# BUILDING PERFORMANCE OF SANDWICH PANELS MADE OUT OF BUILDING DEBRIS AND STABILIZED EARTH

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**Degree of Master of Science**

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The Research Thesis submitted in partial fulfilment of the requirements for the Degree of Master of Science


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# DECLARATION

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Prof. (Mrs.) C. Jayasinghe

ABSTRACT

With the aim of promoting sustainable construction, several building materials with lower life cycle cost have been developed. This in turn would limit the over exploitation of natural resources used to produce conventional building material such as bricks and cement sand blocks. Building demolition waste has added to the environmental impacts created by the building industry. This paper covers a research carried out to investigate the possibility of using recycled building demolition waste (BDW) in constructing some building elements with a comprehensive experimental programme. BDW has been combined with stabilized rammed earth (SRE) which is another greener material, to construct a composite walling material. The optimum mix proportion of BDW and SRE was established together with other important material properties to assess the proposed material for acceptable building performance. Based on the results, the proposed composite walling system made out of BDW and SRE can be confidently used as a load bearing walling material.

**Key words:** - Building demolition waste (BDW), Stabilized rammed earth (SRE), Material properties, and Thermal performance.

# DEDICATION

This Research Paper is lovingly dedicated to our respective parents who have been our constant source of inspiration. They have given us the drive and discipline to tackle any task with enthusiasm and determination. Without their love and support this project would not have been made possible.

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# CONTENTS

# LIST OF TABLES & FIGURES

## List of Tables



## List of Figure

# CHAPTER 01

# INTRODUCTION

## 1.1 Introduction

Rapid urbanization occurs in developing countries together with reconstruction programmes that follow natural disasters (eg - Tsunami, landslides in the years 2010, 2012, and 2013). Disasters cause the generation of building demolition waste (BDW) in large quantities. Waste generated from building demolition is a significant environmental problem in most of the cities all over the world. The research covered by this paper focuses on to the reuse of BDW in wall construction. Reusing BDW is given recognition in the Green rating systems such as LEED (Leadership in Energy & Environmental Design) of US Green Building Council. In order to develop a sound walling material, BDW was combined with stabilized rammed earth and insitu casting of walls as composite panels was carried out using the slip form technique.

Currently BDW is primarily being used as a land filling material without proper management, causing some environmental problems. This problem is coupled with other environmental concerns arise from over exploitation of finite natural resources in the production of building materials such as bricks and cement blocks. Stabilized rammed earth (SRE) has been identified as an alternative material for wall construction [13] [14] [15] [17] [23]. The research covered in this paper is aimed at developing a composite walling material with SRE and BDW.

SRE has been well researched and established [12] [7] as a slip forming construction technique [7] [16]. The cast insitu SRE walls can be used as load bearing elements [12] [19] with desirable strength properties. The composite walling system covered in this paper uses SRE and BDW mixed to a desirable proportion based on the strength parameters.

In order to be comparable with the other walling materials, the composite walling system was tested for strength, durability and thermal properties. The optimum mix proportion was first established after selecting a suitable mix of aggregate from the recycled BDW. The strength and thermal properties of the composite wall were established with a detailed testing programme backed by computer simulations for the thermal modelling. In order to popularize the composite material in the tropical climates, monitoring of the thermal performance is of paramount importance.

There is a high demand for building materials due to rapid urbanization taking place in most of the countries in the world. This causes a significant global environmental degradation due to over exploitation of natural resources such as sand, coral, clay and depleting forest cover. These problems tempt us to explore the possibility of using alternative materials. One such alternative is earth wall construction which has been given a lot of thoughts in the recent past. Earth alone would not fulfill the structural requirements of a building material. Therefore, stabilization techniques have been introduced to improve the strength and durability of earth as a building material. Stabilized rammed earth (SRE) is one such material which consists of compacted soil stabilized with cement [9] or lime [6] and moulded as a wall using the slip form technique. Comprehensive studies have established compressive strength, durability and shrinkage properties [12] of SRE.

A detailed experimental programme was carried out to investigate the engineering properties of proposed composite walls constructed with construction waste and rammed earth. They include the main engineering properties such as mix proportion, strength, durability and thermal properties. Determination of optimum mix proportions, construction techniques, thermal properties and durability aspects are covered in this research.

Thermal properties of a walling material have a significant impact on operational energy consumed by the building. Based on the thermal conductance and specific heat of the material, indoor temperature can vary which will have a major impact on building performance and occupant comfort levels. When introducing a new material it is very important to evaluate the life cycle cost since it can assess performance of the proposed composite comparable with the other walling materials.

The walling system developed with cement stabilized rammed earth (CSRE) and Building Demolition waste (BDW) is termed as “composite wall” in the rest of the sections of the research.

## 1.2 Objectives

The study covered in this report has been aimed at following objectives:

a. Determination of a suitable mix proportion for the composite mix of CSRE and BDW.

b. Determination of compressive strength of the composite mix of SRE and BDW.

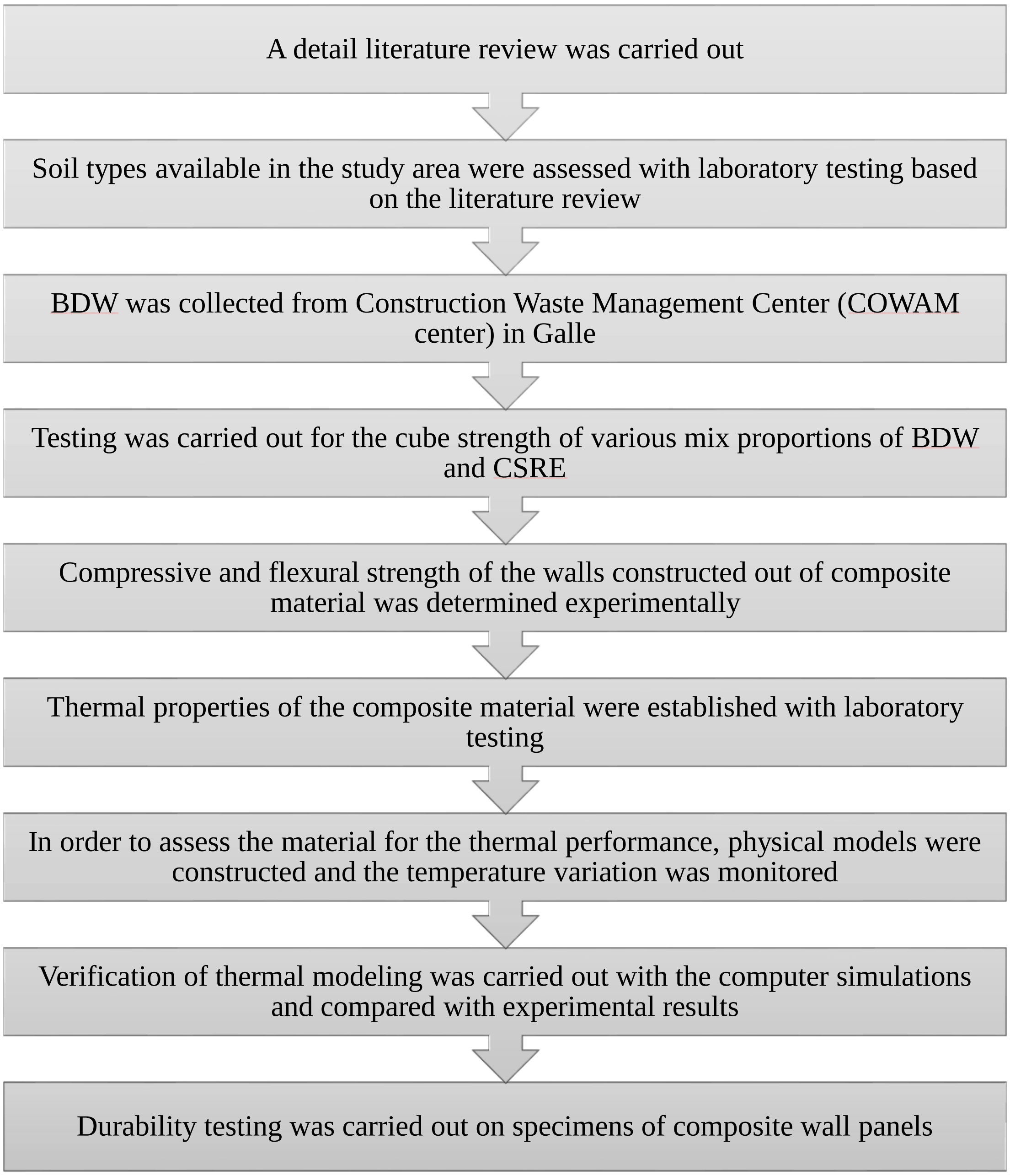
c. Establishing thermal properties of the composite material.

d. Assessing thermal performance of the proposed composite material.

e. Assessing durability of the composite material of CSRE and recycled BDW.

### 1.3 Methodology

In order to achieve the objectives stated in Section 2, following methodology was used:



# CHAPTER 02

# LITERATURE REVIEW

## 2.1 General

The thermal dynamics of the human body is one of the main aspects that affect its health. As buildings are made to accommodate human beings, these properties must be taken into consideration in their design. The thermal comfort is defined in BS EN ISO 7730 [32] as "… that condition of mind which expresses satisfaction with the thermal environment" ie the condition when someone is not feeling either too hot or cold. The human body needs to be shielded from the external environment in order to maintain its heat balance. This shield is the 'environmental envelope' [8] of the building where the heat exchange is conducted. Moreover, it is the thermophysical properties of the construction materials that determines the rate of this heat exchange and provides one of the aspects of thermal comfort within any building.

According to the ASHRAE Handbook of Fundamentals (1989) [2], the environmental factors that affect the quality of indoor environment are Air temperature, Air Velocity, Radiant temperature and Relative Humidity (RH). Air temperature is defined as the temperature of the air that a person is in contact with, measured by the dry bulb temperature. Air velocity is determined by the velocity of air that a person is in contact with (measured in m/s). The faster the air is moving, the greater the exchange of heat between the person and the air. Radiant temperature is the temperature of a person's surrounding (including surfaces, heat generating equipment, the sun and the sky). This is generally expressed as mean radiant temperature and any strong mono-directional radiation such as radiation from sun. Relative humidity is the ratio between the actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature, expressed as a percentage. The higher the relative humidity, the more difficult it is to lose heat through the evaporation of sweat.

Achieving comfort in a building starts with the knowledge of the climate in question and passive strategies to control this climate in order to provide the right design approaches for maintaining comfort. The selections of site, the orientation of the building, vegetation, choice of thermal mass or thermal insulation for the particular climate, as well as the selection of building materials are the major and prime controls in maintaining the thermal comfort of occupants.

Recent studies (de Dear and Brager 1998; ANSI/ASHRAE Standard 55-2000R) [3] have shown that the thermal responses of occupants depend to some extent on the outdoor climate in naturally ventilated buildings with operable windows. Furthermore, an adaptation occurs in these buildings regarding the occupants' previous thermal experiences, the availability of control, and shifts in expectations. Buildings in Central Anatolia are for the most part naturally ventilated. While earlier ones were made of traditional materials such as adobe, recent ones are more commonly of frame structure with brick infill walls. Knowing that materials effect on thermal comfort and indoor air quality (IAQ) of the building, their thermal performance needs to be investigated because they are of vital importance for human life.

As technology advanced, in the second half of the 20$^{th}$ century, a high degree of comfort in buildings using mechanical devices and systems was achieved regardless of climate. The modern building began to be designed alike around the world. The main concern was keeping a microclimate providing comfort inside regardless of the one outside. Mainly air conditioning and heating systems were relied upon for solving the problem of comfort. As time passed, the disadvantages of this design aspect were observed and energy-efficient design became important while a balanced climatic design in regard to local climatic elements became a major issue.

