wall constructions

No.	Description	LWC panels (labour days)			HCB (labour days)			FB (labour days)		
		Sk	U/sk	Total	Sk	U/sk	Total	Sk	U/sk	Total
1	Foundation	4	11	15	4	11	15	4	11	15
2	Floor (GF)	1	4	5	1	4	5	1	4	5
3	Walls (GF)	2	7	9	16	22	38	19	28	47
4	Lintel beams	1	2	2	1	2	2	1	2	2
5	Floor slab (FF)	2	6	9	4	10	14	4	10	14
6	Walls (FF)	3	8	11	19	28	47	24	34	58
7	Lintel beams	1	2	2	1	2	2	1	2	2
8	Roof slab	3	9	13	6	14	20	6	14	20
9	Painting	32	0	32	32	0	32	32	0	32
10	Doors and windows	16	6	22	16	6	22	16	6	22
11	Tiling	12	13	25	12	13	25	12	13	25
	Total	**77**	**68**	**145**	**111**	**112**	**223**	**119**	**124**	**242**

The study showed that LWC panels can be considered as rapid construction method compared to conventional brick and block constructions. Followed by HCB and bricks taking second and third positions in terms of construction time/ labour requirement. However, it should be noted that the erection of 150 mm thick LWC panels requires at least 3 unskilled labourers and a skilled labourer for handling while conventional methods require only an unskilled and a skilled labourer.

5.6 Thermal comfort

In order to assess the thermal performance of the lightweight concrete panels against conventional material, both the thermal conductivity method and time lag and decrement factor method were followed.

5.6.1 Thermal conductivity of lightweight wall panels

The thermal conductivity was measured using Lee’s disc method and it is given by the quantity of heat transmitted through a material in a unit time per unit temperature gradient and per unit cross-section.

The methodology of the testing is described as follows. Three samples were extracted by core cutter from different wall panels with a diameter of 50 ± 2 mm and 5 ± 1 mm thickness. The thickness of the sample is selected as low as possible to minimise the heat loss through the cylindrical face. This will also allow the system to reach a steady-state in a short period of time. In addition, the cylindrical face was thermally insulated to reduce heat loss further. At the steady-state, the amount of heat transfer (Q) across the thickness of the sample is given by equation 5.1.

$$Q = KA(T_1 - T_2)/x \qquad 5.1$$

Where Q – heat transfer through the sample

K - thermal conductivity of the sample

A - cross-sectional area

$(T_1 - T_2)$ - temperature difference between two faces

x - thickness of the aerated concrete sample

The sample was placed between two copper plates with thermocouples connected with data logger and insulated as shown in Figures 21 and 22. After ensuring good contact between the sample and the copper plates, the bottom plate/hot plate was heated with a heating element which could provide constant temperature and temperature readings of both top (cold) and bottom (hot) plates were recorded at an interval of 10 seconds.

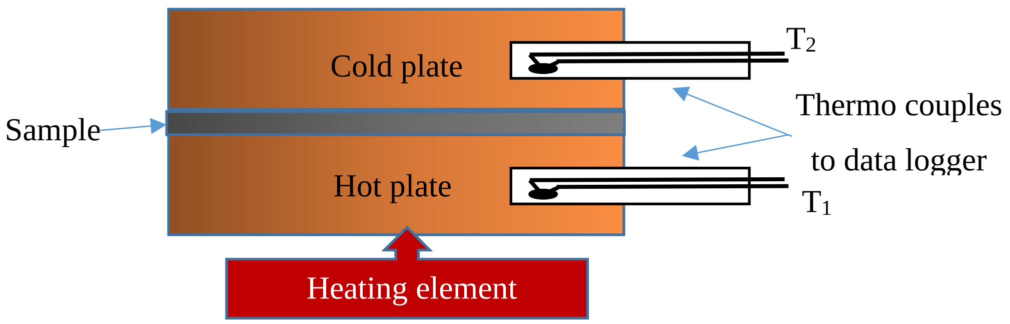


Figure 21: Schematic diagram of the apparatus

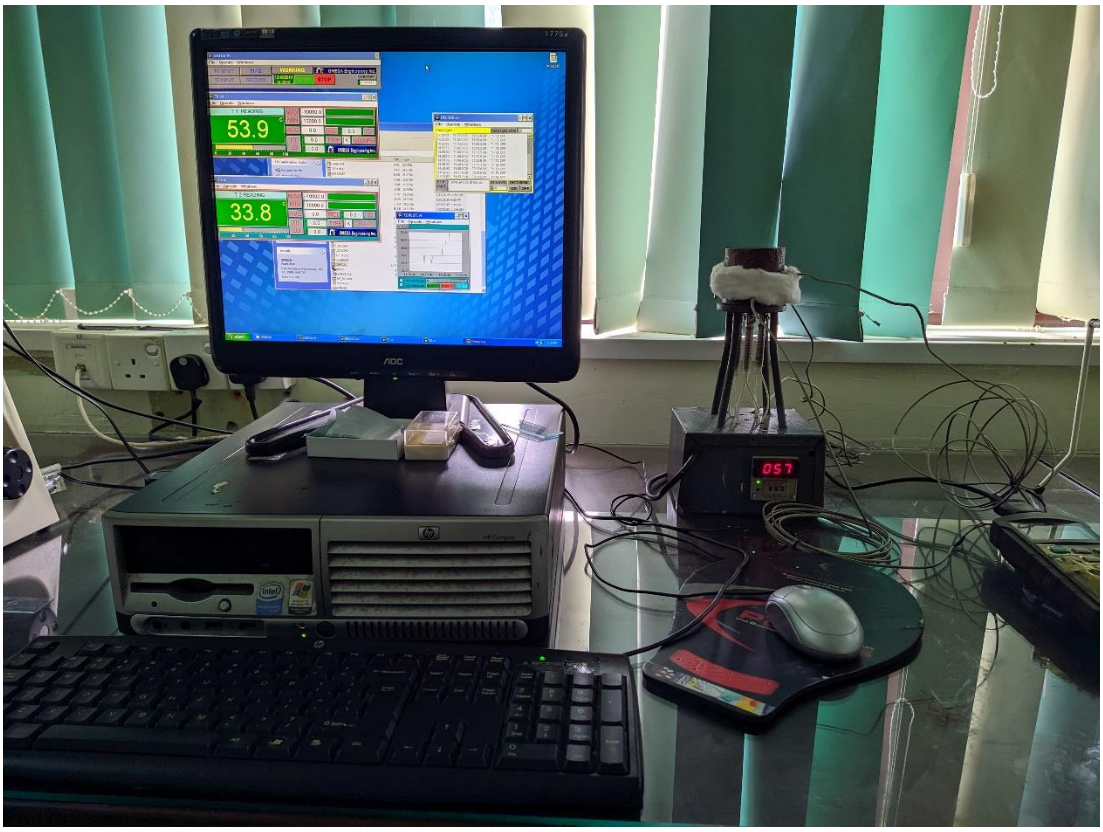


Figure 22: Instrument setup

After ensuring the system is in steady-state, the heating element was turned off. Then the top plate was removed and the face which was in contact with the sample was insulated and allowed to cool in the same environment conditions while recording the temperature readings at the same interval. This was conducted to obtain the cooling curve of the apparatus. At the steady-state, the heat transfer through the sample is equal to the heat loss from the top plate. The heat loss from the top plate is given by equation 5.2.

$$Q = mc\frac{dT}{dt} \qquad 5.2$$

Where Q – heat loss from the plate

m – mass of the plate

c – specific heat capacity of copper

$\frac{dT}{dt}$ – temperature gradient of the cooling curve

From equating equations 5.1 and 5.2, the thermal conductivity of the sample can be expressed as in equation 5.3.

$$K = \frac{mc\left(\frac{dT}{dt}\right)x}{A(T_1 - T_2)} \qquad 5.3$$

The temperature variation is plotted against time and a plot for a sample tested is given in Figure 23.

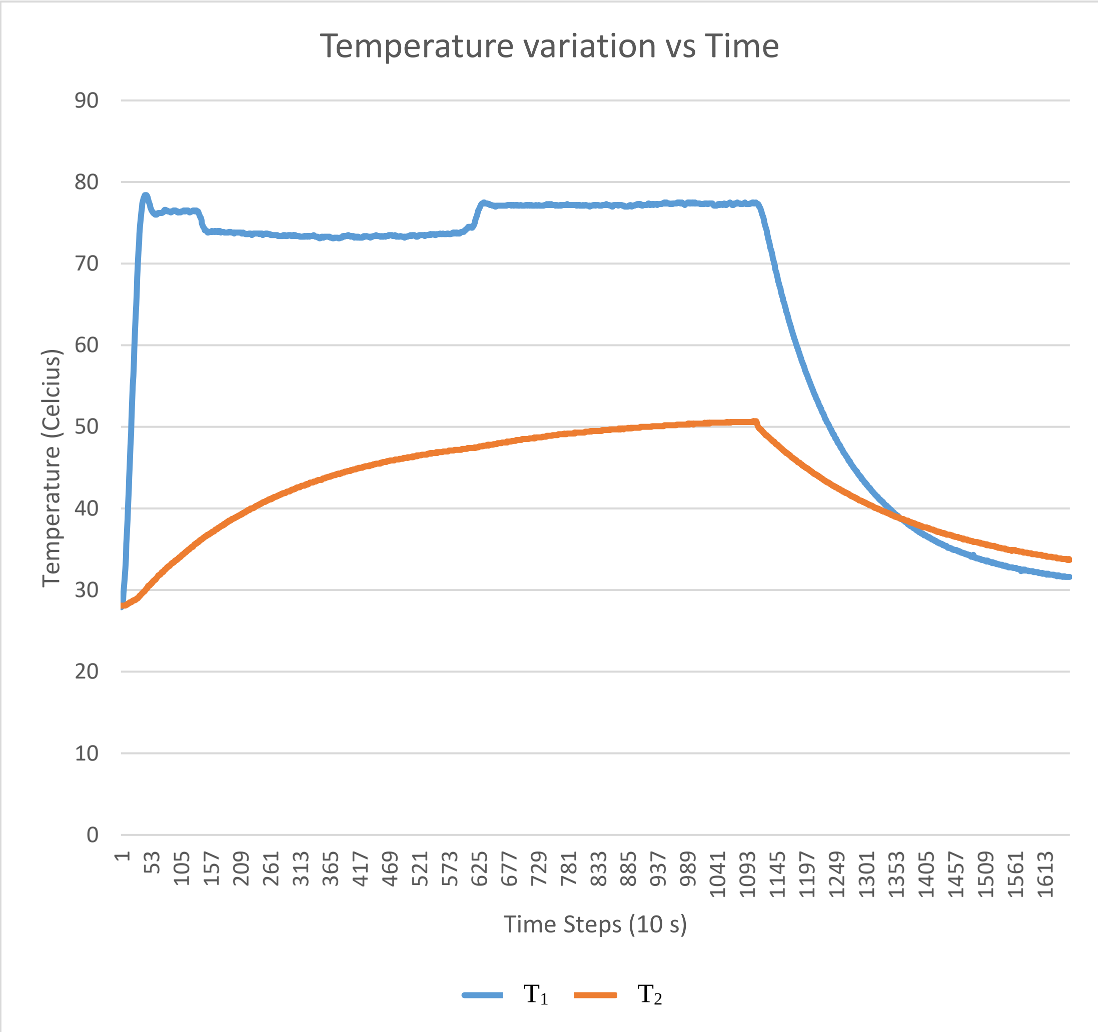


Figure 23: Temperature readings vs Time

The value of $\left(\frac{dT}{dt}\right)$ was calculated from the cooling graph of the Top/Cold plate as shown in Figure 24.

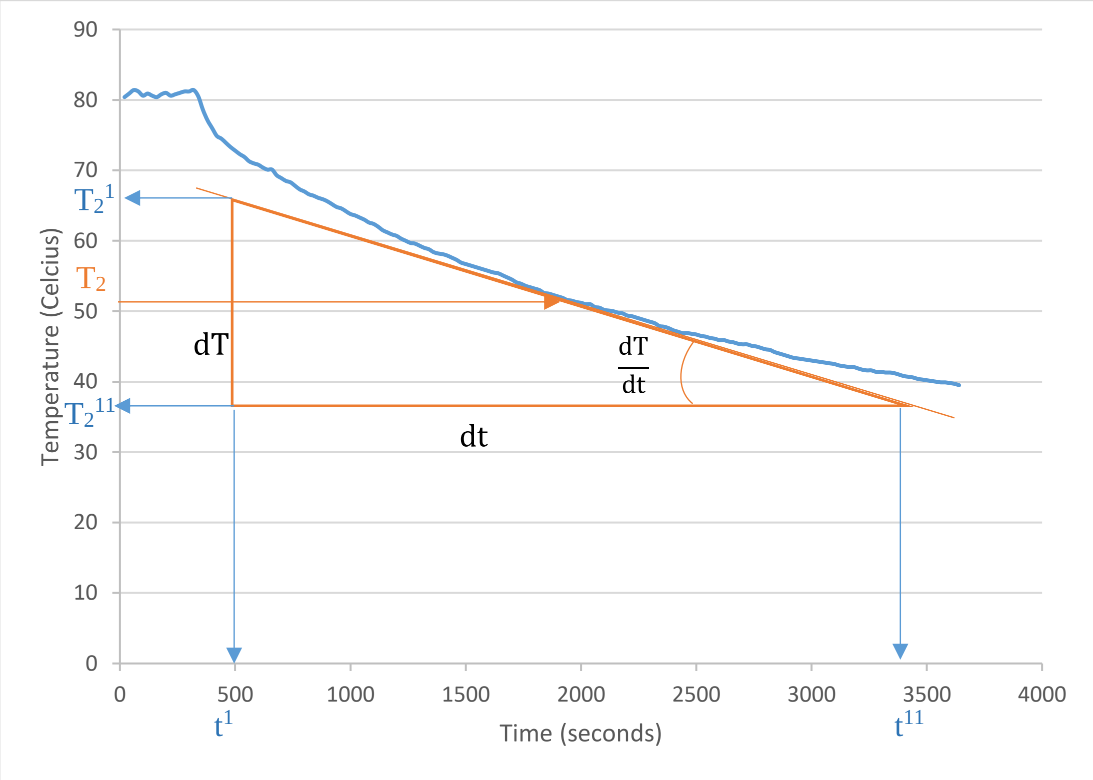


Figure 24: Cooling graph of the cold plate

For a steady state temperature T_2, calculation of $\left(\frac{dT}{dt}\right)$ was carried out as follows:

1. The cooling graph was plotted from the points obtained from the data logger.
2. Tangent to the cooling graph at the steady state temperature (T_2) was traced.
3. $\left(\frac{dT}{dt}\right)$ was calculated from the points identified

$$\frac{dT}{dt} = \frac{T_2{}^{1} - T_2{}^{11}}{t^{11} - t^{1}}$$

Using the above results, the thermal conductivity calculated as follows. Table 13 shows the results obtained for other samples.

$$\frac{dT}{dt} = \frac{51.1 - 43}{2730 - 2020} = 0.0084$$

From equation 5.3:

$$K = \frac{mc\left(\frac{dT}{dt}\right)x}{A(T_1 - T_2)}$$

$$K = \frac{880 \times 0.385 \times 0.0084 \times 0.0045}{0.001963 \times (77.5 - 50.6)}$$

$$K = 0.232\ W/mK$$

Table 13: Thermal conductivity values obtained

Sample No.	Thermal conductivity (W/mK)
1	0.232
2	0.225
3	0.236
Average	**0.231**

A low value was observed for the thermal conductivity of EPS based lightweight concrete with a density of around 740 kg/m^3. Table 14 shows a comparison of thermal conductivities of EPS based lightweight concrete with conventional walling materials.

Table 14: Comparison of thermal conductivities

Material	Thermal conductivity (W/mK)	Source
Bricks	0.84	(Udawattha, 2018)
Cement blocks	1.24	(Udawattha, 2018)
EPS based lightweight concrete	0.231	Experimental study

Lower the thermal conductivity, lesser the effect from outdoor temperature within the building envelope resulting in better thermal performance. From Table 14, it can be seen that the lightweight concrete performs better than bricks and cement blocks with a significant reduction in the thermal conductivity.

5.6.2 Full-scale model and simulations

To assess the thermal performance of the materials in actual construction, a full-scale model and full-scale simulation models were used. A full-scale model was constructed in Bulathsinhala, Kalutara (6°37'58.6"N 80°12'37.2"E) with cement blocks. Exterior and interior surface temperatures of the first floor, and outdoor and indoor ambient temperatures of both ground and first floors were recorded continuously over three days (72 hrs) with 30 minutes interval. The first floor of the refuge space was selected for study as it was exposed to the sun in all directions unlike the ground floor that has two sides adjacent to existing rooms. Surface-mounted thermocouples with battery-backed Delta-T DL2e data logger was used to obtain the readings. Figure 25, 26, and 27 shows the variation of exterior and interior surface temperatures of walls facing directions North East, North West, and South West, correspondingly. The following abbreviations are used in the charts.