It is once again believed that a house in a desert should be different than one in a cool region, and studies have been conducted to achieve human comfort naturally, relying especially on material and design.

## 2.2 Sustainable construction

Sustainable Construction is the construction that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable construction should:

- Enhance living, working and leisure environments for individuals and communities.
- Consume minimum energy over its life cycle
- Generate minimum waste over its life cycle
- Integrate with the natural environment
- Use renewable resources where possible

### 2.2.1 Fundamentals of Sustainable Building Design

- Optimize Site Potential
- Optimize Energy Use
- Protect and Conserve Water
- Optimize Building Space and Material Use
- Enhance Indoor Environmental Quality (IEQ)
- Optimize Operational and Maintenance Practices

### 2.2.2 Sustainable Materials in Construction

A useful indicator of the environmental impact of construction materials is embodied Energy. Embodied energy is the SUM of all the energy required throughout the lifecycle of a material. That is energy in:

- Acquisition of the raw material
- Manufacture of the finished product
- Transportation of the product to site
- Construction of a building
- Maintenance through the life of a building
- Demolition of a building

## 2.3 Principles of Green Materials

- Made from environmental friendly materials
- Reduce environmental impacts during construction, renovation or demolition
- Reduce environmental impacts of building operation
- Contribute to a safe, healthy indoor environment

## 2.4 Alternative Building Materials

- Compressed stabilized earth blocks (CSEB)
- Rammed earth
- Chip concrete blocks
- Pre-cast beam slab system
- Stabilized soil layer as the ground floor
- Construction waste
    - Gabion fill
- Chip Concrete Tiles and Micro Concrete Tiles
- Blocks Using Bottom Ash

## 2.5 Rammed Earth as a sustainable material

Rammed earth, along with other alternative materials are often promoted as ‘sustainable’ building materials. One aspect that makes these materials perceived to be ‘sustainable’ is their embodied energy. If made locally, the embodied energy of rammed earth and mud brick is estimated to be around 0.7 MJ/kg, less than 30% of the embodied energy of clay bricks (2.5 MJ/kg) and less than 20% of the embodied energy of lightweight aerated concrete blocks (3.6 MJ/kg) (Lawson 1996).

Rammed earth walls indeed have high thermal mass. According to the Australian Institute of Refrigeration, Air Conditioning and Heating: the conductivity of 250 mm thick of rammed earth wall with a density of 1540 kg/m$^3$ and specific heat of 1260 J/kg.K is 1.25 W/m.K (AIRAH 2000). Concrete with a density of 2240 kg/m$^3$ will have similar conductivity (which is 1.3 W/m/K or more depending on the quartz or quartzite sand content) however the specific heat would be between 800 to 1000 J/kg.K. (ASHRAE 1997a). This means rammed earth can contain or absorb more heat than concrete does even though it is less dense.

When used internally and exposed to heat source including direct and indirect solar radiation, rammed earth walls absorb and store the heat and release it when the surrounding temperature drops below the walls’ temperature. When used as external walls, thick rammed earth walls provide a long thermal time lag, thus slowing down the heat transfer between the inside and outside.

### 2.6 Thermal Properties of rammed earth

The thermal performance of rammed earth is measured in a number of different ways. The most commonly used properties are:

- Thermal Storage- This is a measure of the specific heat capacity expressed in volume terms and has units of $J/m^{3o}C$. Houben & Guillaud (1994) claims that for rammed earth the thermal storage is around 1830 $J/m^{3o}C$.

- Thermal Resistance (R-value) - This is a measure of the opposition to heat transfer offered by a building element of specified thickness and is measured in $m^2K/W$.
  According to Standards Australia (2002), a 300mm thick rammed earth wall has an R value between 0.35-0.70 $m^2K/W$.

- Thermal Transmittance (U-values) - This is a measure of the overall rate of heat transfer, by all mechanisms under standard conditions, through a particular section of construction and is measured in $W/m^2K$. Minke (2000) claims that the U-values for a 300mm thick rammed earth can be as much as 1.9-2.0 $W/m^2K$

## 2.7 Recycled building waste as a Building Material

### 2.7.1 Different categories of construction waste

In the Sri Lankan context, a substantial component of waste is generated by concrete and cement mortar which are in the range of 21% and 25 % in proportion respectively. A comprehensive study carried out by Nawagamuwa et. al. (2012) [22] has identified concrete as the most suitable category of construction waste as the filling material for the Gabion walls. Waste generated by brick and mortar has failed in the properties such as durability, compressive strength and factor of safety against different failures.

Further testing carried out by Nawagamuwa et al (2012), has shown that bricks and bricks with mortar had failed in all three aspects such as durability, compressive strength and Factor of Safety against different failures.

### 2.7.2 Water absorption

The water absorption in recycled aggregate ranges from 3 to 12% for the coarse and the fine fractions depending upon the type of concrete used for producing the aggregate. It may be noted that this value is much higher than that of the natural aggregates whose absorption is about 0.5–1%. The high porosity of the recycled aggregates can mainly be attributed to the residue of mortar adhering to the original aggregate [21].

## 2.8 Properties of concrete made with recycled aggregate

When designing a concrete mix using recycled aggregate (RA) of variable quality, a higher standard deviation should be employed in order to determine a target mean strength based on a required characteristic strength. When coarse recycled aggregate is used with natural sand, it may be assumed at the design stage, that the free w/c ratio required for a certain compressive strength will be the same for Recycled Aggregate Concrete (RAC) as for conventional concrete [21].

For a recycled aggregate mix to achieve the same slump, the free water content will be approximately 5% more than for conventional concrete. Trial mixes are mandatory and appropriate adjustments depending upon the source and properties of the RA should be made to obtain the required workability, suitable w/c ratio, and required strength, of RAC.

## 2.9 Properties of fresh recycled aggregate concrete (RAC)

The workability of RAC for the same water content in the concrete is lower as reported by many researchers, especially when the replacement levels exceed 50% (Topc¸u and Sengel, 2004 cited by Rao, 2005) [24].

In order to improve the workability, certain measures in the direction of changing the moisture condition of the RA, have been suggested (Oliveira et al., 1996; Poon et al., 2002, 2004 cited by Rao 2005) [24]. Extra water corresponding to absorption of the aggregate mixed during concrete preparation produced the most consistent results as far as workability is concerned.

The bulk density of fresh concrete made with natural aggregates is in the range of 2400 kg/m3, whereas the concrete made with recycled aggregates is significantly lighter, 2150 kg/m3, regardless of the type of cement (Topcu and Guncan, 1995; Katz, 2003 cited by Rao, 2005) [24]. The lower density is the result of the specific gravity of the aggregates, which is related to the type of concrete used for producing the aggregate. In addition, increased air content in the recycled concrete, leads to an additional reduction in the density of the fresh concrete.

### 2.10 Compressive strength

The extent of reduction is related to the parameters such as the type of concrete used for making the RA (high, medium or low strength), replacement ratio, water/cement ratio and the moisture condition of the recycled aggregate. Katz (2003) cited by Rao (2005) [24] found that at a high w/c ratio (between 0.6 and 0.75), the strength of RAC is comparable to that of reference concrete even at a replacement level of 75% (Katz, 2003).

The strength of RAC and reference concrete to be comparable even at 100% replacement, provided that the water–cement ratio was higher than 0.55. As the water–cement ratio is reduced to 0.40, the strength of RAC was only about 75% of the reference mix. Apart from the water–cement ratio, the moisture condition of the RA also appears to affect the compressive strength [24].

### 2.11 Flexural and tensile strength

The ratio of the flexural and the splitting strengths to the compressive strength is in the range of 16–23% and 9–13%, respectively (Katz, 2003 cited by Rao 2005) [24]. These values are about 10–15% lower compared to the recommendations of ACI 363R. A study by Rao, shows a reduction in strength of 15–20% compared to reference concrete at 100% replacement.

Difference in the tensile strength of RAC and reference concrete at 28 days was less than 10%. Use of supplementary cementitious admixtures, such as silica fume, etc. helps to improve the properties of RAC (Ajdukiewicz and Kliszczewicz, 2002, cited by Rao 2005).

### 2.12 Bond strength

The effect of use of RA on the bond stress at failure is quite small when compared to factors such as the type of bars used (plain rounds or ribbed bars). A reduction of upto 10% in the bond strength of the RAC has been reported at 100% replacement by RA (Ajdukiewicz and Kliszczewicz, 2002, cited by Rao, 2005) [24].

### 2.13 Modulus of elasticity

The modulus of elasticity for RAC has been reported to be in the range of 50–70% the normal concrete (Oliveira et al., 1996; Ajdukiewicz and Kliszczewicz, 2002; cited by Rao, 2005)[24] depending on the water–cement ratio and the replacement level of RA.

### 2.14 Creep and shrinkage

The use of RA in concrete induces a large shrinkage due to the high absorption of these aggregates. RAC at the age of 90 days, the shrinkage could be about 0.55–0.8 mm/m, whereas the comparable value for NAC is only about 0.30 mm/m (Katz, 2003 cited by Rao 2005)[25]. However, the test results for creep in normal laboratory conditions are not so clear, though some studies have shown the tendency to be reversed, i.e. the creep after 1 year is about 20% lower than concrete with NA (Ajdukiewicz and Kliszczewicz, 2002 cited by Rao , 2005). It appears that the overall behaviour of RAC and NAC may be comparable when viewing the combined effect of shrinkage and creep.

## 2.15 Durability of hardened RAC

Some studies have shown that RAC is significantly more permeable than NA concretes. Durability properties can be improved by using fly ash, condensed silica fume, etc.

## 2.16 Carbonation

On the basis of carbonation test done after 6 months of curing, the carbonation depth of the recycled concrete has been found to be 1.3–2.5 times greater than that of the reference concrete (Crentsil et al., 2001; Levy Salomon and Paulo, 2004). It is seen that for the same water-binder ratio, the carbonation depths of RAC are slightly higher than that of NAC (Otsuki et al., 2003 cited by Rao 2005) [24]. This increase in the carbonation depth could be attributed to increased permeability of the RAC on account of the presence old mortar adhering to the original aggregate, and the old interfacial transition zone (ITZ) between them.

## 2.17 Stabilized rammed earth (SRE)

The study covered in this report has been aimed at mixing building demolition waste with rammed earth and stabilized with cement to form a walling material. Therefore it is important to study the properties of Stabilized Rammed Earth (SRE). SRE has been introduced as a sustainable building material in most parts of the world. Several studies were carried out to establish the properties of cement stabilized rammed earth.

### 2.17.1 Soil types for Stabilized rammed earth (SRE) walls

The composition of soils in different parts of the world varies considerably due to the origin and the climatic conditions. The literature indicates the use of laterite soils and clayey and sandy soils for cement stabilized soil blocks [12] [7].

### 2.17.2 Compressive Strength and Construction methodology of SRE

The following are the results of the study carried out by Jayasinghe and Kamaladasa (2007) [15] on compressive strength of SRE:

• A comprehensive study carried out in India indicates the strength values in the range of 2.5–10.0N/mm2 for individual blocks and 0.9–3.87 N/mm2 for masonry prisms.

• The dry and wet strength varies with the mortar used for binding. In a detailed study carried out with cement stabilized soil blocks manufactured with a manually operated machine giving a compaction ratio of 1.65 indicated block strengths of about 2–4.5 N/mm2 and wall strengths in excess of 0.9 N/mm2 with 6% and higher cement contents.

• Compaction can be given using a steel rammer and construction can be carried out with steel slip forms

• The slip formed wall will have the same thickness as the block work.

• Operation can be further improved with a mechanical rammer instead of a manually operated rammer. However, for countries with lower labour costs, manual rammer could be a better solution.

• A pneumatic rammer was developed jointly with Mechanical Engineering Department of the University and found successful in application. A detailed study carried out at University of Bath indicates that the compressive strength of about 1.0–3.0 N/mm2 can be obtained with un-stabilized rammed earth.

• Soils recommended were reasonably well graded between gravel and clay sized particles.

• There are strong indications that show laterite soil can perform much better than clayey soils when stabilized with cement.

#### 2.17.3 Strength characteristics of rammed earth in compression

One of the most important strength parameters needed for any load-bearing walling material is compressive strength. Compressive strength can be determined by using wall panels. BS 5628: Part 1:1992 [34] allows the use of any suitable wall panel size when new masonry materials require the determination of wall strengths. From each parameter, two panels should be tested. There were two characteristic compressive strengths using the following formula

$F_k = F_m/A \times (\psi_m \psi_u/1.2)$ …………………………...Equation 1

Where Fm is the mean of the maximum loads carried by the two test panels; A is the cross sectional area of each panel; $\psi_m$ is the reduction factor for strength of mortar; and $\psi_u$ is the unit reduction factor for sample structural strength.

• The unit weight of rammed earth is in the range of 1800–2000 $kg/m^3$.

• In single storey construction, the load is primarily from the self-weight of the walls and the portion of the roof supported. This stress is usually in the range of 0.1 $N/mm^2$.

• This means that characteristic wall strength required is about 0.5 $N/mm^2$ when a factor of safety of 1.4 ($\gamma_f$) is used for dead loads and 3.5($\gamma_m$) is used for material strength variations and workmanship factors as recommended in BS 5628: Part 1: 1992 [34].

• BS 5628: Part 1:1992 also allows the use of $\gamma_m = 2.5$ which will give a lower factor of safety. However, the use of 3.5 is advisable due to less warning given prior to failure.

• This gives an overall factor of safety of 5.

Tables 2, 3 and 4 present the results of compressive strength of SRE together with wet/dry strength ratio.

### 2.17.4 Load deformation curves of SRE

According to the typical load deformation curve obtained for rammed earth panels. It does not indicate much ductility which can be attributed to compressive crushing nature of the failure. Thus, the use of a higher factor of safety is advisable. The strength obtained with laterite soils indicated that it is possible to maintain a high overall factor of safety since the characteristic strengths obtained are high. This curve can be used to determine the modulus of elasticity. The values were in the range of 500 N/mm2. The same value is recommended in the Australian Earth Building Hand Book. The value recommended in New Zealand Standard is 300 X fc and hence in a similar range.

### 2.17.5 Flexural Strength of SRE

There are not yet sufficient studies on the tensile strength and the shear strength of rammed earth. The tensile strength of rammed earth is neglected in general due to its very low value, but in extreme conditions (e.g. seismic), knowing tensile strength is necessary for the structural design.

Shear strength is also required in many cases to check the punching strength of rammed earth walls quickly, such as beams directly placed on a rammed earth wall (roof beams, lintel beams; and vertical ties) in anti-seismic devices.

The shear strength is also identified using a simple method based on compressive strength, tensile strength, and Mohr’s circle theory.

It is possible to determine the flexural strength of masonry using specimen wall panels loaded laterally. The flexural strengths can be determined either parallel to bed joints or perpendicular to the bed joints.

Since the flexural strength parallel to the bed joints is generally low, there is a tendency for the failure to occur at very low lateral loads. Thus, the results tend to indicate a greater scatter since stresses induced during handling of the panels also could trigger failure at low lateral loads. It was shown by Jayasinghe and Konthesinghe(2008) that it is possible to obtain reliable results for flexural strength parallel to bed joints by testing them with low magnitudes of pre-compression. Such pre-compression prevents early failure due to any weakness suffered during handling. The pre compression will ensure a reasonable lateral load and hence a higher flexural strength. The actual flexural strength will be the one obtained after deducting the pre-compression. This method may not be valid if the pre-compressive stresses are high, since heavy vertical loads tend to give higher resistance while developing some arching action when subjected to lateral loads.

In this test series, the pre-compression was limited to 0.06 N/mm2. This is the stress likely to occur at the plinth level of a masonry wall having a height of 3.0 m due to its self-weight. An axial compressive stress of about 0.1 N/mm2 or more would be needed for developing arching action as indicated in BS 5628: Part 1: 1992[34].

For determining the flexural strength perpendicular to bed joints, it is not necessary to apply pre-compression, since the results generally tend to be reliable due to the higher magnitudes of strength. However, in order to simulate the actual conditions to a greater extent, a pre-compression of 0.06 N/mm2 was applied for these panels as well.

Table 1 presents dimensions and flexural strengths of wall panels considered in the experimental programme.

**Table 1: Flexural strength of different walling materials in two orthogonal directions [4]**

| Type of walling material | Dimensions of an Individual unit (mm) | | | Flexural strength ($N/mm^2$) | |
|---|---|---|---|---|---|
| | Length | Width | Height | Parallel to bed joints | Perpendicular to bed joints |
| Burnt clay bricks of water absorption > 12% [13] | 225 | 115 | 75 | 0.3 | 0.9 |
| CSE Bricks-English Bond | 230 | 110 | 75 | 0.365 | 1.491 |
| CSE Bricks-Flemish Bond | 230 | 110 | 75 | 0.397 | 1.283 |
| CSE Bricks-Rat-trap Bond | 230 | 110 | 75 | 0.333 | 1.156 |
| CSE Solid block | 225 | 225 | 115 | 0.243 | 1.284 |
| CSE Interlocking solid block | 235 | 225 | 115 | 0.393 | 1.957 |
| CSE Interlocking hollow block | 300 | 145 | 100 | 0.262 | 0.261 |
| 240 mm thick rammed earth wall section | | | | 0.463 | 0.918 |

Source: http://sustainabilityworkshop.autodesk.com/buildings/thermal-properties-materials

## 2.18 Climatic Elements

The "climate" of a given region is determined by the pattern of variations of several elements and their combinations. The principal climatic elements, when human comfort and building design are being considered, are solar radiation, longwave radiation to the sky, air temperature, humidity, wind and precipitation such as rain, snow, etc. (Givoni, 1976, pp. 1) [11].

Climate, as it affects human comfort, is the result of the air temperature, humidity, radiation-including light- air movement, and precipitation. To achieve comfort, these factors need to be handled in such a way as to establish some form of balance between the environmental stimuli so that body is neither losing nor gaining too much heat, nor is subject to excessive stresses from other variables. In climatic terms, therefore, a building needs to respond to heat, cold, ground and sky radiation, wind and other stresses (Rapoport, 1969, pp. 88-89) [25]. These factors will be described in more detail in the following section.

### 2.18.1 Solar Radiation

Solar radiation is an electromagnetic radiation emitted from the sun which has different wavelengths. These wavelengths are broadly divided into three regions: ultra-violet (UV.), visible and infra-red (IR.). Only the small section of this range is light visible to the eye. Although the peak intensity of solar radiation is in the visible range, over one-half of the energy is emitted as IR radiation (Givoni, 1976, pp 1-2) [11].

Olgyay (1963), reports that radiation effect of inside surfaces can be used to balance higher or lower air temperatures. This means that we can be comfortable at low temperatures if the heat loss of the body can be counteracted with the sun's radiation. At temperatures under $70^0$F a drop of $1^0$F in air temperature can be neutralized by elevating the mean radiant temperature by $0.8^0$ F. However this possibility of neutralization has its limitations cause in practice we shall not find more than $4^0$ or $5^0$ F differences between air and wall temperatures.

The four main channels of radiant heat transfer affecting building are, in the order of importance: direct shortwave radiation of the sun; diffused shortwave radiation from the sky-vault; short-wave radiation reflected from the surrounding terrain; and long-wave radiation from the heated ground and nearby objects. These affect buildings in two ways: First it affects by entering through windows and being absorbed by internal surfaces which causes a heating effect. Secondly it affects through being absorbed by the outside surfaces of the building which creates a heat input. A large proportion of this heat input is conducted through the structure and eventually emitted to the interior. Another major form of heat transfer affecting buildings is the outgoing long-wave radiation exchange from building to sky. This is an effect which is reduced when the sky is clouded and is strongest when the atmosphere is clear and dry as in hot arid zones where it can be utilized as a source of energy for cooling buildings (Konya, 1980, pp. 11-12).

### 2.18.2 Air Temperature

Givoni (1976), reports that the rate of heating and cooling of the surface of the earth is the main factor determining the temperature of the air above it. As the air is transparent to almost all solar radiation, it has only an indirect effect on air temperature.

Givoni further states that the annual and diurnal patterns of air temperature depend on the variations in surface temperature. Wide differences in temperature exist between land and water surfaces. Great bodies of water are affected more slowly than land masses under the same conditions of solar radiation. Therefore land surfaces are warmer in summer and colder in winter than sea surfaces on the same latitude. The air masses originating over these surfaces differ accordingly. The average temperature of air is higher in summer and lower in winter over land than over the sea. Also temperatures are generally lowest just before sunshine, as diffused radiation from sky causes temperatures to rise even before sunrise, and highest over land about two hours after noon, when the effects of the direct solar radiation and the high air temperatures already existing are combined.

A change in altitude also changes the temperature of the air. The air masses in the mountains have lower pressure than in low height regions. So when the air mass rises up, it expands and is cooled. Conversely, when an air mass descends it is compressed and heated. These are known as adiabatic cooling and heating. The rate of temperature change is about $1^0$C/100 m. in altitude (Givoni, 1976, pp. 6-7) [11].

### 2.18.3 Humidity

Givoni reports that the moisture content of the atmosphere can be expressed in several terms, such as the absolute humidity, specific humidity, vapour pressure and relative humidity. Absolute humidity is defined as the weight of water vapour per unit volume of air (g/m$^3$) and the specific humidity as the weight of water vapour per unit weight of air (g/kg). The vapour pressure of the air is the part of the whole atmospheric pressure that is due to the water vapour and is measured in mm Hg. The relative humidity at any temperature is the ratio of the actual absolute humidity to the maximum moisture capacity of the air at that temperature which can be defined as the percentage of the absolute saturation humidity.

Givoni adds that the term atmospheric humidity refers to the water vapour content of the atmosphere. Water vapour enters the air by evaporation, principally from the surfaces of the oceans and also from moist surfaces, vegetation and small water bodies. The vapour is carried and distributed over the earth's surface by the winds. He further insists that the air's capacity for water vapour increases gradually with its temperature. For this reason the vapour distribution over the earth is not uniform. It is highest in the equatorial zones and decreases towards the poles, varying parallel with the pattern of annual solar radiation and temperature averages (Givoni, 1976, pp. 13-14) [11].

Konya (1980) reports that although the absolute humidity of a given body of air does not change unless water vapour is added to or taken from it, the relative humidity of the air concerned will vary with any change in temperature. If the air actually contains all water it can hold, it is said to be saturated and its relative humidity is then 100 percent, but if the actual vapour content is less than the potential content at the same temperature, the relative humidity is then less than 100 percent. Relative humidity, therefore, is the ratio of the actual humidity in a given volume of air to the maximum moisture capacity at that particular temperature.

Konya (1980) further reports that relative humidity affects the behaviour of many building materials and their rate of deterioration, and vapour pressure affects the rate of evaporation from the human body. Whereas the diurnal differences in vapour pressure levels are small, they are subject to wide seasonal variations and are usually higher in summer than in winter. Relative humidity on the other hand may undergo wide variations, as the result of diurnal and annual changes in air temperature which determine the potential moisture capacity, even when the vapour pressure remains almost constant. Moreover humidity affects the perception of IAQ, thermal comfort, occupant health, building durability, material emissions, and energy consumption.