INT – Interior wall surface, EXT – Exterior wall surface

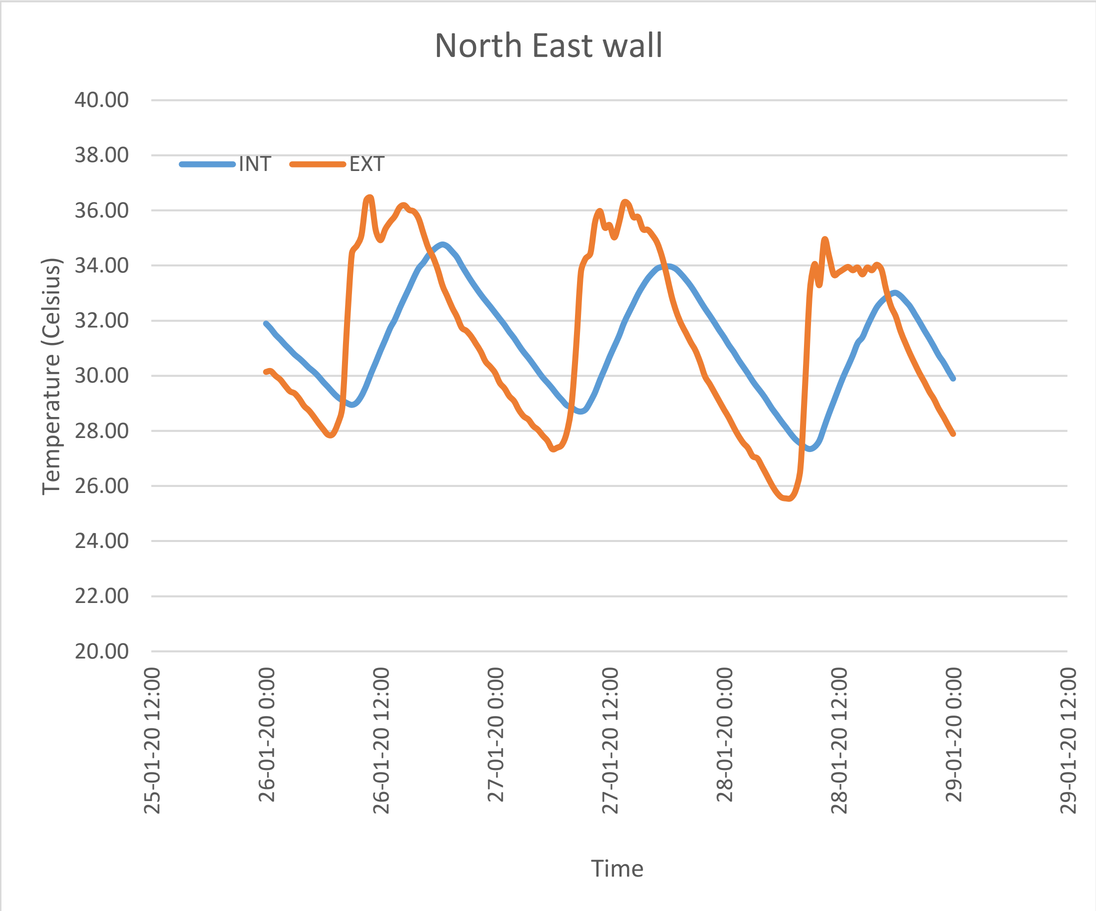


Figure 25: Temperature variation North East wall

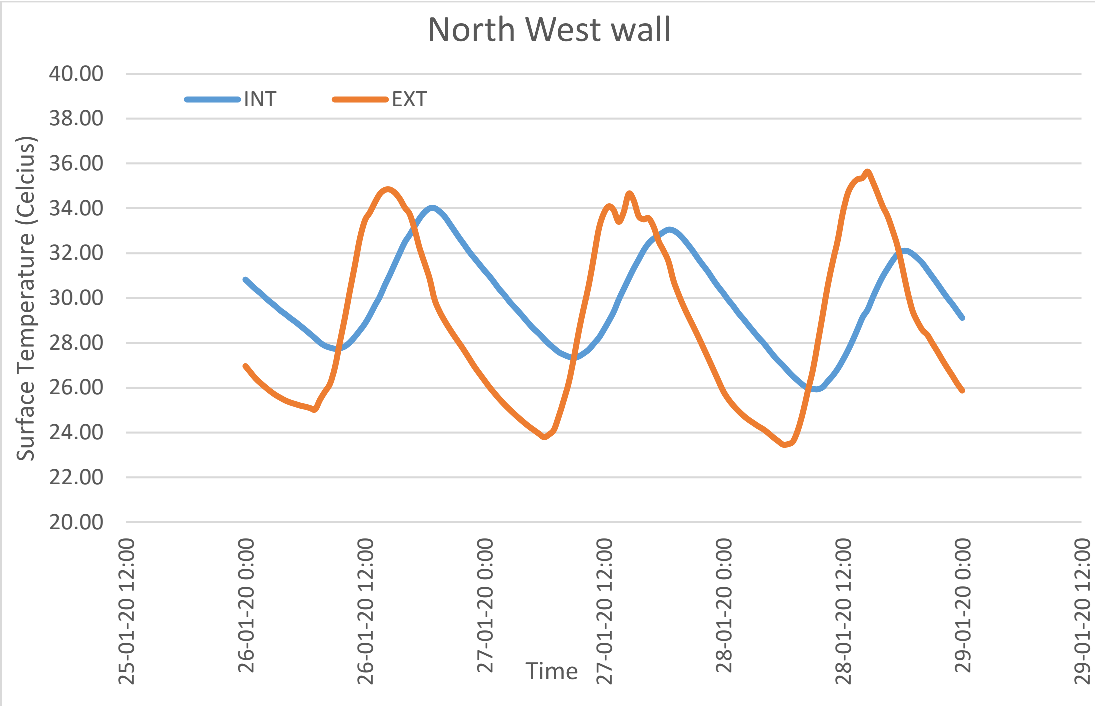


Figure 26: Temperature variation North West wall

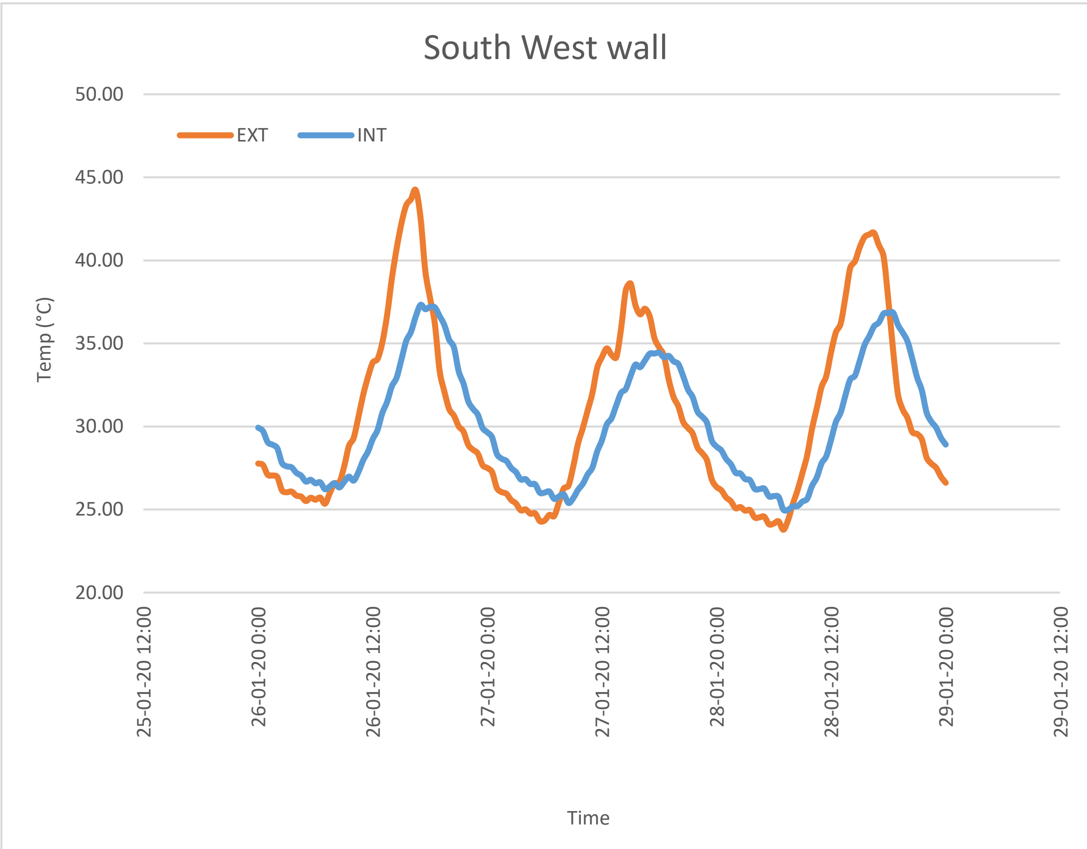


Figure 27: Temperature variation South West wall

These readings were used to validate the simulation models produced with DesignBuilder simulation software with the actual scenario. Figure 28 shows the full-scale sample construction and full-scale simulation model side by side. Figure 29 and Figure 30 show the comparison of results produced by the simulations with the actual reading obtained from the site. Some modifications were made to the model to account for wind speed variations, to match the actual readings obtained from the site with the output of simulation as the climatic data file used in the simulations was from Ratmalana, about 20 km away from the site. The nearest available climate data was from Colombo Airport (Ratmalana) weather station. The thermal properties used in the simulations are given in appendix A.4

Figure 28: Full-scale model and full-scale simulation model

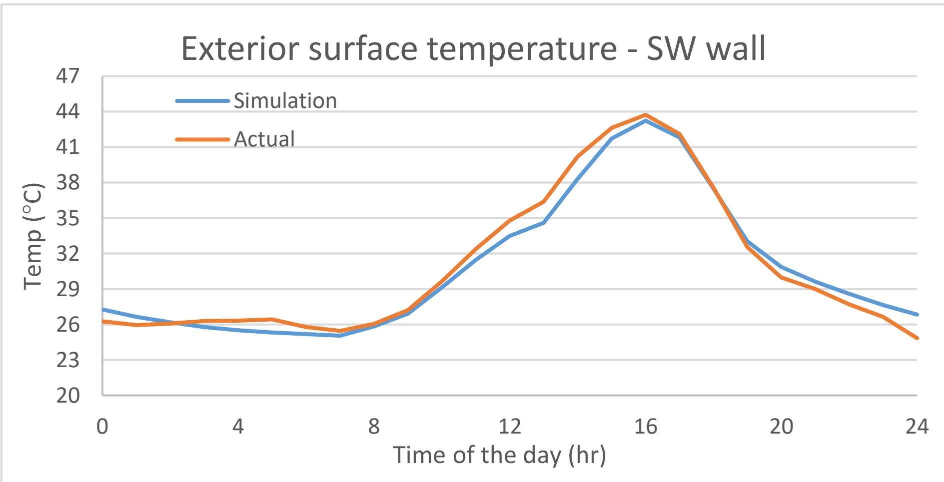


Figure 29: Comparison of Exterior surface temperature

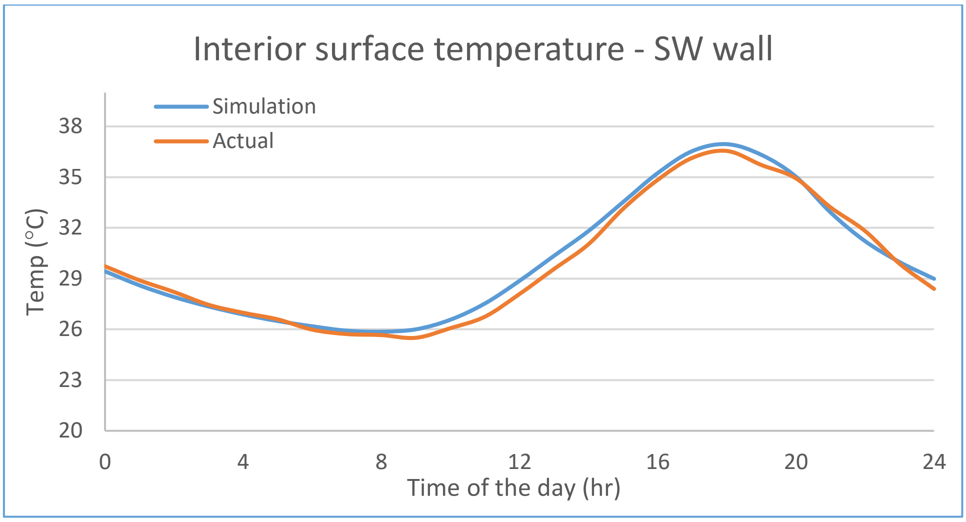


Figure 30: Comparison of Interior surface temperature

As the south-west wall was identified as the wall exposed to severe conditions in this model, the simulation results of south-west walls were considered for the calculation of time lag and decrement factor. Furthermore, the simulation model was modified to match the dimensions considered in this study as the sample construction accommodates the preferences of the residents. The modified model is shown in Figure 31. Adiabatic component blocks were used to represent the adjacent rooms to the refuge space (see Figure 31 (b)) so that there will not be any solar heat gains from those walls as in real scenario.

(a) (b)

Figure 31: The modified model

Figures 32, 33, and 34 depict the surface temperature outputs of the South-West wall of the first floor from the simulations for each walling material.

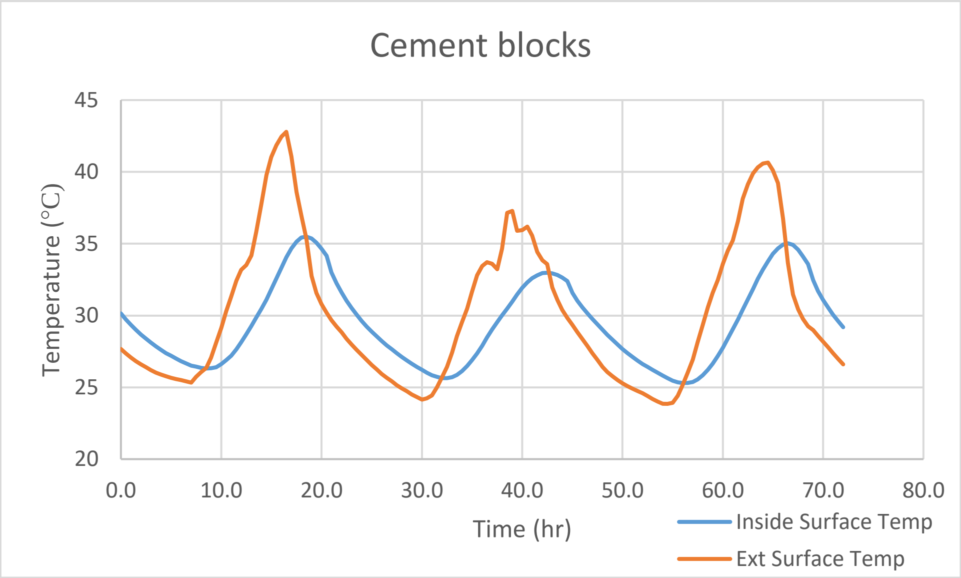


Figure 32: Surface temperature variation - Cement blocks

Figure 33: Surface temperature variation – Fired bricks

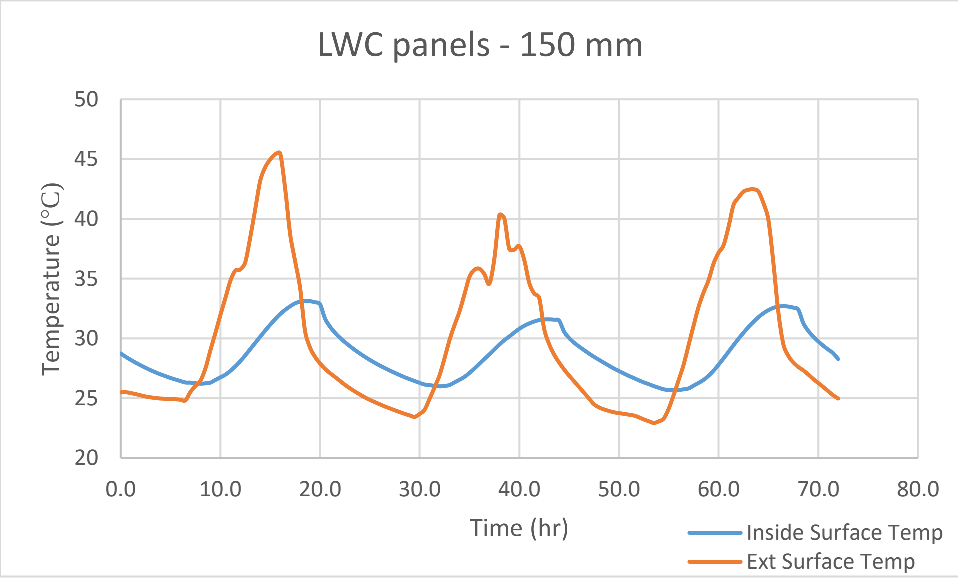


Figure 34: Surface temperature variation – LWC panels – 150 mm

Since the LWC panels are only commercially available in 75 mm, 100 mm, and 150 mm, initially, the simulation was carried out for the 150 mm thick wall construction. However, this will not reflect the material's property on thermal comfort when compared to the other materials as thickness influences the thermal performance. Therefore, the simulation was extended for LWC panel construction of 200 mm thickness. Figure 35 shows the output of the simulation.

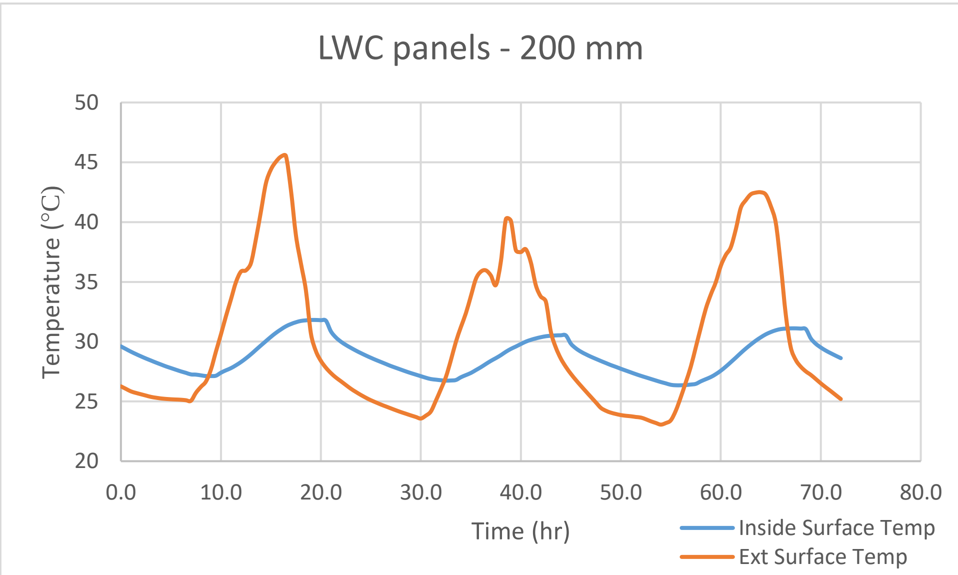


Figure 35: Surface temperature variation – LWC panels – 200 mm

From the simulation results, the time lags, and the decrement factors were calculated, and results are tabulated in Table 15.

Table 15: Time lags and decrement factors

Walling material	Time lag (hr)	Decrement factor
Cement blocks – 200 mm	2	0.526
Fired brick – 200 mm	4.5	0.269
LWC panels – 150 mm	3.5	0.335
LWC panels – 200 mm	4	0.229

The results show that brick masonry has the highest lag time and the second-lowest decrement factor. Regarding LWC panels, the 200 mm construction has the lowest decrement factor and the second-highest time lag. Since both constructions outperform each in one of the two parameters, it can be said that both are performing well in terms of thermal properties. This is followed by the 150 mm construction being the third on both. The cement block masonry has the lowest time lag and the highest decrement factor.

5.7 Greenness and sustainability

Sustainability and greenness of material could be assessed through a wide number of properties. Recent concerns when considering the sustainability of materials have turned towards embodied energy and carbon footprint. Embodied energy is defined as the total energy required for the manufacture of a product. Similarly, embodied carbon or the carbon footprint is the total Carbon Dioxide gas emissions from the manufacture of the product.

5.7.1 Embodied energy and carbon footprint of a lightweight panel

The embodied energy and the carbon footprint depend on various factors which are considered to acquire the relevant data. Those are local conditions like climate, energy resources, transportation distances and the general conditions of the equipment and plant facilities (Nielsen, 2008). Energy and carbon data for Sri Lankan context were not available for all materials considered in this study. In the absence of such information, the most suitable value is selected from the available data.

The factory which produces such wall panels is located in Ekala, Ja-Ela, Sri Lanka (7.10N, 79.93E). The location plays a major role in embodied energy and carbon emissions as the distance to be travelled influences the total energy and carbon emissions. It was observed that the production of wall panels included a crusher and a mixer as the largest machinery used. Movement of goods along the production line and the finished product was mainly manual labour.

Considering the production process, it can be observed that the embodied energy of the wall panels depends mainly on the embodied energy of the materials and the energy spent on transportation of the materials. The material required for a batch of lightweight concrete is shown in Table 16. A batch of lightweight concrete is about 2.7 m^3 in volume, which can produce 25 Nos of 75 mm panels, 18 Nos of 100 mm panels and 12 Nos of 150 mm panels.

Table 16: The material required for a batch of lightweight concrete (Source: EPCI homes (Pvt) Ltd.)

Material	**Material quantity (kg)**
Cement	750
Sand	350
EPS (Recycled)	25
Cement Fibre sheets	232
Fly ash	225
Polycarboxylate superplasticizer	7.5
Forming agent	0.05
Water	275

The embodied energy and the embodied carbon details for each material are collected from various sources from Sri Lanka, India and the Inventory of Carbon and Energy (ICE database) of the University of Bath. Fresh/virgin EPS is a material with high embodied energy (88.6 MJ/kg) and carbon (2.55 kg CO_2/kg). This research study is considering the wall panels made from entirely recycled EPS. The embodied energy of recycled EPS is considered to be zero as it is a waste material. The energy required for crushing recycled EPS can be negligible as it is powered by a small motor (Dissanayake et al., 2017). Similarly, fly ash is a waste product from coal power plants. The fly ash is acquired from the power plant situated in Norochcholai (8.01 N, 79.71E), Sri Lanka. However, the transportation energy requirement for both fly ash and recycled EPS will need to be considered. The embodied energy of materials to produce 12 Nos of 150 mm panels is shown in Table 17. This shows a value of 6355 MJ for 12 Nos of 150 mm panels. It implies 530 MJ for a panel or 368 MJ/m^2. Similarly, for 100 mm panels, the values found to be 420 MJ and 292 MJ/m^2 respectively.

In addition to the embodied energy of the materials, it is required to add energy for transport. As the common fuel used in trucks is diesel, an energy intensity of 45.6 MJ/kg is used here to transform fuel consumption into energy intensity (Energy Statistics Division, 2005). The fuel consumption was acquired from the vehicle operators and was converted to MJ/ton/km. When the distance and the weight of the goods transported, the energy consumption for transportation can be determined. Table 18 shows such energy consumptions of various vehicles related to this study.

Table 17: Embodied energy for 12 Nos. of 150 mm panels

Material	Material quantity (kg)	Energy intensity of materials (MJ/kg)	EE intensity for transportation (MJ/kg)	EE of materials (MJ)	EE for transportation (MJ)	Total EE (MJ)
Cement	750.00	4.90	0.15	3675	115	3790
Sand	350.00	0.08	0.03	28	12	40
EPS (Recycled)	25.00	0.00	0.32	0	8	8
Cement fibre sheets	232.00	10.40	0.13	2413	30	2443
Fly ash	225.00	0.00	0.17	0	38	38
Polycarboxylate superplasticizer	7.50	31.40	0.33	236	2	238
Foaming agent	0.05	14.20	0.33	1	0	1
Water	275.00	0.01	0.00	3	0	3
Total				**6355**	**205**	**6560**

For example, 750 kg of cement from 115 km on a 25-ton truck would consume 0.76×075×115=65.5 MJ of energy. This would only cover one-way transportation. But in a real situation, an empty vehicle would have to go from the factory and collect the goods and return to the factory. To include this, one-way energy consumption is multiplied by 1.75 resulting in 115 MJ for the transportation energy (Dissanayake et al., 2017). Similar calculations were carried out for Fly ash which was from Norachcholai power plant which is situated at 126 km. Sand used to produce EPS panels is from a distance of 25 km. The waste EPS is brought from various places within a range of 10 km. As EPS has a very low density, it was assumed that one ton of EPS is brought in a 25-ton truck. Hence, the values given in Table 18 cannot be used directly for EPS. It was determined to be for 1 ton of used EPS boards, the transportation energy is 19 MJ/km. Hence, for 25 kg of EPS transported over 10 km, it is 8 MJ. The cement fibre sheets used are imported from India and distance was assumed to be 1750 km (from Jawaharlal Nehru Port, India to Colombo port, Sri Lanka).