Relative humidity is important for human comfort mostly for its effect on the evaporation of sweat. In order to evaporate, there needs to be a source of high temperature from which the latent heat of vaporization can be drawn, and sufficient vapour pressure to allow vaporization. In hot dry climates sweat is readily evaporated. In humid or tropical environments there is abundant heat, but very low vapour pressure as the air is already almost at saturation point, so sweating is much less effective. At relative humidity above 80%, sweat is produced but most of it cannot evaporate as the air immediately surrounding the body quickly becomes saturated. Humidity less than 20% result in large amounts of evaporation or both sweat and other bodily fluids, drying out the eyes and mucous membranes which can greatly increase susceptibility to infection.

#### 2.18.4 Wind

According to Givoni (1976), the distribution and characteristics of the winds over a region are determined by several global and local factors. The main determinants are the seasonal global distribution of air pressure, the rotation of the earth, the daily variations in heating and cooling of land and sea and topography of the given region and its surroundings (pp. 8).

Olgyay (1963) asserts that desirable air movements should be utilized for cooling in hot periods, and as a relief from vapour pressure during times of high absolute humidity. Conversely air movements should be blocked and avoided during the cold season. He further adds that air movement affects body cooling. It does not decrease temperature but causes a cooling sensation due to heat loss by convection and due to increased evaporation from the body. As velocity of air movement increases, the upper comfort limit is raised. However, this rise slows as higher temperatures are reached.

#### 2.18.5 Condensation and Precipitation

Givoni (1976) reports that if air containing water vapour is cooled, its moisture holding capacity is reduced so that the relative humidity is increased. This continues until it becomes saturated. The temperature at which this air becomes saturated is known as the dew point. The dew point at a given atmospheric pressure depends only on the vapour pressure of the air. Any cooling below the dew point causes the condensation of the vapour in excess of the air's capacity. Givoni further adds that cooling of the air may be effected by three processes: contact with cooler surfaces, mixing with cooler air and expansion associated with rising air currents (adiabatic cooling). The first two processes result in dew and fog formation; the third is the one that can cause large-scale precipitation (pp. 15).

Condensation can damage building materials. It is often more serious problem in "well-sealed" but under insulated buildings. Humidity within a space can be removed from the building in two ways: by additional heating which raises the temperature so that relative humidity is reduced and by ventilation which removes the humidified air. [26]

## 2.19 Thermal Comfort

According to ANSI/ASHRAE 55 Standard-2000R (2001) [3], thermal comfort can be defined as that condition of mind, which expresses satisfaction with the thermal environment. The main criteria for thermal comfort for the human body as a whole can be divided into environmental variables: air temperature, mean radiant temperature, humidity, air velocity and personal variables: clothing and metabolic rate (activity). In addition there are other environmental parameters that can cause local thermal discomfort such as draught, a high vertical temperature difference between head and feet, radiant temperature asymmetry and warm or cold floors (pp. 9-24).

He further points out that the measurement of climatic effects has been investigated in many ways of which two will be mentioned here. The first method describes the negative effects of climate on man, expressed as stress, pain, disease, and death. The second defines the conditions in which man's productivity, health, and mental and physical energy are at their highest efficiency. Both approaches may be combined, to show overlapping and opposite relationships, in defining desirable or unpleasant atmospheric and thermal conditions. The experiments done by Huntington, as reported by Olgyay related to man's physical strength and mental activity are at their best within a given range of climatic conditions, and that outside this range efficiency lessens, while stresses and the possibility of disease increase (Olgyay, 1963, pp. 14).

Again, according to the ASHRAE Handbook of Fundamentals (1989) [2] human beings spend 95% of their time indoors and it is a controlled environment. It is also mentioned that certain aspects of heath , such as mortality and heat stress in heat waves, and the effects of hot and cold extremes on specific diseases has strong physiological basis linked to outdoor temperature. These show that outdoor climate should be considered in terms of human health and comfort (pp. 8.26).

Thermal comfort exists when a body's heat loss equals its heat gain or vice versa.

The body exchanges:

62% of this heat via radiation,

15% by evaporation,

10% by convection,

10% by respiration and

3% by conduction.

Hence, when considering normal comfort conditions inside a building the radiative effect of surrounding surfaces is at least as important as air temperature. Relatively small changes in mean radiant temperature have a far greater effect than similar changes in air temperatures (Ballinger 1992). This gives rise to the importance of recognizing the overall Environmental Temperature [T (env)], as opposed to just the dry bulb temperature.

T (env) = 2/3 Mean radiant surface temperature + 1/3 Air temperature

Thermal mass influences bodily comfort by providing heat source and heat sink surfaces to support the radiative heat exchange comfort processes

## 2.20 Thermal Properties of Materials

Every material used in an envelope assembly has fundamental physical properties that determine their energy performance like conductivity, resistance, and thermal mass. Understanding these inherent properties will help to choose the right materials to manage heat flow.

### 2.20.1 Thermal Conductivity (k)

Thermal conductivity can be define as the material's ability to conduct heat. Each material has a characteristic rate at which heat will flow through it. The faster heat flows through a material, the more conductive it is. Conductivity (k) is a material property given for homogeneous solids under steady state conditions.

It is used in the follow equation: $q = \frac{kA\Delta T}{L}$

Where

q = the resultant heat flow (Watts)

k = the thermal conductivity of the material (W/mK).

A = the surface area through which the heat flows ($m^2$)

$\Delta T$ = the temperature difference between the warm and cold sides of the material (K),

L = the thickness / length of the material (m)

**Units for conductivity**

Imperial – BTU*in/h ft ºF: In the Imperial system, conductivity is the number of British thermal units per hour (Btu/h) that flow through 1 square foot ($ft^2$) of material that is 1 inch thick when the temperature difference across that material is 1ºF (under conditions of steady heat flow).

SI - W/m ºC or W/m K: The System International (SI) equivalent is the number of watts that flow through 1 square meter ($m^2$) of material that is 1 m thick when the temperature difference across that material is 1 K (equal to 1ºC) under conditions of steady heat flow.

### 2.20.2 Thermal Conductance (C)

Conductivity per unit area for a specified thickness is named as Thermal Conductance. In basic building materials, heat flow is usually measured by conductance (C), not conductivity. Conductance is a material's conductivity per unit area for the object's thickness (in units of $W/m^2K$ for metric and $BTU/hr \cdot ft^2 \cdot {}^\circ F$ for Imperial). Conductance is an object property and depends on both the material and its thickness.

### 2.20.3 U-Factor (U)

Overall conductance of a combination of building element is define as U factor. In layered assemblies, conductance are combined into a single number called the "U-factor" (or sometimes the "U-value"). U is the overall coefficient of thermal transmittance, expressed in terms of Btu/h ft$^2$ ºF (in SI units, W/m$^2$ K). This is the same unit as conductance because it's a measure of the same thing: conductance is used for a specific material, U-factor is used for a specific assembly. Lower U-factors mean less conduction, which means better insulation.

#### 2.20.4 Thermal Resistance (R-value = 1/U)

Thermal resistance is meant by material's ability to resist heat flow and designated as R (R-value). Thermal resistance indicates how effective any material is as an insulator. The reciprocal of thermal conductance, R is measured in hours needed for 1 Btu to flow through 1 ft$^2$ of a given thickness of a material when the temperature difference is 1ºF. In the Imperial system, the units are ft$^2$•°F•hr/BTU. SI units are m$^2$K/W.

Insulation, which prevents heat flow through the building envelope, is often measured by its R-value. A higher R-value indicates a better insulating performance. When looking at specification sheets, be sure you are reading the R-value in the right units, as the units are not always explicitly written.

#### 2.20.5 Thermal Mass

Thermal mass is a material's resistance to change in temperature as heat is added or removed, and is a key factor in dynamic heat transfer interactions within a building. The four factors to understand are: density, specific heat, thermal capacity, and thermal lag.

### 2.21 Density

Density is the mass of a material per unit volume. In the Imperial system, density is given as lb/ft$^3$; in the SI system, it is given as kg/m$^3$. For a fixed volume of material, greater density will permit the storage of more heat.

### 2.22 Specific Heat

Specific heat is a measure of the amount of heat required to raise the temperature of given mass of material by 1º. In the Imperial system, this is expressed as Btu/lb ºF; in the SI system, it is expressed as kJ/kg K. It takes less energy input to raise the temperature of a low-specific-heat material than that of a high-specific-heat material.

**Table 2: Heat Capacities of common building materials [4]**

| **Material** | **Heat capacity J/(g·K)** |
|---|---|
| Brick | 0.84 |
| Concrete | 0.88 |
| Granite | 0.79 |
| Gypsum | 1.09 |
| Soil | 0.80 |
| Wood | 1.2-2.3 |
| Water | 4.2 |

Source - *http://sustainabilityworkshop.autodesk.com/buildings/thermal-properties-materials*

### 2.23 Thermal Capacity (Thermal Mass)

Thermal capacity is an indicator of the ability of a material to store heat per unit volume. The greater the thermal capacity of a material, the more heat it can store in a given volume per degree of temperature increase. Thermal capacity for a material is obtained by taking the product of density and specific heat. Units are J/Kº.

Higher thermal capacity can (but will not always) reduce heat flow from the outside to the inside environment by storing the heat within the material. Heat entering a wall construction during the daytime, for example, can be stored within the wall for several hours until it flows back out to the cool night air-assuming appropriate weather conditions and adequate thermal capacity.

#### 2.23.1 Thermal Lag (Time Lag)

With high thermal mass, it can take hours for heat to flow from one side of the envelope to the other. This slowing of the flow of heat is called "thermal lag" (or time lag), and is measured as the time difference between peak temperature on the outside surface of a building element and the peak temperature on the inside surface. Some materials, like glass, do not have much of a thermal lag. But the thermal lag can be as long as eight or nine hours for constructions with high thermal mass like double-brick or rammed earth walls.

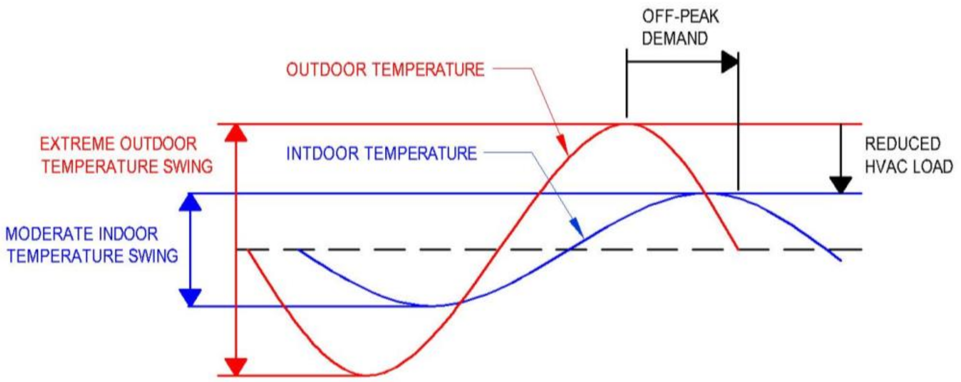



**Figure 1 - Lag-time and moderation of temperatures due to thermal mass [4]** ***(http://sustainabilityworkshop.autodesk.com/buildings/thermal-properties-materials)***

As an example, if the sun comes out from behind clouds and strikes a building envelope with high thermal capacity at 10AM, the exterior surface temperature will rise quickly. It may be several hours, however, before this temperature “spike” is seen at the inside surface of the wall. The reason is that some heat is being stored in the wall material. This heat is stored in the wall material until it has absorbed as much as it can (saturated). Heat will then flow to the inside, based on the conductivity of the material. [27]

### 2.24 Comfort Zone

The range of conditions in which thermal comfort is experienced is called comfort zone which differs according to individuals preferences and is affected by the clothing worn, geographical location, age, and sex. Although the comfort zone is defined as a subjective assessment of the environmental conditions, the limits of the zone do have a physiological basis; the range of conditions under which the thermo-regulatory mechanisms of the body are in a state of minimal activity. Comfort, is dependent on several aspects and cannot be expressed in terms of any one of these aspects as they affect the body simultaneously and influence of any aspect depends on the levels of the other factors. Several attempts have been made to evaluate the combined effects of these factors on the physiological and sensory response of the body and to express any combination of them in terms of a single parameter or "thermal index" which can be set out on a monogram (Konya, 1980, pp. 27-28).