Table 18: Energy consumption of vehicles (Dissanayake et al., 2017)

Vehicle	Energy consumption	Unit
25-ton truck	0.76	MJ/ton/km
Container ship	0.054	MJ/ton/km
7-ton truck	2.17	MJ/ton/km
750 kg truck	3.2	MJ/ton/km
Backhoe loader	114	MJ/h

Work studies by Dissanayake et al., (2017) revealed that for a batch of concrete the energy requirement is 5kWh. Converting it to MJ gives us 18 MJ at the manufacturing stage (1kWh = 3.6MJ (Energy Statistics Division, 2005)).

Thus, the total embodied energy for 12 Nos of 150 mm panels is 6355+205+18=6578 MJ. That gives us a total of 548 MJ for a panel or 381 MJ/m^2. A similar study was done for 100 mm panels resulting in 433 MJ for a panel and 301 MJ/m^2.

Similarly, assessment of embodied carbon was carried out. Though the carbon emissions from the vehicles can be related to fuel consumption, it is uncertain that the generalised data would match the real condition. The carbon emissions will depend on the condition of the vehicle and the level of combustion in the engine. Considering these, the study only focuses on the embodied carbon of the materials. Carbon coefficients are acquired from Inventory of Carbon and Energy (ICE) of the University of Bath (Hammond & Jones, 2011) and carbon emission is calculated for each ingredient of the lightweight panel. Table 19 shows the summary of embodied carbon for a 150 mm thick panel. For water and recycled EPS, a small amount was added to incorporate pumping of water and crushing of EPS. Hence, for 150 mm panel embodied carbon footprint was 69 kg per panel or 48 kg/m^2. Similarly, it was found embodied carbon for 100 mm panels, 53 kg per panel or 37 kg/m^2.

Table 19: Carbon footprint for 12 Nos of 150 mm panels

Material	**Carbon footprint intensity (kg CO_2/kg)**	**Carbon footprint (kg)**
Cement	0.730	547.50
Sand	0.005	1.68
EPS (Recycled)	0.001	0.03
Cement fibre	1.090	379.32
Fly ash	0.065	14.63
Polycarboxylate superplasticizer	1.880	14.10
Forming agent	0.527	0.03
Water	0.001	0.28
Total		**958**

5.7.2 Comparison of Embodied energy

The total embodied energy was calculated by breaking down each building element into materials such as cement, sand, steel, bricks and blocks, etc. This allows the identification of each process related to the construction as well as transportation energies. Using the data collected through the work studies and energy data from Sri Lanka, India and the Inventory of Carbon and Energy of the University of Bath, embodied energy of each refuge spaces with each material type has been determined and the summary is shown in Table 20.

Table 20: Summary of Embodied energy of each building

Material	Construction with lightweight panels (MJ)	Construction with cement blocks (MJ)	Construction with fired clay bricks (MJ)
Cement	46,387	45,585	37,134
Sand	1,153	5,586	2,621
Coarse agg. & Rubble	3,034	7,109	7,169
Bricks	0	0	52,994
EPS (recycled)	7,045	0	0
Steel	18,270	29,692	29,692
Ceramic Tile	11,153	11,153	11,153
Tile Adhesives	9,546	9,546	9,546
Paint	8,271	8,271	8,271
Putty	215	215	215
Timber	375	1,202	2,040
Copper	87	87	87
PVC	2,429	2,429	2,429
LDPE tank	4,686	4,686	4,686
Cement fibre sheets	28,913	0	0
Plywood	211	3,319	3,319
Total Energy	**141,774**	**128,881**	**171,355**
Embodied energy per unit floor area (GJ/m^2)	**5.30**	**4.82**	**6.41**

5.7.3 Comparison of carbon footprint

Similarly, carbon footprints of three refuge spaces with the above mentioned cases were determined. However, carbon emission from the transportation of the material was not considered due to the inconsistency and unreliability of the data as discussed earlier. The summary of results is shown in Table 21.

Table 21: Embodied carbon of materials

Material	Carbon emission ($kgCO_2$)		
	Lightweight construction	**Cement block construction**	**Fired brick construction**
Cement	6,311	6,202	5,052
Sand	38	185	87
Coarse aggregates	34	79	80
Bricks	0	0	3,428
EPS	0	0	0
Steel	588	969	969
Ceramic Tiles	684	684	684
Paints	138	138	138
PVC	58	58	58
Timber	41	107	173
Plywood	14	223	223
Cement fibre sheet	2,993	0	0
Total	**10,900**	**8,646**	**10,893**

From the study carried out, it can be observed that the lightweight wall panels have the potential to be implemented as a mainline construction material with a comparable embodied energy and carbon footprint with conventional materials. It is clear that it consumes a large amount of industrial waste and convert it into a useful construction material while reducing the use of natural resources in scarce such as sand. It is evident that the cement block construction is performing well in the fields of embodied energy and carbon footprint. Lightweight wall panels consume less energy despite the additional energy required for transportation from the factory to the site unlike other methods considered which could be obtained from the nearest hardware suppliers. The widely used construction method in Sri Lanka i.e. the fired clay brick construction has the highest embodied energy of all the three materials studied. The cement fibre boards have a noticeable contribution to the embodied energy of the building.

Regarding carbon footprint, lightweight wall panels have a footprint much closer to that of fired clay bricks and higher than the cement blocks. Furthermore, cement fibre boards can be seen adding up a lot of carbon footprint to the building. Due to the use of precast slab system, it can be seen plywood and timber requirement is lower for the refuge space with lightweight wall panels as it requires less formwork.

6. CASE STUDY

Responses of a respondent of the survey carried out was selected to carry out a case study on selecting a material for the construction of refuge space by Analytical Hierarchy Process (AHP) as a Multi-Criterion Decision Problem. The responses obtained are given in Table 22. This response was used to formulate pairwise matrix according to the AHP. The formulated pairwise matrix is shown in Table 23.

Table 22: Responses of the selected respondent

Pair	Preference	Level of importance
Cost Strength	Strength	6
Cost Durability	Durability	7
Cost Const. Time	Const. time	4
Cost Thermal comfort	Thermal comfort	7
Cost Sustainability	Sustainability	7
Strength Durability	Durability	1
Strength Const. Time	Strength	4
Strength Thermal Comfort	Thermal comfort	3
Strength Sustainability	Strength	1
Durability Const. time	Durability	5
Durability Thermal Comfort	Durability	2
Durability Sustainability	Durability	3
Const. time Thermal Comfort	Thermal comfort	3
Const. time Sustainability	Sustainability	3
Thermal Comfort Sustainability	Thermal comfort	2

Table 23: Pairwise matrix

	Cost	Strength	Durability	Const. time	Thermal comfort	Sustainability
Cost	1	1/6	1/7	1/4	1/7	1/7
Strength	6	1	1	4	1/3	1
Durability	7	1	1	5	2	2
Const. time	4	1/4	1/5	1	1/3	1/3
Thermal comfort	7	3	1/2	3	1	2
Sustainability	7	1	1/2	3	1/2	1
Total	32	6.417	3.343	16.25	4.31	6.476

Dividing each value in the columns with the respective column total, the normalised pairwise matrix is obtained and shown in Table 24.

Table 24: Normalized pairwise matrix

	Cost	Strength	Durability	Const. time	Thermal comfort	Sustainability	Total	Average/ Weightage	Consistency measure
Cost	0.031	0.026	0.043	0.015	0.033	0.022	0.171	0.029	6.299
Strength	0.188	0.156	0.299	0.246	0.077	0.154	1.120	0.187	6.296
Durability	0.219	0.156	0.299	0.308	0.464	0.309	1.754	0.292	6.396
Const. time	0.125	0.039	0.060	0.062	0.077	0.051	0.414	0.069	6.216
Thermal comfort	0.219	0.468	0.150	0.185	0.232	0.309	1.561	0.260	6.529
Sustainability	0.219	0.156	0.150	0.185	0.116	0.154	0.979	0.163	6.325
						Consistency Index			**0.069**
						Random Index			**1.240**
						Consistency Ratio			**0.055**

Obtained normalized matrix is then checked for consistency. According to Saaty, (1990), if the consistency ratio exceeds 0.1, then the pairwise comparison must be redone until the consistency ratio is less than 0.1. The mathematical theory behind the consistency ratio is attached in appendix A.5. The weightage distribution for the considered response is given in Figure 36. For sub indicators of each property, the weightage is divided equally. However, this also can be included in the pairwise comparison for more versatile framework. Percentage weightages can be obtained by multiplying weightages by 100. Percentage weightages obtained are as follows:

1. Durability – 29.2%

2. Thermal comfort – 26.0%
3. Strength – 18.7%
4. Sustainability – 16.3%
5. Construction time – 6.9%
6. Cost – 2.9%

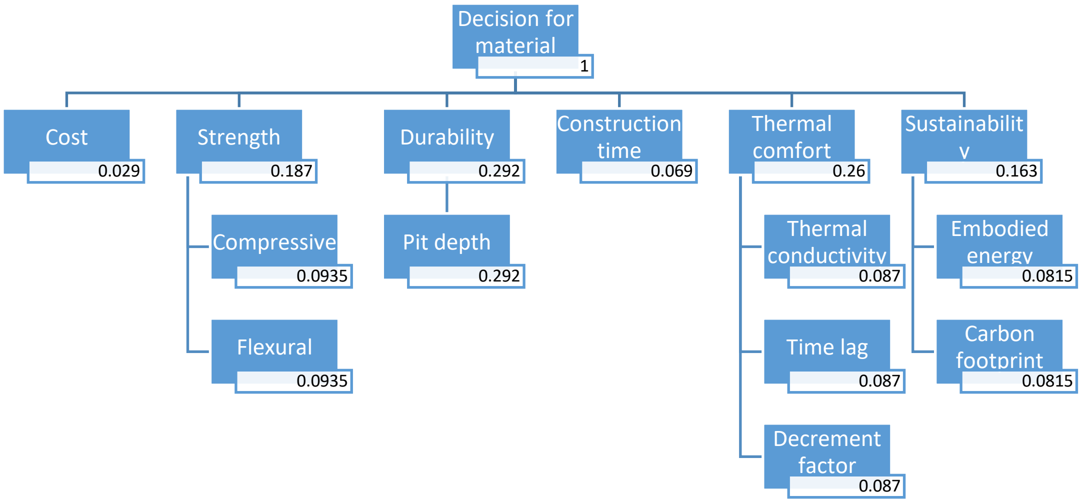


Figure 36: Weightage distribution

Once the weightages were determined, the properties of the materials were classified into two as beneficial and non-beneficial property. Beneficial properties are the properties that are considered desirable when the numerical value of the property is increased such as strength of a material. Non-beneficial properties are the properties that are considered desirable when the numerical value of a property is decreased like cost of construction. The properties considered in this study are classified as follows.