The comfort zones are intended to provide acceptable thermal environment for occupants wearing typical indoor clothing and at a near sedentary activity. Acceptable thermal environment is an environment that at least 80% of the occupants would find thermally acceptable. [8]

Konya (1980) points out that a systematic procedure for adapting the design of a building to human requirements and climatic conditions is proposed by Olgyay (1963). His method is based on a Bioclimatic Chart on which comfort zones for summer and for winter can be determined for the climatic region to which it is to be applied. Once the chart is produced, any climatic condition can then be plotted on the chart to evaluate comfort requirements and deviations from the comfort zone. Whether these deviations can be eliminated by natural means, is ascertained.

# CHAPTER 03

# EXPERIMENTAL PROGRAM

## 3.1 General

Based on the findings of Literature Review experimental program was designed. The experimental program consisted of four major components, namely Sample Collection (soil and waste), Determination of a suitable mix, Physical Models and Testing. All the tests were carried out in accordance to the given standards. Testing were carried out at the National Building Research Organisation and University of Moratuwa under the close supervision of the experts in relevant fields.

Experimental program was designed to achieve the ultimate goal of determining thermal performance of the composite panels made out of rammed earth and building waste.

## 3.2 Sample Collection

### 3.2.1 Construction Waste

Based on the Literature Review, concrete debris were selected to cast composite walls with high strength and the erosion protection. If masonry or brick debris were used, they would yield some inherent detrimental qualities like vulnerability for erosion, inferior strength and powdery nature [22].

As recommended in the literature, concrete waste was selected for the composite construction. Construction Waste Management Center (COWAM Centre) of Galle Municipal Council is the place where the waste was obtained for the experimental program. COWAM (Construction Waste Management in Sri Lanka) is a project within the framework of the European Union Post-Tsunami Programme. The main objective of this project is to optimize the sustainable use and management of construction waste in Sri Lanka. Main activities of the Centre include the collection, sorting and recycling or reuse of construction waste as road construction material. Grinding of concrete waste was carried out at the crushing plant of COWAM Centre.


**Figure 2 - COWAM Centre, Galle**

### 3.2.2 Sieve Analysis for construction waste

The recycling centre in Galle crushes the construction waste into 3 different particle sizes. They are 19 mm-12 mm, 12 mm-2.36 mm and the dust(<2.36 mm). Particle size distribution test was performed in accordance with ISO 17892 - 4 [29] methods for determination of the particle size distribution of different particle size categories.

A mix design was performed to obtain a well graded recycled BDW mixture for the study. The obtained proportion achieved for the well graded curve is presented in Table 3.

**Table 3 - Obtained mix proportion for a well graded curve**

| Particle size | Proportion | Mix Proportion |
|---|---|---|
| < 2.36 mm | 1.0 | |
| 2.36 mm- 12 mm | 2.0 | 2:4:1 |
| 12 mm – 19 mm | 0.5 | |

The above mix proportion was used for all the test procedures in the research.

### 3.2.3 Selection of Soil Type

To choose suitable soil for the rammed earth wall construction was done based on sieve analysis. According to the literature laterite soil is better than other types of soils for rammed earth construction [7]. The laterite soil samples were obtained within the

University of Moratuwa premises. Laterite soils are abundant in Sri Lanka which makes the research more applicable. For the determination of suitability of soils, particle size distribution test was performed in accordance with ISO 17892 – 4: Methods for determination of particle size distribution [29].

According to the literature the soil percentage passing through 0.075 mm should be less than 30 % from the total soil weight to have a well compacting soil mix [7].

Sample calculation for a soil sample which was taken from the construction site of new IT building at University of Moratuwa

Weight of the small tray = 9.04g

Tray + water+ soil= 48.8 g

Soil + tray = 42.53g

Water content of the soil sample = $\frac{48.8-42.53}{42.53-9.04}$ ×100 = 18.72 %

Weight of total soil sample = 1463 g

Weight of the container= 400g

Sieved soil container weight = 404.18g

Dried soil sample + container weight = 648.18 g

Total dry soil weight = $\frac{1463-400}{100} \times (100 - 18.72)$ = 864g

Dry weight of soil passing through 0.075mm = 648.5-404.18=244.32 g

Soil percentage passing through the sieve= $\frac{244.32}{864} \times 100 = 28.28$ %

### 3.3 Determination of a Suitable Mix

Then the concrete waste and the laterite soil were both sieved from 12 mm mesh for the testing program. Table 4 presents the mix proportions (cement: waste: soil) and compressive strength of cubes cast from the mixes. A detail experimental program was carried out to select a proper soil for stabilization and to determine a feasible mix proportion for the composite walling material. This was done by casting 66 cubes for different arbitrary soil proportions. Compressive strength of the cubes was obtained at the age of 7 days and 28 days. Compressive strength was obtained at the age of 28 days both in dry and wet states.

**Figure 3 - Casting of test cubes**

**Figure 4 - Testing cubes for compression strength**

**Table 4 - Cube Test Results**

| Mix proportion | Compressive strength (7 days) N/mm$^2$ | Dry Compressive strength (28 days) N/mm$^2$ | Wet Compressive Strength (28 days) N/mm$^2$ | Density (kg/m$^3$) |
|---|---|---|---|---|
| 1:4:6 | 2.67 | 3.0 | 2.0 | 1763 |
| 1:3:7 | 3.17 | 3.5 | | 1812 |
| 1:6:4 | 3.67 | 5.67 | | 1961 |
| 1:5:5 | 4.8 | 6.33 | 6.0 | 2064 |
| 1:10 (Rammed earth) | 3.0 | 3.5 | | 1828 |

According to the results of testing compressive strength the mix proportion of 1:5:5 show the best performance over other mix proportions. Therefore, the 1Cement: 5 Building Waste: 5 Soil mix proportion was selected as the most suitable mix design for this study.

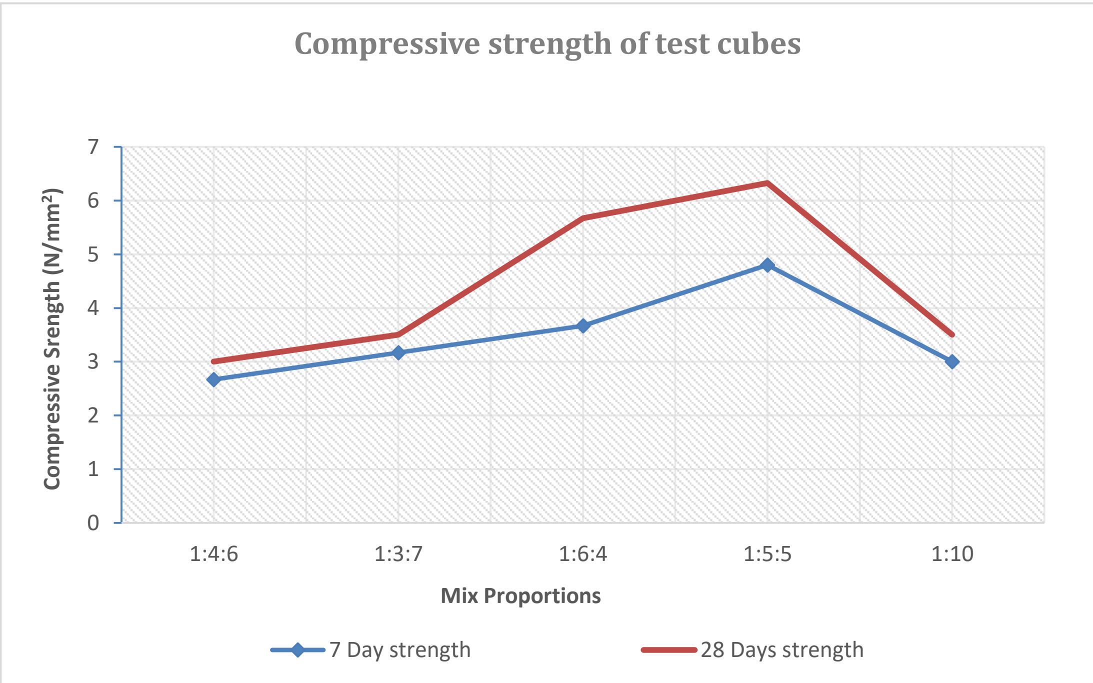



**Figure 5 - Compressive Strength of Test Cubes for Different Proportions**

### 3.4 Structural performance

Two panels each from the sizes 1000 × 800 ×150 mm, 550 × 1000 × 150 mm and 1000 ×750 ×150 mm were cast from the composite material and they were tested for Flexure Parallel to Bed, Flexure Perpendicular to Bed and Compression test to determine the structural performance of the composite material.

**Table 5 - Casting of Wall Panels**

| Test | Panel Dimensions(mm) | | | Number of Panels |
|---|---|---|---|---|
| | Length | Height | Thickness | |
| Flexure Parallel To Bed | 1000 | 800 | 150 | 2 |
| Flexure Perpendicular To Bed | 550 | 1000 | 150 | 2 |
| Compression test | 1000 | 750 | 150 | 2 |

**Table 6 - Test results of flexural strength**

| Test | Panel 1 | Panel 2 | Average Strength |
|---|---|---|---|
| Flexural Strength parallel to bed ($N/mm^2$) | 1.32 $N/mm^2$ | 1.36 $N/mm^2$ | 1.34 $N/mm^2$ |
| Flexural Strength perpendicular to bed ($N/mm^2$) | 1.60 $N/mm^2$ | 1.75 $N/mm^2$ | 1.67 $N/mm^2$ |

**Table 7 - Test Results of compression test**

| Compression test | Load at first crack (KN) | Load at failure (KN) | Compressive Strength ($N/mm^2$) | Average Compressive Strength ($N/mm^2$) |
|---|---|---|---|---|
| Panel 1 | 297.6 | 315.8 | 2.1 | 2.05 |
| Panel 2 | 284.8 | 299.2 | 2 | |

**Table 8 - Test Result Summary**

| Test | Panel 1 | Panel 2 | Strength |
|---|---|---|---|
| Compressive Strength | 2.1 N/mm$^2$ | 2N/mm$^2$ | 2.05N/mm$^2$ |
| Flexural Strength parallel to bed | 1.324 N/mm$^2$ | 1.363 N/mm$^2$ | 1.3435 N/mm$^2$ |
| Flexural Strength perpendicular to bed | 1.6 N/mm$^2$ | 1.7544 N/mm$^2$ | 1.6772 N/mm$^2$ |

**Figure 6 - A panel testing for flexural strength**

**Figure 7 - A panel testing for compressive Strength**

### 3.5 Physical Models

Walling materials significantly contribute towards indoor thermal comfort. When a new walling material is introduced, thermal modeling has to be carried out to assess the performance and indoor comfort levels. Therefore, a comprehensive experimental program was conducted with physical models constructed out of the proposed walling material and two other conventional materials for comparison purpose. The internal dimensions of the models were 820mm (length) × 800mm (width) × 1000mm (height) with 150mm wall thickness. Roof is covered by corrugated asbestos sheets and the rear of the models covered by 9mm thick 1000mm (height) ×800mm (width) plywood sheets. The front face of all models were facing the Eastern direction. The composite walls were constructed using a plywood framework and a wall thickness of 150 mm was used to construct the models and walls were compacted manually with the compaction ratio of 2, for CSRE and BDW.

**Figure 9 - Physical Models**

**Figure 8 - Making of Physical Models**

To get the thermal measurements of the physical models, thermocouples were used for 8 consecutive days and the data logger was programmed to take the temperature measurements at every ten minute interval to identify the heating and cooling patterns of temperature variation. Ambient temperature and external and internal surface temperature measurements in southern and eastern walls were taken. Figure 10 shows the layout of the temperature sensors. Figure 18 presents the variation of the indoor temperate in different walling materials

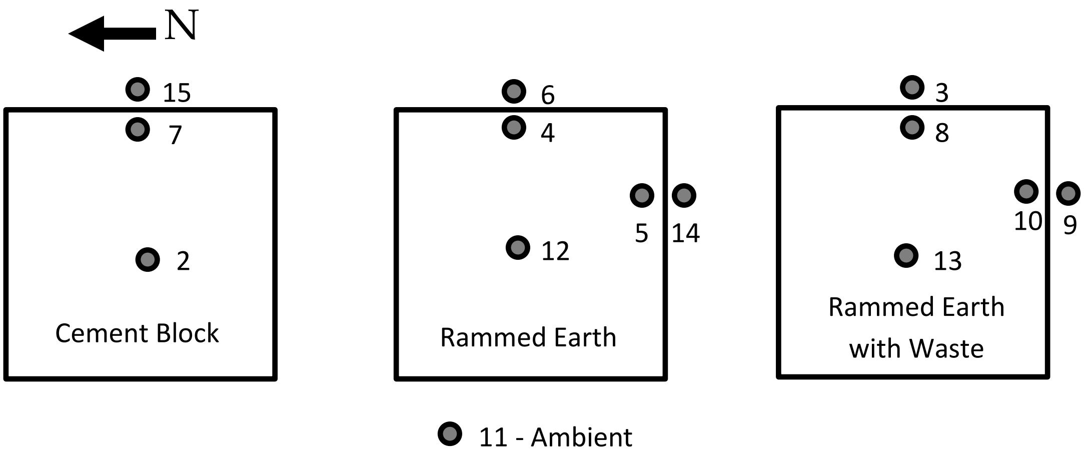



**Figure 8 - Thermal Sensors arrangement**

### 3.6 Properties of the composite material with BDW and CSRE

The proposed composite material would be a potential candidate for wall construction as load bearing and as infill panels. In order to assess the performance of this material the key properties were investigated and compared with that of similar, conventional walling materials. The key properties included the density, compressive strength, flexural strength, building performance properties such as specific heat, conductivity and water absorption. Also the durability aspects were assessed experimentally.

Results obtained as compressive strength of test cubes made out of BDW and CSRE have indicated that the maximum value is with the proportion 1 cement: 5 BDW: 5 soil. The wall strength properties were given in another publication. In order to assess the performance of the composite material, a detailed experimental programme was carried out to determine the density, thermal conductivity, specific heat and thermal performance with physical models. Durability of the material was assessed experimentally with accelerated spray erosion testing.

#### 3.6.1 Density of the Composite Material

Density of the composite material was determined by using the cubes cast for the testing programme. A sample of ten cubes of 150 mm× 150mm × 150 mm was used to measure the dimensions and the weight to determine the density of the material. The oven dried weight was obtained together with the dimensions of all the cubes. The average values for the density was worked out to be 2234 $kg/m^3$ for the bulk density and the 2021 $kg/m^3$ for the dry density. The density of the composite material is comparable with the conventional masonry materials.

### 3.6.2 Specific Heat Capacity of the composite material

Specific heat is the amount of energy needed to raise the temperature of 1 kg of a material by 1 unit of temperature. This property is needed to assess the thermal performance of the material. An experimental programme was conducted to determine the specific heat of the composite material. Test specimens were prepared as per the ASTM D4611 [30] and the testing was carried out in following steps:

1. Dry weight of the sample of specimens was determined (average value of the sample is 0.107 g).
2. The specimens were heated in an oven upto $100^0$C.
3. An insulated jar was filled with a known quantity of water (325 ml in this experiment) and the initial temperature of water was recorded with the average value of 27.77 $^0$C.
4. Each specimen was taken out of the oven and immersed in water contained in the insulated jar.
5. The temperature variation of water was recorded in 30 second interval until the steady state is reached where the temperature of the water in the jar and that of the specimen becomes equal. This has taken nearly one hour (the average value was recorded as 33.08 $^0$ C).
6. Figure 13 indicates the steady state where the heat loss of the specimen and the heat gain of the water become equal.

**Figure 9 - Test Specimen** **Figure 10 - Specific Heat Testing**

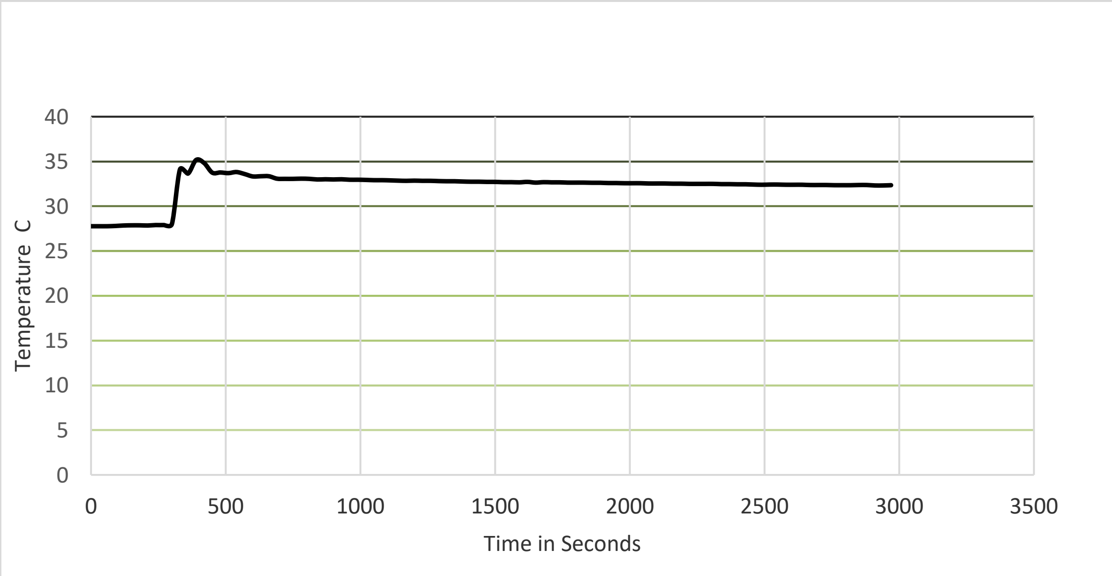



**Figure 11 - Variation of Temperature over Time**

Specific Heat Capacity of the Composite Material can be obtained by the following equation

$$E = m\,S\Theta \qquad (1)$$

Where E – Energy (J)

m – Mass (kg)

S - Specific heat capacity J $^{0}C^{-1}$ kg $^{-1}$

Ө - Change in temperature ($^{0}$C)

$S \times 0.107 \times (100-33.08) = 0.325 \times 4179\ (33.08-27.77)$

$$S = 1007.19\ {}^{J}/_{K\ .Kg}$$

$$S = 0.28\ \ {}^{Wh}/_{K\ .Kg}$$

Weight of the specimen 0.107 kg

Weight of water 0.325 kg

Specific Heat of water = 4179 J/k.Kg

Conversion =

3600 J/k.Kg = 1 Wh/k.kg                    1007.19 J/k.kg / 3600 = 0.28 Wh/k.kg

Specific heat of the composite of BDW and CSRE has been found to be 0.28 Wh/kg.k which is comparable with similar conventional materials such as burnt clay brick 0.25 – 0.27 Wh/kg.k, cement block 0.25 Wh/kg.k, CSRE 0.28 Wh/kg.k [18]

### 3.6.3 Thermal Conductivity of the composite material

Thermal conductivity is the property of a material that indicates its ability to conduct heat. Conduction will take place when there is a temperature gradient in a solid medium. Where steady state heat transfer is given by equation 2.

$$H= \frac{KA\ (T_2-T_1)}{X} \qquad (2)$$

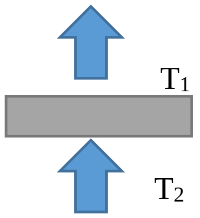



**Figure 12 - Heat flow through the specimen**

Where,

H- Steady state rate of heat transfer

K- Thermal Conductivity

A- Cross Sectional area

$$H= \frac{KA\ (T_2-T_1)}{X}$$

$T_2$-$T_1$ = Temperature difference across the sample thickness ‘X’

Heat loss from the side of the sample through glass wool is assumed to be negligible. Lee’s disk method was used to determine the conductivity of BDW and CSRE sample.

The experimental specimen in the form of a disc was made with a smaller thickness and a large cross sectional area, as shown in Figure 14.

In the apparatus used, there were two circular copper plates. The specimen has been made to suit the diameter of these copper plates. Thermo couples were attached to both plates, copper plates to read the temperature variation. Once the specimen is placed between the copper plates, it was insulated using glass wool. The copper plate at the bottom recorded the temperature of 101.6 $^0$C at the steady state. The heating was carried out by an electric heater.  At the steady state the upper copper plate recorded 48.7$^0$ C. The heat flow through the specimen H, is given by KA dT/dt.  Then the temperature variation of the upper copper plate while cooling down in air, was plotted with time which is represented in figure 16.  The gradient of the graph presents the rate of cooling which is dT/dt.

**Figure 13 - Thermal Conductivity Testing**

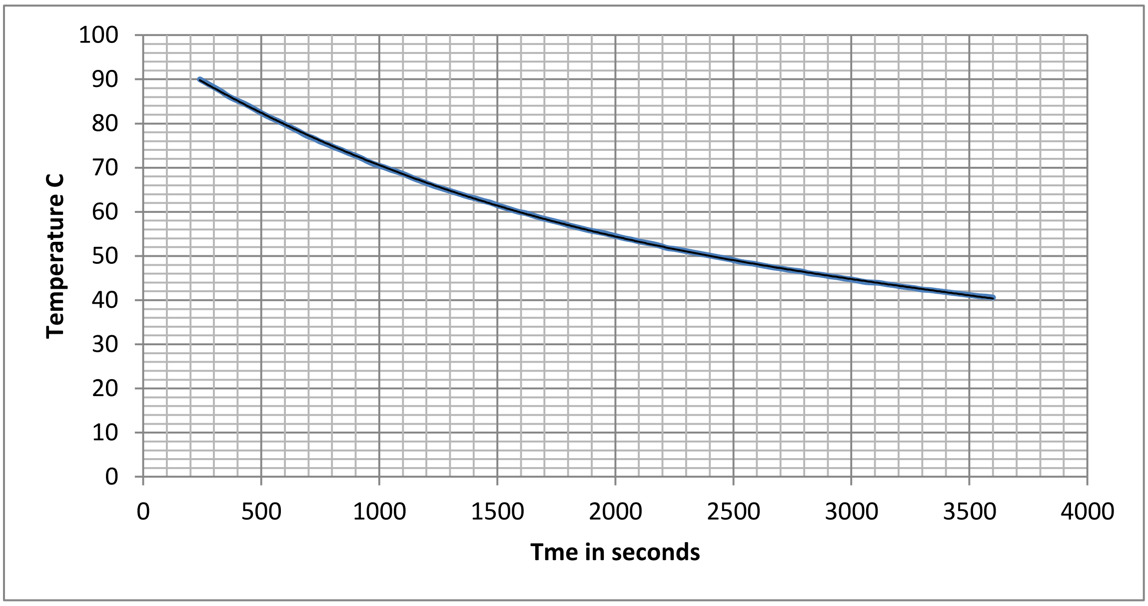



**Figure 14 - Heat Dissipation of the Plate**

Using the above experimental data and equation, thermal conductivity can be calculated.

$$K \times A \times \left(\frac{dT}{X}\right) = M \times C \left(\frac{dT}{dt}\right) \ldots\ldots\ldots\ldots\ldots.. (2)$$