1. Beneficial
    a. Compressive strength
    b. Flexural strength
    c. Time lag
2. Non-beneficial
    a. Cost

b. Pit depth
c. Thermal conductivity
d. Decrement factor
e. Construction time
f. Embodied energy
g. Carbon footprint

Performance values of each alternative is tabulated in Table 25.

Table 25: Performance values of alternatives

	Strength		Thermal comfort			Cost	Durability	Const. time	Sustainability	
Alternative	**Compressive strength (N/mm^2)**	**Flexural strength (N/mm^2)**	**Time Lag (hr)**	**Thermal conductivity (W/mk)**	**Decrement factor**	**Cost (Rs.)**	**Pit depth (mm)**	**Construction time (lab. Hours)**	**Embodied energy (MJ)**	**Carbon footprint ($kgCO_2$)**
Bricks	1.39	0.4	4.5	0.84	0.269	1,242,601	1.1	242	171,355	10,893
HCB	3.96	0.22	2	1.24	0.526	1,122,442	2.1	223	128,881	8,646
LWC panels	2.33	1.03	3.5	0.231	0.335	1,056,622	0.01	145	141,774	10,900

The performance values were then normalized (see Table 26) considering whether it is beneficial or non-beneficial property. The normalized performance value is calculated as follows:

For beneficial property:

$$X_{ij} = \frac{x_{ij}}{Max(x_{ij})}$$

For non-beneficial property:

$$X_{ij} = \frac{Min(x_{ij})}{x_{ij}}$$

Obtained normalized performance values were then multiplied by weightages and totalled to acquire the final ranks of the alternatives. The process is tabulated in Table 27.

Table 26: Normalized performance values

Alternatives	Strength		Thermal comfort			Cost	Durability	Const. time	Sustainability	
	Compressive strength	Flexural strength	Time Lag	Thermal conductivity	Decrement factor	Cost	Pit depth	Construction time	Embodied energy	Carbon footprint
Bricks	0.351	0.388	1.000	0.275	1.000	0.850	0.009	0.599	0.752	0.794
HCB	1.000	0.214	0.444	0.186	0.511	0.941	0.005	0.650	1.000	1.000
LWC panels	0.588	1.000	0.778	1.000	0.803	1.000	1.000	1.000	0.909	0.793

Table 27: Calculation of rank score

	0.187		0.26			0.029	0.292	0.069	0.163		
	Strength		Thermal comfort			Cost	Durability	Const. time	Sustainability		
	0.094	0.094	0.087	0.087	0.087	0.029	0.292	0.069	0.082	0.082	
Alternative	Compressive strength	Flexural strength	Time Lag	Thermal conductivity	Decrement factor	Cost	Pit depth	Construction time	Embodied energy	Carbon footprint	Rank score
Bricks	0.033	0.036	0.087	0.024	0.087	0.025	0.003	0.041	0.061	0.065	0.461
HCB	0.094	0.020	0.039	0.016	0.044	0.027	0.001	0.045	0.082	0.082	0.449
LWC panels	0.055	0.094	0.067	0.087	0.070	0.029	0.292	0.069	0.074	0.065	0.901

From the above results, it can be seen that the LWC panels takes the first rank, the Fired bricks on the second position and the Hollow cement blocks on the third position. Therefore, the most preferable material for the considered respondent would be LWC panels according to the AHP.

As can be seen, the methodology presented here in this case study can deliver decision makers a strong decision support data on relative suitability of different walling materials for the construction of refuge space. However, it should be noted that the achieved ranking is a reflection of view of stakeholder towards the particular project considered in this study and the results of this study should not be considered as the universal ranking of suitability of walling materials considered here. The relative ranking or performance of the walling materials considered could be varied considerably according to the requirements and the project specific situations. Furthermore, the weightages or the relative importance of different criteria could differ significantly depending on the stakeholder and national priorities at the time of consideration. Bearing in mind the need of the hour, changes on weightages and inclusion or exclusion of various criteria could be made to provide a more suitable decision support data.

It should be noted that the Analytical Hierarchy Process is a lengthy process if conducted manually for each problem. However, it can be simplified and automated to calculate the results with a simple programming with basic platforms like spreadsheets and Python or any other programming platforms.

7. CONCLUSIONS AND FUTURE WORKS

7.1 Conclusions

The properties and characteristics that affects the selection of building materials were explored and discussed in detail from a thorough literature study. Generally used conventional building materials and commercially produced alternative building materials were identified and checked for suitability from the literature study. Widely accepted method on multi-criterion decision making was discussed in detail for the suitability in this study.

The concept of Refuge space was developed by discussing the probable failures and the preventive measures need to be taken to minimize the damages. The resistant features against scouring of soil, earthquakes, cyclones and lightning were discussed in depth. A layout for refuge space was developed including a first floor that could be utilised in a flash flood or river flood situation. The details of pantry with storage facilities to feed the occupants in a prolonged flood, where the rescue might take longer to reach the occupants, was discussed. Provision of fresh water supply with rooftop tank and prevention of cross contaminations were stated. Details of sanitary facilities with lightweight partitions were discussed briefly. In addition, particulars of rooftop and the access to the rooftop by a steep ladder which could be used in an extreme flood event where the flood levels reach the first-floor level is specified. Furthermore, the cost-effective features and soil improvement methods were stated.

The details of online survey carried out in finding the properties and their importance were stated. The survey responses showed that most of the properties of the material which could be considered as benefits were preferred over the cost of construction. Furthermore, sustainable materials and materials that could provide more thermally comfortable spaces were observed to be preferred over most of the properties.

A comparative study was carried out considering the performances of EPS based lightweight concrete (LWC) panels, fired bricks and hollow cement sand blocks in the areas of cost, compressive and flexural strengths, durability, time taken for the construction, thermal performance and sustainability were discussed in depth. The

LWC panels were found to be performing exceptionally well in most of the properties and at a comparable level in others considered in this study compared to the conventional materials. This included a full-scale work study and thermal performance analysis. Furthermore, work norms for the LWC panel construction were established in this study. The embodied energy of EPS lightweight concrete panels based on 100% recycled EPS were found to be 548MJ and 433MJ for 150 mm and 100 mm thick panels, respectively. Furthermore, the carbon footprints of these panels were found to be 69 $kgCO_2$ and 53 $kgCO_2$ for a panel correspondingly.

Finally, the results of the comparative study were applied as a multi-criterion decision problem and the suitable solution for the considered case study from the survey responses was suggested using the Analytical Hierarchy Process. It should be noted that the criteria and weights presented in this study are project specific and the applicability for other projects should be assessed before use.

7.2 Future works

- The dynamic performance of LWC panels and the effects of impact loads from debris and flood or tsunami waves could be studied in order to expand the implementation.
- The effects of joints of LWC panels and adhesive materials on compressive and flexural strengths could be studied.
- Cost effective solutions for the use of AAC blocks in prolonged immersion situations could be explored.

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APPENDIX - A

A.1. Cost study

Table 28, 29, and 30 show the detailed cost calculation for the refuge space.

Table 28: Refuge space with LWC panels

No.	Description	Quantity	Unit	Rate (Rs)	Cost (Rs)
1	**Foundation**				**60,403**
	Excavation of trenches	1.430	cube	4,915	7,027
	Screed concrete	0.179	cube	43,215	7,719
	Rubble work	0.953	cube	44,285	42,208
	Backfilling	0.988	cube	3,490	3,450
2	**Floor (GF)**				**32,882**
	Reinforcement	19.000	kg	280	5,320
	Formwork	0.215	Sq	12,945	2,783
	Floor concrete	0.434	cube	57,070	24,779
3	**Walls (GF)**				**179,168**
	Walls 150 mm	4.451	Sq	40,258	179,168
4	**Lintel beams**				**3,212**
	Reinforcement	1.851	kg	280	518
	Formwork	0.147	Sq	7,935	1,164
	Concrete	0.027	cube	57,070	1,530
5	**Floor slab (FF)**				**77,833**
	Precast purlings	108	Lft	372	40,219
	Reinforcement (GI mesh)	176.500	Sq.ft	91	16,062
	Formwork	1.389	Sq	3,556	4,939
	Floor concrete	0.342	cube	48,570	16,614
6	**Walls (FF)**				**234,353**
	Wall 150 mm	4.683	Sq	44,284	207,368
	Wall area 100 mm	0.718	Sq	37,607	26,986
7	**Lintel beams**				**3,271**
	Reinforcement	1.851	kg	287	531
	Formwork	0.147	Sq	7,935	1,164
	Concrete	0.027	cube	58,780	1,576
8	**Roof slab**				**101,988**
	Precast purlings	135	Lft	372	50,274
	Reinforcement (GI mesh)	202.000	Sq.ft	96	19,301
	Formwork	1.989	Sq	3,734	7,426
	Roof concrete	0.490	cube	50,999	24,987
9	**Painting**				**100,048**
	Walls	19.702	Sq	3,970	78,215
	Soffit	3.378	Sq	4,715	15,926
	Wood	0.750	Sq	4,670	3,503
	Steel	0.500	Sq	4,810	2,405
10	**Doors and windows**				**129,677**
	Doors	37.278	Sq.ft	1,790	66,727
	Windows	34.212	Sq.ft	1,840	62,950

11	**Tiling**				**133,784**
	Floor tiles GF	1.505	Sq	45,145	67,943
	Floor Times FF	1.389	Sq	47,405	65,841
	Total				**1,056,622**