K= Thermal Conductivity of the composite material

A= Area of the specimen

$\frac{dT = \text{Temperature difference between two plates at the steady state}}{X = \text{Thickness of the specimen}}$

M= Mass of the copper plate

C= thermal conductivity of copper

$\frac{dT}{dt}$ Factored gradient of the above graph at 48.7 $^{0}$C

Cross sectional area of the specimen A= 2.248 $\times 10^{-3}$ $m^2$

Temperature variation, dT= 101.6-48.7 = 52.9$^{o}$

Thickness of the specimen, X= 0.022 m

C= 3900 $^{J}/_{C\,.Kg}$

Gradient

Y= $-1 \times 10^{-9} \times X^3 + 7.513 \times 10^{-6} \times X^2 - 3.372 \times 10^{-2} \times X^1 + 97.4837$

At the steady state:

Gradient at Y= 48.7 and X= 2220.75

$$\frac{dy}{dx} = -1 \times 10^{-9} \times X^2 \times 3 + 7.513 \times 10^{-6} \times X^1 \times 2 - 3.372 \times 10^{-2} \times 1$$

= -0.01515

0.0924× $\frac{dy}{dx} = 0.01515 \times 0.0924 = 1.399 \times 10^{-3}$

K $\times 2.248 \times 10^{-3} \times \frac{52.9}{22\times10^{-3}} = 0.988 \times 3900 \times 1.399 \times 10^{-3}$

K= 1 $\frac{W}{m.K}$

Thermal conductivity of the composite of BDW and CSRE has been found to be 1 W/mk which is comparable with similar conventional materials such as burnt clay brick 0.6 – 1.0 W/mk., cement block 1.0 W/mk., CSRE 0.80 W/mk. [17]

#### 3.6.4 3.6.4 Water absorption

Since the proposed material will be used in wall construction, it is important to assess the strength in saturated condition such as floods. Water absorption was investigated as per BS 1881-122, 2011 [33]. Specimens were placed in the drying oven for 72 hours. Then each specimen was cooled down for 24 hours in dry air tight vessel and the initial weight of each sample was recorded. Subsequently the samples were immersed in water and left there for 30 minutes. After 30 minutes, specimens were taken out and free water was removed from the surface. Finally the weight of the specimen was recorded. The following values indicated the water absorption and density of the composite material. The result (12.5%) was comparable with the burnt clay brick which is 12% water absorption.

Water absorption - 12.5%

Moisture content - 3.2 %

Density (Saturated) - 2158 kg/m3

Density (Dry) - 1919 kg/m3

### 3.6.5 Durability

Durability of the composite material was assessed through the Accelerated erosion test. Erosion test was done according to the SLS 1382 [31] for Compressed Stabilized Earth Blocks.150mm × 150mm × 150mm cubes were used for the determination of durability. Selected specimens were mounted in the test apparatus in the same orientation as intended in wall construction. The sample was placed 500 mm from the shower rose as shown in Figure 6 and water was sprayed horizontally at a pressure of 50 kPa. Each specimen was subject to a water spray for 60 minutes. In 15 minute intervals, pit depth was measured using a 10-mm diameter flat ended rod. Maximum depth of eroded hole observed was 6 mm which is less than the permissible maximum (Sri Lankan standards).

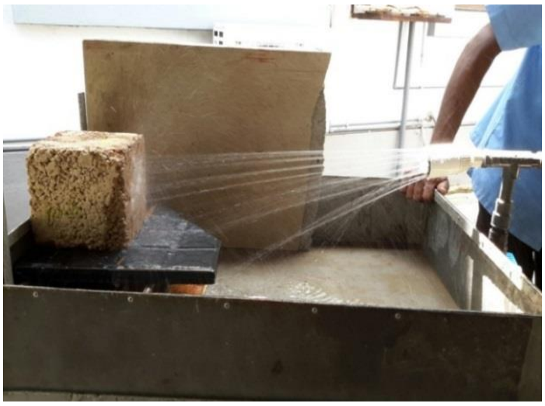


**Figure 15 - Accelerated erosion test**

# CHAPTER 04

# RESULTS AND ANALYSIS

## 4.1 General

The purpose of this chapter is to discuss the empirical values obtained from the experimental processors and the comparison of temperature values obtained from DEROB-LTH and actual values.

## 4.2 Mix proportions

**Table 9 - Cube strength Results**

| Mix proportion | Compressive strength (7 days) $N/mm^2$ | Dry Compressive strength (28 days) $N/mm^2$ | Wet Compressive Strength (28 days) $N/mm^2$ | Density ($kg/m^3$) |
|---|---|---|---|---|
| 1:4:6 | 2.67 | 3.00 | 2.0 | 1763 |
| 1:3:7 | 3.17 | 3.50 | | 1812 |
| 1:6:4 | 3.67 | 5.67 | | 1961 |
| 1:5:5 | 4.80 | 6.33 | 6.0 | 2064 |
| 1:10 (Rammed earth) | 3.00 | 3.50 | | 1828 |

According to the results of testing compressive strength, mix proportion 1:5:5 shows best performance over other mix proportions. Since that we selected 1Cement: 5 Building Waste: 5 Soil mix proportion as the most suitable mix design for this study. This strength values are higher than the conventional rammed earth cube strengths (1:10). Therefore by using construction waste, it is possible to enhance the strength characteristics of the wall panels while recycling the waste.

**Table 10 - Comparison of strength parameters of different materials**

| Material | Strength Parameters | | |
|---|---|---|---|
| | Compressive Strength ($N/mm^2$) | Flexural strength Parallel to Bed ($N/mm^2$) | Flexural Strength Perpendicular to bed ($N/mm^2$) |
| Burnt Clay bricks of water absorption >12% (115mm thick) | 2.01 | 0.3 | 0.9 |
| CSE bricks- English bond (110mm thick) | N/A | 0.365 | 1.491 |
| CSE solid block (225mm thick) | 2.032 | 0.243 | 1.284 |
| CSE interlocking hollow block (145mm thick) | 1.3 | 0.262 | 0.261 |
| 240mm thick cement stabilized rammed earth wall section with 8% cement | 2.06 | 0.463 | 0.918 |
| 150mm thick wall material made from the new material with 9% cement | 2.05 | 1.34 | 1.67 |

## 4.3 Thermal Properties

According to the test results, the density of new composite material is slightly higher than the conventional rammed earth material (2000 $Kg/mm^2$), it means the new composite material has enhanced compacting qualities.

Thermal conductivity of composite material is somewhat less than the normal rammed earth material (0.38). Since the thermal conductivity of new material is less than the cement block and normal rammed earth, heat transfer will be reduced.

Specific heat capacity is approximately equal in both new composite material and the rammed earth material.

**Table 11 - Composite Material Properties**

| Material Property | Value |
|---|---|
| Density | 2200 $kg/m^3$ |
| Thermal Conductivity | 0.35 W/mk |
| Specific Heat Capacity | 0.28 Wh/kg.k |

### 4.3.1 Temperature Variation

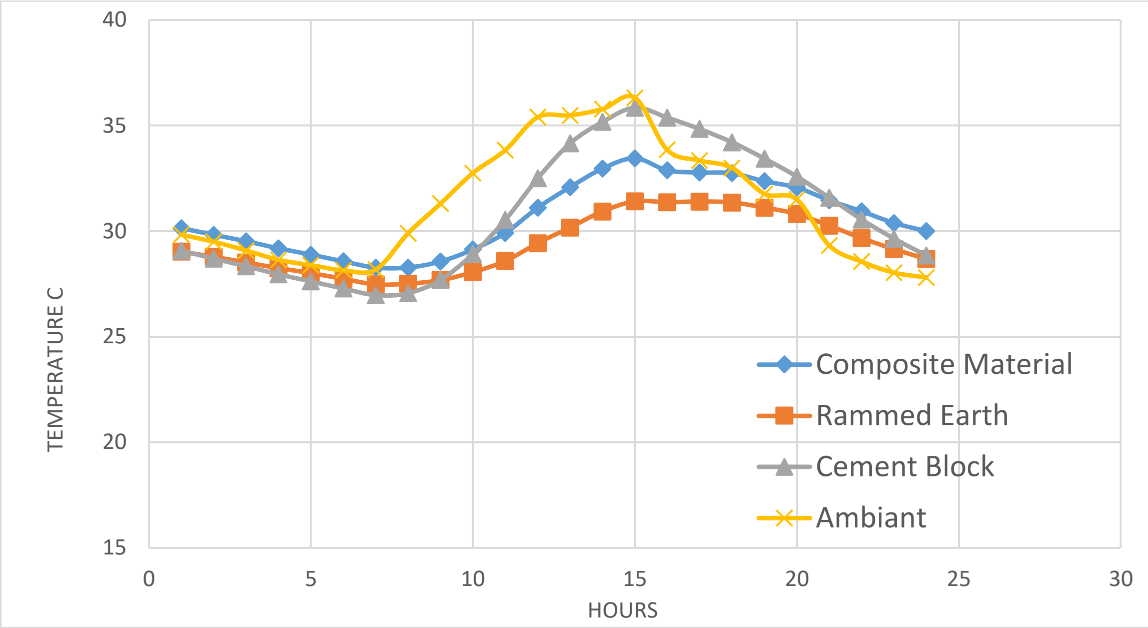



**Figure 16 - Indoor surface temperature comparison of different materials**

According to the figure 19, it can be seen that the variation of the temperature of the cement block wall is slightly higher than the other material walls over the time. The variation of the temperature in Composite Material wall is also higher with relative to the rammed earth wall in the day time. Therefore the variation of the surface temperature in the wall that was made with composite material is comparatively have medium indoor surface temperature with respect to the other conventional materials.

### 4.3.2 Computer simulation of temperature variation

The results obtained from the experimental program was backed by the computer simulation so that it can be used in evaluating the walling material for thermal comfort in green rating system.

Computer simulation was carried out by using a software package called DEROB-LTH (Dynamic Energy Response of Buildings-LTH). This is capable of simulating the condition on hourly basis considering the heat gains, losses and ambient condition. The thermal properties established by the research were used as input parameters of the program. In order to validate the outputs of the experiments, computer simulation has been carried out. By conducting a computer simulation using DEROB-LTH, it is possible to compare the actual temperature measurements and the hourly temperature values that is given by the software.

The output of the computer simulation was compared with the results obtained from the experimental study with physical models. If the two sets of results are significantly close the computer simulation can be used to establish the comfort with this material under any other circumstances such as different time of the year with different finishing materials etc. Table 12 shows the experimental values of the new building material and Table 13 shows the parameters of other conventional building materials.

**Table 12 - Properties of composite building material**

| Material Property | Value |
|---|---|
| Density | 2200 $kg/m^3$ |
| Thermal Conductivity | 1W/mk |
| Specific Heat Capacity | 0.28 Wh/kg.k |

For simulation, an average climatic data file for April was used since the exact variation in solar radiation intensities that took place during the actual measurements are difficult to simulate with an interval of one hour. However computer simulation provides a reasonable comparison with the results of actual temperature measurements and the isolated, ideal condition surface temperature variation of the models. Three models were created in DEROB by inserting the parameters of building materials. Experiments were conducted without any surface finishes. Thus the comparisons were also carried out with absorption of similar colours where there was a coefficient of absorption of 60% and emittance of 80%.