Table 29: Refuge space with 200 mm hollow cement blockwork

No.	Description	Quantity	Unit	Rate (Rs)	Cost (Rs)
1	**Foundation**				**60,403**
	Excavation of trenches	1.430	cube	4,915	7,027
	Screed concrete	0.179	cube	43,215	7,719
	Rubble work	0.953	cube	44,285	42,208
	Backfilling	0.988	cube	3,490	3,450
2	**Floor (GF)**				**32,882**
	Reinforcement	19.000	kg	280	5,320
	Formwork	0.215	Sq	12,945	2,783
	Floor concrete	0.434	cube	57,070	24,779
3	**Walls (GF)**				**205,925**
	Wall area	4.451	Sq	28,710	127,774
	Wall plaster	8.901	Sq	8,780	78,151
4	**Lintel beams**				**3,889**
	Reinforcement	1.851	kg	280	518
	Formwork	0.168	Sq	7,935	1,331
	Concrete	0.036	cube	57,070	2,040
5	**Floor slab (FF)**				**84,317**
	Reinforcement	89.750	kg	287	25,758
	Formwork	1.389	Sq	18,035	25,049
	Floor concrete	0.570	cube	58,780	33,510
6	**Walls (FF)**				**248,713**
	Wall area 200 mm	4.683	Sq	30,146	141,162
	Wall area 100 mm	0.718	Sq	17,729	12,722
	Wall plaster	10.801	Sq	8,780	94,829
7	**Lintel beams**				**3,963**
	Reinforcement	1.851	kg	287	531
	Formwork	0.168	Sq	7,935	1,331
	Concrete	0.036	cube	58,780	2,101
8	**Roof slab**				**118,841**
	Reinforcement	125.650	kg	292	36,690
	Formwork	1.989	Sq	20,065	39,904
	Roof concrete	0.705	cube	59,925	42,247
9	**Painting**				**100,048**
	Walls	19.702	Sq	3,970	78,215
	Soffit	3.378	Sq	4,715	15,926
	Wood	0.750	Sq	4,670	3,503
	Steel	0.500	Sq	4,810	2,405
10	**Doors and windows**				**129,677**
	Doors	37.278	Sq.ft	1,790	66,727
	Windows	34.212	Sq.ft	1,840	62,950

11	**Tiling**				**133,784**
	Floor tiles GF	1.505	Sq	45,145	67,943
	Floor Tiles FF	1.389	Sq	47,405	65,841
	Total				**1,122,442**

Table 30: Refuge space with 220 mm brickwork

No.	Description	Quantity	Unit	Rate (Rs)	Cost (Rs)
1	**Foundation**				**60,403**
	Excavation of trenches	1.430	cube	4,915	7,027
	Screed concrete	0.179	cube	43,215	7,719
	Rubble work	0.953	cube	44,285	42,208
	Backfilling	0.988	cube	3,490	3,450
2	**Floor (GF)**				**32,882**
	Reinforcement	19.000	kg	280	5,320
	Formwork	0.215	Sq	12,945	2,783
	Floor concrete	0.434	cube	57,070	24,779
3	**Walls (GF)**				**259,837**
	Wall area	3.215	cube	56,510	181,687
	Wall plaster	8.901	Sq	8,780	78,151
4	**Lintel beams**				**3,889**
	Reinforcement	1.851	kg	280	518
	Formwork	0.168	Sq	7,935	1,331
	Concrete	0.036	cube	57,070	2,040
5	**Floor slab (FF)**				**84,317**
	Reinforcement	89.750	kg	287	25,758
	Formwork	1.389	Sq	18,035	25,049
	Floor concrete	0.570	cube	58,780	33,510
6	**Walls (FF)**				**314,958**
	Wall area 220 mm	3.383	cube	59,335	200,723
	Wall area 110 mm	0.718	Sq	27,045	19,406
	Wall plaster	10.801	Sq	8,780	94,829
7	**Lintel beams**				**3,963**
	Reinforcement	1.851	kg	287	531
	Formwork	0.168	Sq	7,935	1,331
	Concrete	0.036	cube	58,780	2,101
8	**Roof slab**				**118,841**
	Reinforcement	125.650	kg	292	36,690
	Formwork	1.989	Sq	20,065	39,904
	Roof concrete	0.705	cube	59,925	42,247
9	**Painting**				**100,049**
	Walls	19.702	Sq	3,970	78,215
	Soffit	3.378	Sq	4,715	15,927
	Wood	0.750	Sq	4,670	3,503
	Steel	0.500	Sq	4,810	2,405
10	**Doors and windows**				**129,677**
	Doors	37.278	Sq.ft	1,790	66,727

	Windows	34.212	Sq.ft	1,840	62,950
11	**Tiling**				**133,784**
	Floor tiles GF	1.505	Sq	45,145	67,943
	Floor Tiles FF	1.389	Sq	47,405	65,841
	Total				**1,242,601**

A.2. Strength calculations

EN 1996-1-1:2005 equation (3.2):

$$f_k = K f_b^{0.7} f_m^{0.3}$$

where:

- f_k is the characteristic compressive strength of the masonry, in N/mm^2
- f_b is the normalised mean compressive strength of the units, in the direction of the applied action effect, in N/mm^2
- f_m is the compressive strength of the mortar, in N/mm^2

For Group 1 clay bricks with general purpose mortar,

$$K = 0.5$$

BS EN 772-1:2000, Table A.1,

$$f_b = 0.85 \times f_{ck}$$

where:

- f_{ck} – characteristic strength

$$f_b = 0.85 \times 2.8 = 2.38\ N/mm^2$$

Mortar: Cement Sand – 1:5, therefore, M4 (UK national annex, Table NA.1)

$$f_m = 4\ N/mm^2$$

Therefore,

$$f_k = 0.5 \times 2.38^{0.7} \times 4^{0.3} = 1.39\ N/mm^2$$

A.3. Labour requirements

Table 31: Labour requirement - LWC panel construction

Description	Quantity	Unit	Sk. Lab rate	Usk. Lab rate	Sk. Lab days	Usk. Lab days	Total
Foundation					**3.96**	**11.07**	**15.03**
Excavation of trenches	1.430	cube		2.25		3.22	3.22
Screed concrete - mixing	0.179	cube	0.33	2.00	0.06	0.36	0.42
Screed concrete - Placing	0.726	Sq	0.13	0.75	0.09	0.54	0.63
Rubble work	0.953	cube	4.00	6.00	3.81	5.72	9.53
Backfilling	0.988	cube		1.25		1.24	1.24
Floor (GF)					**1.44**	**3.77**	**5.21**
Reinforcement	0.380	Cwt	1.00	1.00	0.38	0.38	0.76
Formwork	0.215	Sq	0.75	3.00	0.16	0.65	0.81
Floor concrete - mixing	0.434	cube	0.33	2.00	0.14	0.87	1.01
Floor concrete - placing	1.505	Sq	0.50	1.25	0.75	1.88	2.63
Walls (GF)					**2.23**	**6.68**	**8.90**
Wall area	4.451	Sq	0.50	1.50	2.23	6.68	8.90
Lintel beams					**0.55**	**1.52**	**2.07**
Reinforcement	0.037	Cwt	1.00	1.00	0.04	0.04	0.07
Formwork	0.168	Sq	2.73	7.27	0.46	1.22	1.68
Concrete - mixing	0.036	cube	0.33	2.00	0.01	0.07	0.08
Concrete - placing	10.064	Lft	0.00	0.02	0.04	0.19	0.23
Floor slab (FF)					**2.36**	**6.25**	**8.61**
Placing precast beams	108	Lft	0.01	0.01	0.54	1.08	1.62
Reinforcement	176.500	Sq.ft	0.00	0.00	0.32	0.32	0.64
Formwork	1.389	Sq	0.50	0.50	0.69	0.69	1.39
Floor concrete - mixing	0.342	cube	0.33	2.00	0.11	0.68	0.80
Floor concrete - placing	1.389	Sq	0.50	2.50	0.69	3.47	4.17
Walls (FF)					**2.84**	**8.13**	**10.96**
Wall area 150 mm	4.683	Sq	0.53	1.58	2.46	7.38	9.83
Wall area 100 mm	0.718	Sq	0.53	1.05	0.38	0.75	1.13
Lintel beams					**0.57**	**1.59**	**2.16**
Reinforcement	0.037	Cwt	1.03	1.03	0.04	0.04	0.08
Formwork	0.168	Sq	2.86	7.64	0.48	1.28	1.76
Concrete - mixing	0.036	cube	0.33	2.00	0.01	0.07	0.08
Concrete - placing	10.064	Lft	0.00	0.02	0.04	0.20	0.24
Roof slab					**3.33**	**9.23**	**12.55**
Placing precast beams	135	Lft	0.01	0.01	0.71	1.42	2.13
Reinforcement	176.500	Sq.ft	0.00	0.00	0.33	0.33	0.65
Formwork	1.989	Sq	0.53	0.53	1.04	1.04	2.09
Roof concrete - mixing	0.610	cube	0.33	2.00	0.20	1.22	1.42
Roof concrete - placing	1.989	Sq	0.53	2.63	1.04	5.22	6.26
Painting					**31.66**	**0.38**	**32.04**
Walls	19.702	Sq	1.25		24.63		24.63
Soffit	3.378	Sq	1.75		5.91		5.91
Wood	0.750	Sq	0.50	0.50	0.38	0.38	0.75
Steel	0.500	Sq	1.50		0.75		0.75
Doors and windows					**16.13**	**6.12**	**22.26**
Doors	37.278	Sq.ft	0.22	0.07	8.19	2.46	10.65
Windows	34.212	Sq.ft	0.23	0.11	7.94	3.67	11.61
Tiling					**11.69**	**13.15**	**24.83**

Floor tiles GF	1.505	Sq	4.00	4.50	6.02	6.77	12.79
Floor Tiles FF	1.389	Sq	4.08	4.59	5.67	6.38	12.04
Total					**77**	**68**	**145**

Table 32: Labour requirement - Hollow cement block construction

Description	Quantity	Unit	Sk. Lab rate	Usk. Lab rate	Sk. Lab days	Usk. Lab days	Total
Foundation					**3.96**	**11.07**	**15.03**
Excavation of trenches	1.430	cube		2.25		3.22	3.22
Screed concrete - mixing	0.179	cube	0.33	2.00	0.06	0.36	0.42
Screed concrete - Placing	0.726	Sq	0.13	0.75	0.09	0.54	0.63
Rubble work	0.953	cube	4.00	6.00	3.81	5.72	9.53
Backfilling	0.988	cube		1.25		1.24	1.24
Floor (GF)					**1.44**	**3.77**	**5.21**
Reinforcement	0.380	Cwt	1.00	1.00	0.38	0.38	0.76
Formwork	0.215	Sq	0.75	3.00	0.16	0.65	0.81
Floor concrete - mixing	0.434	cube	0.33	2.00	0.14	0.87	1.01
Floor concrete - placing	1.505	Sq	0.50	1.25	0.75	1.88	2.63
Walls (GF)					**15.58**	**22.25**	**37.83**
Wall area	4.451	Sq	1.50	2.50	6.68	11.13	17.80
Wall plaster	8.901	Sq	1.00	1.25	8.90	11.13	20.03
Lintel beams					**0.55**	**1.52**	**2.07**
Reinforcement	0.037	Cwt	1.00	1.00	0.04	0.04	0.07
Formwork	0.168	Sq	2.73	7.27	0.46	1.22	1.68
Concrete - mixing	0.036	cube	0.33	2.00	0.01	0.07	0.08
Concrete - placing	10.064	Lft	0.00	0.02	0.04	0.19	0.23
Floor slab (FF)					**4.21**	**10.00**	**14.21**
Reinforcement	1.795	Cwt	1.03	1.03	1.84	1.84	3.68
Formwork	1.389	Sq	0.75	3.00	1.04	4.17	5.21
Floor concrete - mixing	0.570	cube	0.33	2.00	0.19	1.14	1.33
Floor concrete - placing	0.570	cube	2.00	5.00	1.14	2.85	3.99
Walls (FF)					**19.47**	**27.97**	**47.44**
Wall area 200 mm	4.683	Sq	1.58	2.63	7.38	12.29	19.67
Wall area 100 mm	0.718	Sq	1.05	2.10	0.75	1.51	2.26
Wall plaster	10.801	Sq	1.05	1.31	11.34	14.18	25.52
Lintel beams					**0.57**	**1.59**	**2.16**
Reinforcement	0.037	Cwt	1.03	1.03	0.04	0.04	0.08
Formwork	0.168	Sq	2.86	7.64	0.48	1.28	1.76
Concrete - mixing	0.036	cube	0.33	2.00	0.01	0.07	0.08
Concrete - placing	10.064	Lft	0.00	0.02	0.04	0.20	0.24
Roof slab					**5.92**	**14.01**	**19.93**
Reinforcement	2.513	Cwt	1.05	1.05	2.64	2.64	5.28
Formwork	1.989	Sq	0.79	3.15	1.57	6.26	7.83
Roof concrete - mixing	0.705	cube	0.33	2.00	0.23	1.41	1.64
Roof concrete - placing	0.705	cube	2.10	5.25	1.48	3.70	5.18
Painting					**31.66**	**0.38**	**32.04**

Walls	19.702	Sq	1.25		24.63		24.63
Soffit	3.378	Sq	1.75		5.91		5.91
Wood	0.750	Sq	0.50	0.50	0.38	0.38	0.75
Steel	0.500	Sq	1.50		0.75		0.75
Doors and windows					**16.13**	**6.12**	**22.26**
Doors	37.278	Sq.ft	0.22	0.07	8.19	2.46	10.65
Windows	34.212	Sq.ft	0.23	0.11	7.94	3.67	11.61
Tiling					**11.69**	**13.15**	**24.83**
Floor tiles GF	1.505	Sq	4.00	4.50	6.02	6.77	12.79
Floor Tiles FF	1.389	Sq	4.08	4.59	5.67	6.38	12.04
Total					**111**	**112**	**223**

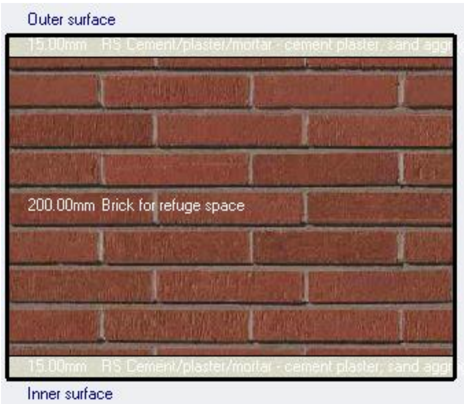
Table 33: Labour requirement - Brick construction

Description	Quantity	Unit	Sk. Lab rate	Usk. Lab rate	Sk. Lab days	Usk. Lab days	Total
Foundation					**3.96**	**11.07**	**15.03**
Excavation of trenches	1.430	cube		2.25		3.22	3.22
Screed concrete - mixing	0.179	cube	0.33	2.00	0.06	0.36	0.42
Screed concrete - Placing	0.726	Sq	0.13	0.75	0.09	0.54	0.63
Rubble work	0.953	cube	4.00	6.00	3.81	5.72	9.53
Backfilling	0.988	cube		1.25		1.24	1.24
Floor (GF)					**1.44**	**3.77**	**5.21**
Reinforcement	0.380	Cwt	1.00	1.00	0.38	0.38	0.76
Formwork	0.215	Sq	0.75	3.00	0.16	0.65	0.81
Floor concrete - mixing	0.434	cube	0.33	2.00	0.14	0.87	1.01
Floor concrete - placing	1.505	Sq	0.50	1.25	0.75	1.88	2.63
Walls (GF)					**18.91**	**27.82**	**46.73**
Wall area	4.451	Sq	2.25	3.75	10.01	16.69	26.70
Wall plaster	8.901	Sq	1.00	1.25	8.90	11.13	20.03
Lintel beams					**0.55**	**1.52**	**2.07**
Reinforcement	0.037	Cwt	1.00	1.00	0.04	0.04	0.07
Formwork	0.168	Sq	2.73	7.27	0.46	1.22	1.68
Concrete - mixing	0.036	cube	0.33	2.00	0.01	0.07	0.08
Concrete - placing	10.064	Lft	0.00	0.02	0.04	0.19	0.23
Floor slab (FF)					**4.21**	**10.00**	**14.21**
Reinforcement	1.795	Cwt	1.03	1.03	1.84	1.84	3.68
Formwork	1.389	Sq	0.75	3.00	1.04	4.17	5.21
Floor concrete - mixing	0.570	cube	0.33	2.00	0.19	1.14	1.33
Floor concrete - placing	0.570	cube	2.00	5.00	1.14	2.85	3.99
Walls (FF)					**23.53**	**34.12**	**57.65**
Wall area 220 mm	4.683	Sq	2.36	3.94	11.06	18.44	29.50
Wall area 110 mm	0.718	Sq	1.58	2.10	1.13	1.51	2.64
Wall plaster	10.801	Sq	1.05	1.31	11.34	14.18	25.52
Lintel beams					**0.57**	**1.59**	**2.16**
Reinforcement	0.037	Cwt	1.03	1.03	0.04	0.04	0.08
Formwork	0.168	Sq	2.86	7.64	0.48	1.28	1.76

Concrete - mixing	0.036	cube	0.33	2.00	0.01	0.07	0.08
Concrete - placing	10.064	Lft	0.00	0.02	0.04	0.20	0.24
Roof slab					**5.92**	**14.01**	**19.93**
Reinforcement	2.513	Cwt	1.05	1.05	2.64	2.64	5.28
Formwork	1.989	Sq	0.79	3.15	1.57	6.26	7.83
Roof concrete - mixing	0.705	cube	0.33	2.00	0.23	1.41	1.64
Roof concrete - placing	0.705	cube	2.10	5.25	1.48	3.70	5.18
Painting					**31.66**	**0.38**	**32.04**
Walls	19.702	Sq	1.25		24.63		24.63
Soffit	3.378	Sq	1.75		5.91		5.91
Wood	0.750	Sq	0.50	0.50	0.38	0.38	0.75
Steel	0.500	Sq	1.50		0.75		0.75
Doors and windows					**16.13**	**6.12**	**22.26**
Doors	37.278	Sq.ft	0.22	0.07	8.19	2.46	10.65
Windows	34.212	Sq.ft	0.23	0.11	7.94	3.67	11.61
Tiling					**11.69**	**13.15**	**24.83**
Floor tiles GF	1.505	Sq	4.00	4.50	6.02	6.77	12.79
Floor Times FF	1.389	Sq	4.08	4.59	5.67	6.38	12.04
Total					**119**	**124**	**242**

A.4. Simulation data sets

Table 34: Data used for the thermal simulations

Walling material	**Wall section details**	**Thermal conductivity (W/mK)**		
		Outermost layer	**Second layer**	**Innermost layer**
Bricks		0.5	0.84	0.5

HCB		0.5	1.26	0.5
LWC panels		0.172	0.231	0.172

A.5. Mathematical theory behind AHP

For a matrix of pairwise elements = $\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{32} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$

Sum the values in each column pf pairwise matrix:

$$C_{ij} = \sum_{i=1}^{n} C_{ij}$$

Divide each element in the matrix by its column total to generate a normalised pairwise matrix:

$$X_{ij} = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} \quad \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}$$

Divide the sum of normalised row of matrix by the number of criteria used (n) to generate weighted matrix

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n} \quad \begin{bmatrix} W_{11} \\ W_{21} \\ W_{31} \end{bmatrix}$$

Consistency analysis

Consistency vector is calculated by multiplying the pairwise matrix by the wights vector

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{32} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \times \begin{bmatrix} W_{11} \\ W_{21} \\ W_{31} \end{bmatrix} = \begin{bmatrix} Cv_{11} \\ Cv_{21} \\ Cv_{31} \end{bmatrix}$$

Then the weighted sum vector obtained is divided by the criterion weights

$$Cv_{11} = \frac{1}{W_{11}} [C_{11}W_{11} + C_{12}W_{21} + C_{13}W_{31}]$$

$$Cv_{21} = \frac{1}{W_{21}} [C_{21}W_{11} + C_{22}W_{21} + C_{23}W_{31}]$$

$$Cv_{31} = \frac{1}{W_{31}} [C_{31}W_{11} + C_{32}W_{21} + C_{33}W_{31}]$$

λ is calculated by averaging the value of consistency vector

$$\lambda = \sum_{i=1}^{n} Cv_{ij}$$

Consistency index measures the deviation:

$$CI = \frac{\lambda - n}{n - 1}$$

Consistency Ratio:

$$C_r = \frac{CI}{RI} < 0.10$$

Random inconsistency index is obtained from pre-determined values

Table 35: Random indexes

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

A.6. Photographs of sample refuge space constructions

Lightweight concrete panel based refuge space

Figure 37: LWC panel based Refuge space construction

Figure 38: Cement block based Refuge space (External view)

Figure 39: Cement block based Refuge space (Internal arrangement)