**Table 13 - Properties of conventional building materials [4]**

| Material | Conductivity (W/mk) | Specific Heat (Wh/kg.k) | Density ($kg/m^3$) |
|---|---|---|---|
| Cement Blocks | 1.00 | 0.25 | 1200 |
| Soil Blocks | 0.85 | 0.24 | 1800 |
| Rammed Earth | 0.80 | 0.28 | 2000 |
| Asbestos | 0.40 | 0.25 | 1600 |
| Plywood | 0.135 | 0.75 | 550 |

**Table 14 - Weather Details**

| Day | Temperature | | Sunshine hours | Total Solar Radiation ($MJ/m^2$) | Average Vapour Pressure (mb) | RH (%) | |
|---|---|---|---|---|---|---|---|
| | Max | Min | | | | Max (Day) | Min (Day) |
| 3/30/2015 | 31.6 | 24.8 | 9.5 | 25.39 | 31 | 94 | 64 |
| 3/31/2015 | 32.5 | 25.4 | 6.3 | 18.6 | 30.1 | 93 | 61 |
| 4/1/2015 | 31.4 | 25 | 7.9 | 21.61 | 29.8 | 93 | 61 |
| 4/2/2015 | 32.2 | 24 | 10.9 | 27.14 | 30.5 | 95 | 66 |
| 4/3/2015 | 31.8 | 25.2 | 10.2 | 27.31 | 32.3 | 91 | 67 |
| 4/4/2015 | 32.5 | 26.8 | 9.8 | 25.46 | 31.1 | 89 | 66 |
| 4/5/2015 | 32.7 | 25.5 | 10.4 | 24.85 | 31.8 | 89 | 69 |
| 4/6/2015 | 32.6 | 25.5 | 9.8 | 23.52 | 31.2 | 89 | 68 |

**Table 15 - Rainfall Details**

| Date | Hourly Rain Fall |
|---|---|
| 3/30/2015 | 7.2 mm |
| 3/31/2015 | 7.8 mm |
| 4/1/2015 | 9.5 mm |
| 4/2/2015 | - |
| 4/3/2015 | - |
| 4/4/2015 | - |
| 4/5/2015 | - |
| 4/6/2015 | - |

Source – Department of Metrology

As shown in above tables, the weather variation in eight days has been obtained from the Department of Meteorology. In 2015/04/04 there was not rain and also have normal sunshine hours. Therefore 2015/04/04 was chosen to get the temperature measurements to compare with DEROB-LTH hourly temperature values.
To get the Hourly temperature values from the DEROB-LTH, the physical models that is constructed in the site have to be modeled in DEROB-LTH and some data regarding the position of the station have to be inserted to get the actual conditions to the analysis.

Thermal comfort is defined in British Standard BS EN ISO 7730 [33] as: 'that condition of mind which expresses satisfaction with the thermal environment. 'So the term 'thermal comfort' describes a person's psychological state of mind and is usually referred in terms of whether someone is feeling too hot or too cold. Thermal comfort is very difficult to define because you need to take into account a range of environmental and personal factors when deciding what will make people feel comfortable. These factors make up what is known as the 'human thermal environment'.

For the analysis of thermal performance, the surface temperature is the best for comparison. Both indoor and outdoor surface temperature could indicate the idea about thermal mass and time lag. Hence, indoor temperatures are used for comparison purpose.

Figure 20 represents the variation of indoor temperatures of the values obtained from both actual measurements and the DEROB-LTH in the model that has been made with composite material. Figure 21 represents the variation of indoor temperatures of the values obtained from both actual measurements and the DEROB-LTH in the model that has been made with soil and cement mix. Figure 22 represents the variation of indoor temperatures of the values obtained from both actual measurements and the DEROB-LTH in the model that has been made with cement blocks.

It can be seen that the DEROB-LTH simulations also has given a similar trend of variation and approximately equal values. This is an important step since DEROB-

LTH could be used for comparison based on actual hours and also with different surface finishes and materials.

figure 20 represents the variation of indoor surface temperature of the models different types of materials. From this graph it is easy to compare the thermal performance of different materials. The results shows that the inside surface temperature of the block wall has the highest values at the day time with respect to other materials. Next to the cement block wall temperature, the wall that has been made using composite material gives the highest surface temperature in the day time. At the day time rammed earth wall gives the minimum tamperature values. The thermal performance of the proposed composite wall can be considered as comparable and also better than the cement – block walls.

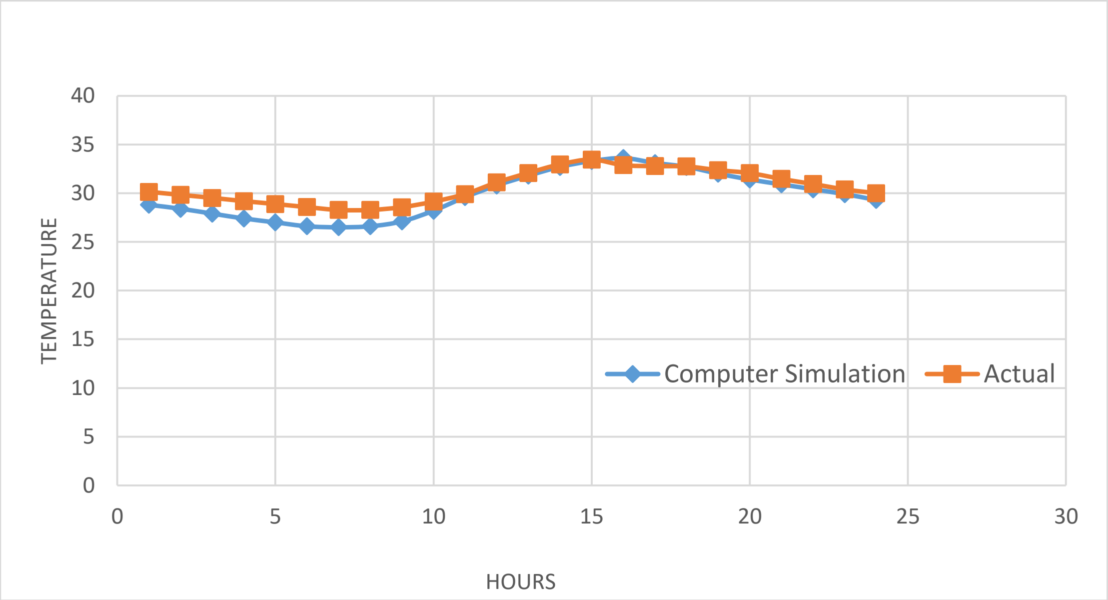



**Figure 17 - DEROB vs Actual temperature values of composite material wall, eastern side**

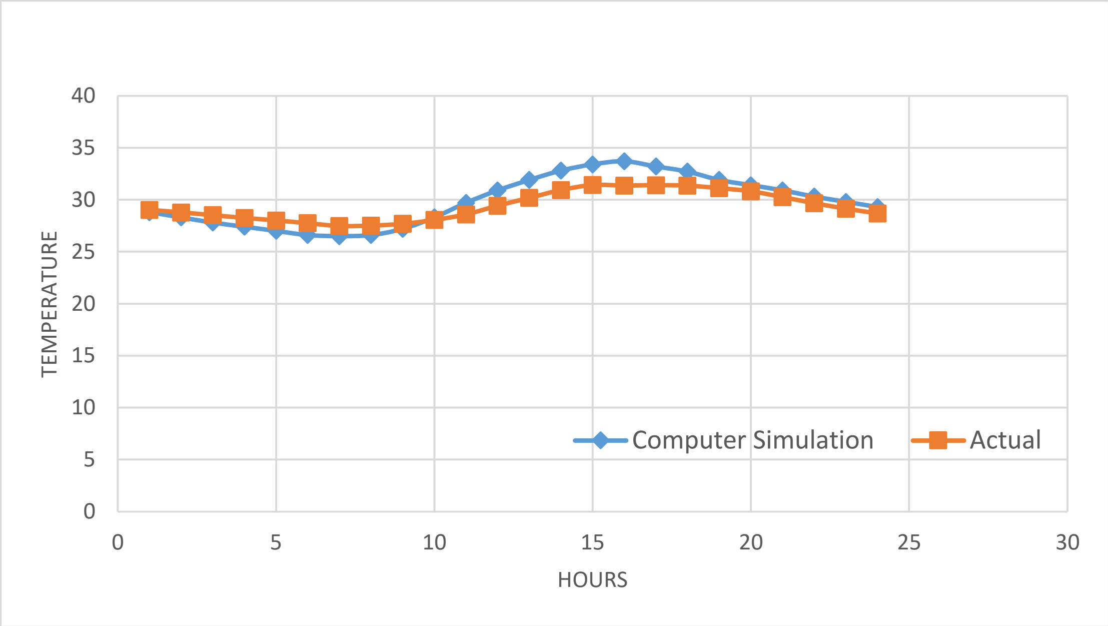



**Figure 18 - DEROB vs Actual temperature values of rammed earth wall, eastern side**

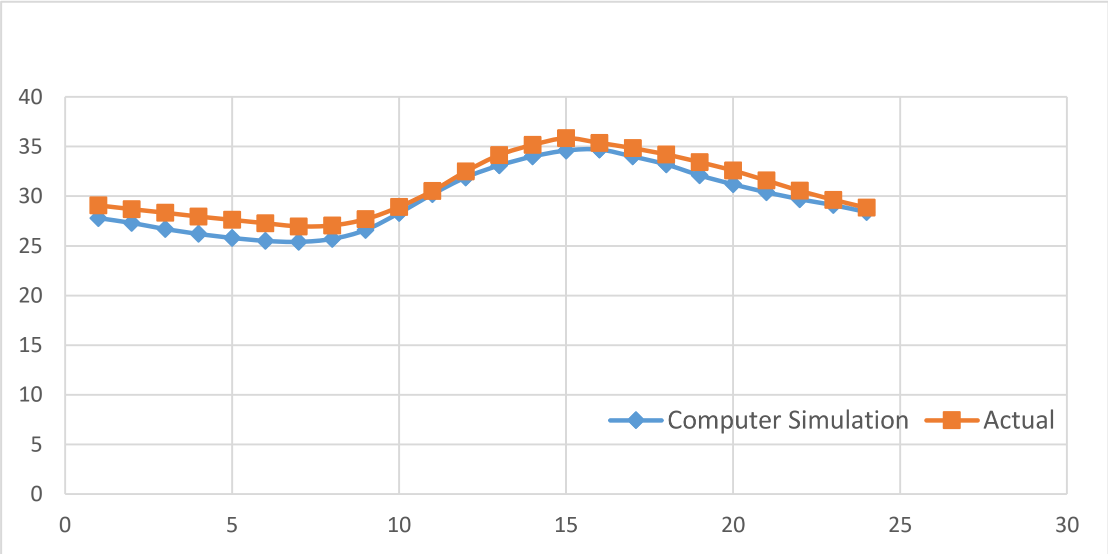



**Figure 19 - DEROB vs Actual temperature values of cement block wall, eastern side**

# CHAPTER 05

# CONCLUSION AND RECOMMENDATION

## 5.1 Computer Simulation

As the results of the analysis, the hourly temperature values that are given by the DEROB-LTH is tally with the actual hourly mean temperature values. So it is possible to use DEROB-LTH for different materials with different properties and surface conditions in different shapes of buildings.

Also we can predict the indoor and outdoor surface temperature values of the building for a day in the future.

Therefore DEROB-LTH is validated for the predictions of surface temperatures and acquiring surface temperatures for different materials, surface colors and various kind of shaped buildings.

## 5.2 Comparison of Materials

According to the comparison of surface temperature variation of physical models in different conventional materials with new composite material, Cement Block model has a higher variation with time. The variation of the temperature in Composite Material wall is also higher with relative to the rammed earth wall in the day time. Therefore the variation of the surface temperature in the wall that was made with composite material is comparatively have medium indoor surface temperature with respect to the other conventional materials.

Since the new composite material is an ideal solution for recycling the construction waste that is generating from the demolition of buildings and other structures, this walling material can be used with improved thermal characteristics to enhance the thermal performance and sustainable aspects.

Also according to the cube testing results, the new composite material and the rammed earth, the composite material gives the higher strength values more than the conventional rammed earth cubes. Therefore the structural performance of the composite material is also at a satisfactory level for the construction of buildings.

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